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Full Length Research Paper

Determination of drillability of some natural stones and their association with rock properties

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Rapid and economic drilling of the holes for placement of diamond wires of diamond wire cutting machine which are opened in development work and production activities in underground, open pit mining and boreholes are important issues. For this purpose, drilling rates on different natural stone of diamond bit which mounted to a laboratory scale core drilling machine were determined. Later, relationships between mechanical properties and penetration rates of natural stones were investigated and interpreted. As a result, this study has demonstrated that to estimate penetration rates of natural stones, it would be appropriate to consider several characteristics.

Key words: Drillability, penetration rate, natural stone, marble, drilling rate, drillability.

INTRODUCTION

Drilling and blasting play vital roles in opencast mining. These operations do not only affect the cost of production directly but as well the overall operational costs (Busuyi, 2009). The penetration rate and economic of the holes opened (blastholes, diamond wire holes in natural stone mine, groundwork construction) during the development and production activities in underground and open-pit mines and dam, tunnel, road construction and also sewerage systems play crucial role. Therefore, prediction of the penetration rate is very important in rock drilling. The penetration rate is a necessary value for the cost estimation and the planning of the project. Drillability and penetration rate can be defined as similar terms. While drillability indicates whether penetration is easy or hard, penetration rate indicates whether it is fast or slow. Rock drilling is performed with a number of techniques ranging from rotary/percussive drilling in very hard rock, via rotary/crushing drilling in medium hard rock, down to cutting in soft rock types.

It mainly depends on operational variables and rock characteristics. Operational variables are known as controllable parameters: rotational speed, thrust, blow frequency and flushing. However, rock properties and geological conditions are uncontrollable parameters (McGregor, 1967; Beste et al., 2007). Taking into consideration the optimum penetration rate, choosing the correct drilling machine, the petrographic structure of the rock, its hardness, abrasion, physical characteristics and mechanical properties are to be determined firstly by *in-situ* and laboratory studies.

Penetration rate is the progression of the drilling bit into the rock in a certain period of time, which is generally expressed as "m/min". According to the factors that affect, penetration rate can be classified as changeable and unchangeable factors (Wirth, 1981). These factors are rock characteristics, mechanic and hydraulic factors, mud properties and complementary factors. Among them the hardness of the rock, uniaxial compressive strength and abrasion are the most important unchangeable factors.

The most important changeable factors are bit type and design characteristics, the amount of compression applied and drill rotation speed. Fast and economical penetration depends on the mineralogical structure of the rock, drilling machine, geo-mechanic characteristics, the driller used and the choice of drilling tools appropriate to the rock (Onan and Müftüoğlu, 1993). The prediction of penetration rate is very important in mine planning. Total drilling costs could be estimated by using prediction equations. Also, one could use prediction equation to select the drilling rig type which best suits for given conditions.

Performance of a drilling is dependent on technical characteristics of the drilling, drillability of rock and work organization. First of all, rock characteristics are to be determined very precisely and drilling and drill bit type is to be chosen accordingly. It is very important that pressure, torque, rotation speed and impact frequency called as operational parameters to be applied according to formation characteristics. In addition to them, if work organization is designed carefully, maximum performance from the drilling machine can be achieved (Kahraman and Mülazımoğlu, 1999). Kahraman (1999) developed penetration rate models for rotary, down the hole and hydraulic top hammer drills using multiple curvilinear regression analysis. Besides, for rotary drills uniaxial compressive strength, for DTH drills Schmidt hammer rebound number and for hydraulic top hammer drills uniaxial compressive strength and quartz content have been determined as the dominant rock property. Various experimental methods and drillability models were developed to determine drillability or to predict penetration rate (Bilgin, 1983; Schneider, 1988; Gehring, 1997; Thuro and Plinninger, 1999; Tandanand and Unger, 1975; Protodyakonov, 1962; Morris, 1969). Among them some of them are drilling rate index (DRI), bit wear index (BWI) and coefficient of rock strength (CRS) (Yaralı et al., 2008).

Yenice et al. (2009) studied the relation between drillability index of marbles (DRI) and their physical, mechanical and textural characteristics. As a result, they determined significant relations between marbles density, hardness, uniaxial compressive strength, tensile strength and DRI. Kahraman et al. (2000) showed that for the rocks tested, the drillability index is closely related to rock compressive strength, tensile strength, N type Schmidt hammer rebound number and impact strength. Kahraman et al. (2003) found that uniaxial compressive strength, tensile strength, the point load strength and the Schmidt hammer value are the dominant rock properties affecting the penetration rate of percussive drills. Pathinkar and Misra (1980) concluded that conventional rock properties such as uniaxial compressive strength, tensile strength, specific energy, shore hardness and mohs hardness do not individually give good correlation with the penetration rate of percussive drilling. Miranda and Mello-Mendes (1983) stated that rock drillability definition based on Vickers microhardness and specific energy seems to point to a logical selection scheme for the most adequate rock drilling equipment based only on rock laboratory tests.

There are both laboratory and *in-situ* studies on the correlation between drilling machine performance and characteristics of the drilling formation. For example, Fish (1961) found out that there is a linear relation between the rate of force applied to drill to penetration rate and uniaxial compressive strength of some sedimentary rocks. Schmidt (1972), who studied on 25 different types of rock with hammer drilling machine, examined the relation between uniaxial compressive strength and penetration rate. Singh (1969) showed that compressive strength is not directly related to the drilling rate of a drag bit. Leighton et al. (1982) developed a rock quality index which is the rate of the pressure strength to progression rate, and used them successfully in an open-pit copper mine in the arrangement of loosening holes and determination of the amount of explosive to be used. As a result of the *in-situ* and laboratory drillability studies with diamond core drills, Paone and Madson (1966) observed that there is an exponential relation between penetration rate and uniaxial compressive strength and tensile strength.

The aim of this study is to determine physico-mechanical characteristics of natural stones which are determinant in their drillability. In this study, the experimental studies were carried out in two stages which are composed of mechanical tests and drillability rates. Mechanical tests include uniaxial compressive strength, indirect tensile strength, point load strength, Schmidt hardness and sonic velocity tests. The drillability rates were determined by core retrieval machine. The relations between mechanical characteristics of natural stones and their drillability rates were examined and interpreted.

PREPARATION OF EXPERIMENT SAMPLES

Some mechanical experiments on natural stones samples transported from Central Anatolia Region (Andesite, Marble, Tuff, Travertine, and Limestone) were planned to carry out (Figure 1). The cylindrical core samples from the blocks of samples brought to the laboratory were prepared with core retrieval machine. The ISRM (1981) suggested methods were used in sample preparations. In addition, during the extraction of core samples from blocks, time-dependent measurements on core retrieval machine drillability rates were made.

EXPERIMENTAL STUDIES

Experimental studies are presented under two different headings as studies carried out to determine physico-mechanical properties and penetration rate.

Determination of physico-mechanical properties

The physico-mechanical tests on core samples were carried out according to test standards suggested by ISRM (1981).

Uniaxial compressive strength test (UCS)

An electro-hydraulic servo-controlled stiff testing machine was used for determination of the uniaxial compressive strength. The hydraulic press with 3000 kN capacity was used to apply uniform axial load on the rock sample. Loading speed was determined to be 1.5 kN/sec. Uniaxial compressive strength tests (UCS) were carried out on a total of 10 different rock types, with the length/diameter rates ranging between 2.5 to 3 at 54 mm diameter. 10 core samples were used for each of the different rock types. Thanks to a load cell

Figure 1. Location of the samples carrying out the tests.

Table 1. Means of physico-mechanical experiment results.

Rock type	UCS (MPa)	ITS (MPa)	PLT (MPa)	Schmidt hardness	P-Wave velocity (km/sec)	Porosity (%)	Density (gr/cm^3)
Andesite	72.04±6.88	3.68±0.36	5.19±0.27	55.70±1.46	3.85±0.17	2.46±0.13	2.54±0.04
Afyon marble	84.81±8.14	4.58±2.20	3.69±0.62	62.21±2.99	7.04±0.09	0.90±0.33	2.66±0.04
Beige marble	81.33±9.20	4.31±0.87	3.78±0.49	59.53±2.23	6.98±0.10	0.62±0.25	2.63±0.05
Grey tuff	39.71±5.69	2.17±0.40	1.76±0.05	57.22±3.47	2.23±0.21	20.85±0.29	1.82±0.01
Pink tuff	21.03±4.89	3.17±0.77	1.84±0.18	47.00±3.71	1.86±0.16	29.87±0.37	1.72±0.02
Yellow tuff	4.42±1.31	0.68±0.18	0.59±0.09	27.12±2.33	1.52±0.11	36.57±0.36	1.28±0.02
Travertine-1	18.22±6.77	2.91±0.92	3.18±0.72	49.21±5.50	4.83±0.32	4.87±2.40	2.20±0.08
Travertine -2	21.33±4.62	2.02±0.54	1.40±0.42	37.50±5.88	3.52±0.45	16.39±2.54	2.05±0.08
Travertine -3	23.95±6.86	2.02±0.36	1.43±0.71	48.51±5.77	5.00±0.50	7.90±3.22	2.16±0.10
Argillaceous limestone	13.42±3.81	1.53±0.15	1.21±0.45	27.63±4.55	2.55±0.30	15.70±4.78	1.72±0.14

placed on hydraulic press and connected to a data logger, both breaking loads and instant load changes of the samples could be monitored. The UCS values determined for different rock types were presented in Table 1.

Indirect tensile strength test (ITS)

For this test hydraulic press was used. In the experiments, loading speed was chosen to be 0.2 kN/sec. and applied to 10 core samples prepared for each different rock types. Both breakage loads and instant load changes the samples could be monitored via load cell. The indirect tensile strength values varied between 0.68 to 4.58 MPa. Test results were presented in Table 1.

Point load strength test (PLT)

In the point load strength test ISRM (1981) suggested method was used. The axial type point load test was carried out on core samples. The point load tests were repeated at least ten times for each material type and the average value was recorded as the point load strength. Test results were given in Table 1. According to the point load strength values, while the strongest rock type was andesite, the weakest rock type was yellow tuff.

Schmidt hardness test

ISRM (1981) suggested that 20 rebound values from single impacts separated by at least a plunger diameter should be recorded and averaged the upper ten values. The test method was carried out on all rock types. For the test, L type digital Schmidt hammer was used. Schmidt hammer tests were performed on block samples. Tests were performed with an L-type Schmidt hammer having impact energy of 0.735Nm with the hammer held vertically downwards. According to the test results shown in Table 1, the Schmidt hammers values change between 27 to 62.

Sonic velocity test

The velocity of ultrasonic pulses traveling in a solid material depends on the density and elastic properties of the material. P-wave velocities of different rocks (km/sec.) were determined by using a Portable Ultrasonic Nondestructive Digital Indicating Tester (PUNDIT). Using the device, firstly sound propagation time (μs) values were measured and propagation speeds were calculated. The tests applied to 10 core samples were prepared for each different rock types. The test results were presented in Table 1. The sonic velocity values range from 1.52 to 7.04 km/sec.

Density and porosity test

In the density and porosity test, ISRM (1981) suggested method was used. In porosity experiment "Buoyancy Method" was used. Through Buoyancy method, bulk volume of regular or irregular samples can be calculated with Archimedes principle. As some of

Table 2. Penetration rate test results.

Rock type	Penetration rate (cm/min)
Andesite	0.208±0.06
Afyon marble	0.997±0.18
Beige marble	0.269±0.02
Grey tuff	1.853±0.64
Pink tuff	3.165±0.76
Yellow tuff	35.910±5.25
Travertine-1	0.283±0.03
Travertine -2	2.507±0.86
Travertine -3	2.393±0.66
Argillaceous limestone	27.825±5.66

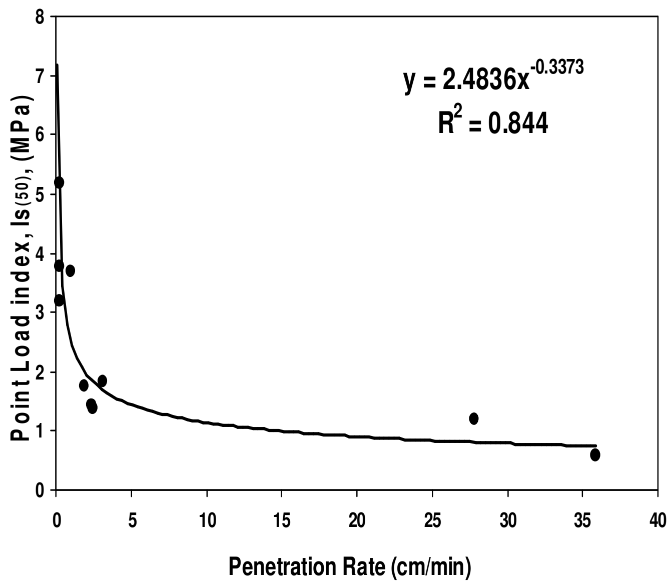

Figure 2. The relation between penetration rate and point load index.

the samples had cavities inside, this method was used. The weight of the specimen was determined by a balance, capable of weighing to an accuracy of 0.01 g or % of the sample weight. An electronic precision balance was used to weigh samples' weight and a drying oven was used to dry samples. Density and porosity test applied on 10 samples were prepared for each different rock types.

Penetration rate test

A laboratory scaled core retrieval machine was used to determine rocks' penetration rates. Penetration rate tests were carried out on five samples for each natural stone type. Thus, penetration rate test were carried on a total of 50 samples. A new drill bit was used in penetration rate tests and all tests were carried out with this bit. Rotational speed of the drill bit was determined to be 1479 rpm in all penetration tests. It was decided that while penetration rates of rocks are determined, water debit and drilling force parameters are constant at all tests. In all penetration tests, water debit was utilized to be 2.4 lt/min and drilling force applied during all the tests was 137 N. The experimental penetration rate results of natural stones

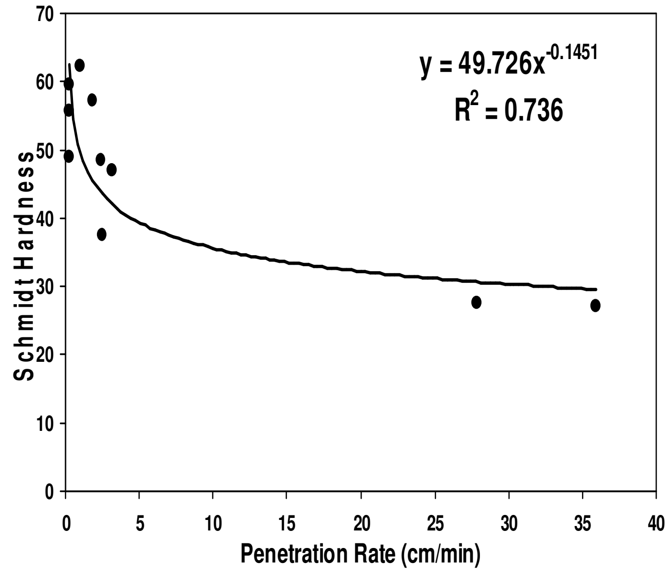

Figure 3. The relation between penetration rate and Schmidt hardness.

are given in Table 2. While the highest penetration rate was yellow rock type, it was shown that the smallest penetration rate was determined for andesite rock type.

RESULTS

Penetration rates obtained from penetration experiments were compared to physico-mechanical properties of natural stones. The graphics shown the relations between these parameters are given in Figures 2 to 8. In the Figures, the relation coefficients are presented in descending order. As it can be seen in the figures, the biggest relation value was found between penetration rate and point load strength value (Figure 2). However, the results also indicate that there is not a significant relation between P-wave velocity and penetration rate values of rocks (Figure 8). The other interesting result shown in Figure 4 is that there was a strong relation between density values and penetration rate. In fact, it is already known that there is a relation between density values of rocks and penetration rates in rock units with a high density. In other rock types, we do not generally expect a very high relation between density and penetration rates. The reason of high relation seen in Figure 4 can be explained with the tests done with natural stones because natural stones have a more compact structure compared to other rocks.

There found a moderate relation between uniaxial compressive strength value and penetration rate (Figure 6). In fact, in similar studies on this issue it is seen that a higher relation between uniaxial compressive strength and penetration rate is expected. The relation between these two parameters turns out to be smaller than expected results from petrographic characteristics of Travertine 1

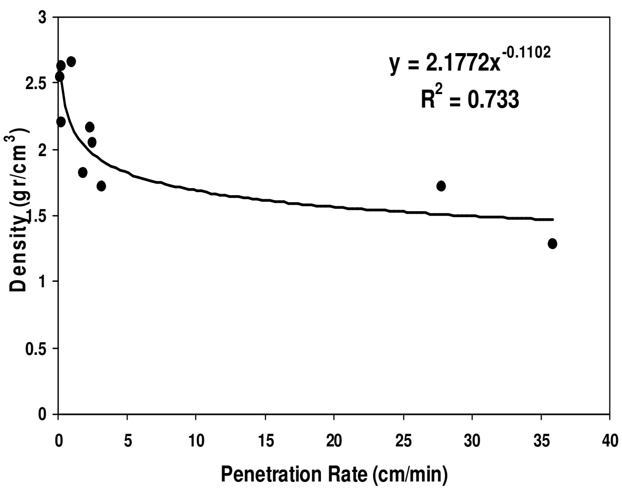

Figure 4. The relation between penetration rate and density.

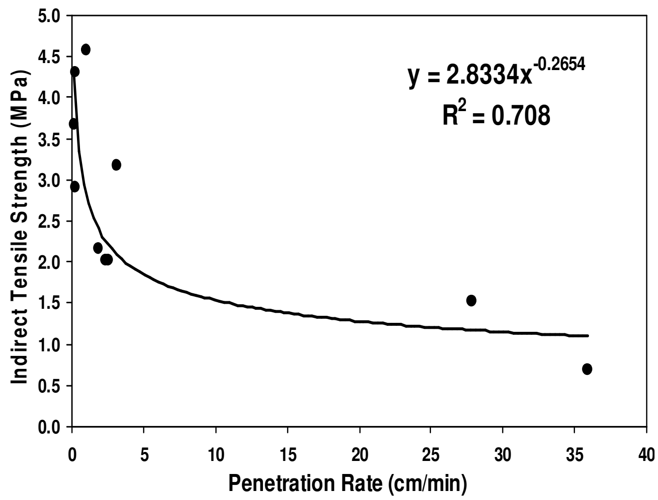

Figure 5. The relation between penetration rate and indirect tensile strength.

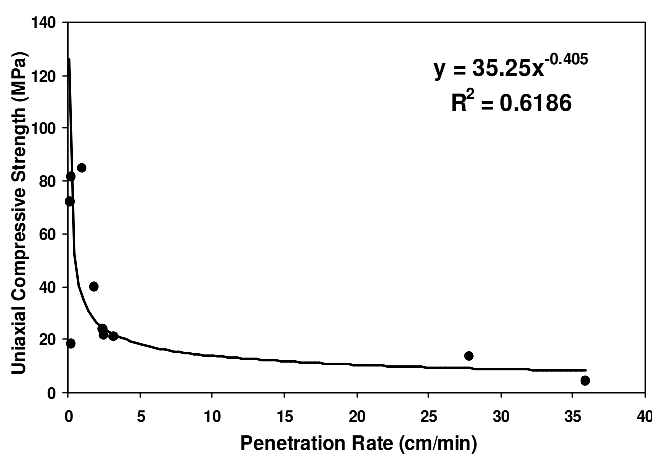

Figure 6. The relation between penetration rate and uniaxial compressive strength.

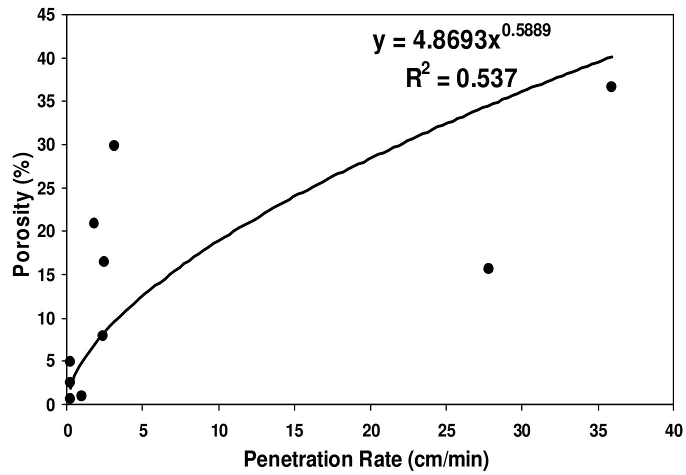

Figure 7. The relation between penetration rate and porosity.

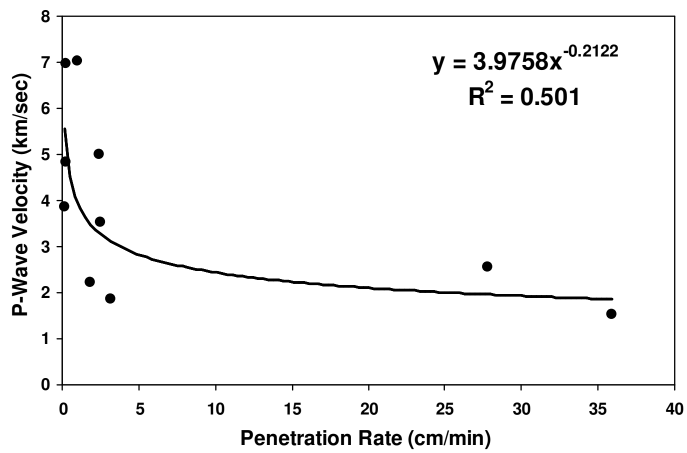

Figure 8. The relation between penetration rate and P-wave velocity.

sample. This sample has defect as planes of weakness and small holes. While these defects in rocks did not have significant effect in penetration rate tests on Travertine 1 rock type, these defects had a great effect on uniaxial compressive strength and strength value obtained to be lower than expected. Therefore, relationships between uniaxial compressive strength value and penetration rate was obtained less than expected. Another noticeable result was that penetration rate was higher in argillaceous limestone and yellow tuff samples compared to other rocks types. This can be attributed physico-mechanical characteristics of rock types and their being more affected from water.

DISCUSSION AND CONCLUSIONS

In natural stone mines, natural stone blocks are cut from faces with diamond wire saw machine. For diamond wires to be placed holes are to be drilled on the surface of the block to be cut. Generally pneumatic drill machines are used to open these holes. Most of the manufactures producing these drilling machines used in natural stone industry do not specify estimated penetration rates of the machines according to rock characteristics. They generally provide an estimated penetration rate range. Therefore, the firms to buy these machines cannot estimate time required drilling holes in the natural stones they produce and thus they cannot make precise estimations about the time required to retrieve a block. However, it is possible to find information about how penetration varies according to rock characteristics in the catalogues of the jumbo and wagon drilling machines. The manufacturers of jumbo machines and the like generally specify uniaxial compressive strength values and penetration rates. The strength characteristics of rocks have been used as drillability criteria for a long time. Recent studies have shown that using strength features alone can be misleading (Pool and Farmer, 1978; Bilgin and Shahriar, 1986). Therefore, in this study besides uniaxial compressive strength other mechanical characteristics of the rocks used by drilling machine manufacturers were discussed, as well.

As a result, the manufacturers' of drilling machines used in natural stone enterprises specification of penetration rates of drilling machines in relation to rock characteristics will enable those who are to purchase drilling machine to make correct and wise choices. Besides, this study has demonstrated that to estimate penetration rates of natural stones it would be appropriate to consider several characteristics (point load strength, density etc.) altogether instead of considering uniaxial compressive strength alone.

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