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Dominant rock properties affecting the penetration rate of percussive drills

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Abstract

Percussive blast hole drills were observed in eight rock types at an open pit mine and three motorway sites. The net penetration rates of the drills were calculated from the performance measurements. Rock samples were collected from the drilling locations and the physical and mechanical properties of the rocks were determined both in the field and in the laboratory. The penetration rates were correlated with the rock properties. The uniaxial compressive strength, the Brazilian tensile strength, the point load strength and the Schmidt hammer value exhibit strong correlations with the penetration rate. Impact strength shows a fairly good correlation with penetration rate. Weak correlations between penetration rate and both elastic modulus and natural density were found. Any significant correlation between penetration rate and P-wave velocity was not found.

It was concluded that, among the rock properties adopted in this study, the uniaxial compressive strength, the Brazilian tensile strength, the point load strength and the Schmidt hammer value are the dominant rock properties effecting the penetration rate of percussive drills. Theoretical specific energy as defined by different research workers is proved also to be well correlated with penetration rate of percussive drills which verifies basic theoretical works on the subject. In addition, the point load and the Schmidt hammer test can practically be used in the field as a predictive tool for the estimation of penetration rate.

1. Introduction

Percussive drills have been extensively used in open pit mines, quarries and construction sites. An accurate estimation of drilling rate helps to make more efficient the planning of the rock excavation projects. The drillability of the rocks mainly depends on operational variables and rock characteristics. Operational variables known as the controllable parameters are rotational speed, thrust, blow frequency and flushing. Rock properties and geological conditions are the uncontrollable parameters. In this study, the penetration rates of the percussive drills were measured in the field and the rocks were tested both in the field and in the laboratory. Then, the penetration rates were correlated with the rock properties for the development of reliable equations in order to allow engineers predict the penetration rate from rock characteristics.

2. Previous investigations

Many researchers have investigated theoretically or experimentally the percussive drilling and correlated the penetration rate of percussive drills with various rock properties. Hartman [1,2] performed drop-test studies and proposed a drilling-rate model incorporating the volume of the bit crater produced in the drop test as the parameter that expressed the behaviour of the rock under the action of a drill bit. Protodyakonov [3] described the coefficient of rock strength (CRS) test used as a measure of the resistance of rock by impact. The CRS test was then, modified by Paone et al. [4], Tandanand and Unger [5], and Rabia and Brook [6,7]. Paone et al. conducted research work on percussion drilling studies in the field. They concluded that uniaxial compressive strength (UCS), tensile strength, Shore hardness and static

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Young's modulus correlated tolerably well with penetration rates in nine hard, abrasive rocks.

A much better correlation was obtained by using a coefficient of rock strength (CRS). Tandanand and Unger obtained simple relationships between the CRS and compressive strength. Rabia and Brook used the modified test apparatus to determine the rock impact hardness number and developed an empirical equation for predicting drilling rates for both DTH and drifter drills. They also determined the surface area of drill cuttings and found that there was no correlation between the surface area of drill cuttings and the penetration rate of a down-the-hole drill.

The early works done on drilling were reviewed in detail by Maurer [8]. He concluded that, as drill bits are loaded, both tensile and shear strength are produced in the rock near the bit and as a result either tensile or shear failures can occur, depending on which strength is first exceeded. Several models, which are proposed, are oversimplified because of the dynamic complexity of rock drilling. Hartman [9] and Gnirk [10] studied the role of indexing—the influence of adjacent craters on each other—in rock drilling. Bailey [11] investigated the impact systems of a family of conventional down-hole drills for the optimization of percussive systems. Selmer-Olsen and Blindheim [12] performed percussion drilling tests in the field using light drilling equipment with chisel bits. They found a good correlation between penetration rate and the drilling rate index (DRI) and expressed the rock properties that are important in drilling as hardness, strength, brittleness and abrasivity. Selim and Bruce [13] carried out percussive drilling experiments on nine rocks in the laboratory. Two drill rigs were used in the experiments. The drill rig included in this study was 6.67 cm-bore jackleg type. The drill was backstroke rifle-bar-rotation machine and bit diameter was confined to 3.81 cm cross bits. They correlated the penetration rate with compressive strength, tensile strength, Shore hardness, apparent density, static and dynamic Young's modulus, shear modulus, coefficient of rock strength (CRS) and percentage of quartz and established linear predictive equations.

Hustrulid and Fairhust [14–16] first carried out a detailed theoretical and experimental study of the percussive drilling of rock. Then, they applied the model to actual percussive drilling [17]. Hakalehto [18] reported the results of actual percussive drilling experiments. He stated that penetration rate depends primarily on the energy used to fracture the rock under the drill bit. Though the energy which is transmitted elastically to the rock is generally estimated to be negligible, in some rock types under this investigation the elastic energy is a considerable amount of the total energy transferred to the rock.

Dutta [19] developed a theory of percussive bit penetration. In developing the theory he assumed a mathematical model which is based on some of his experimental observations. Schmidt [20] reported the performance characteristics of two percussive drills mounted on a truck in 25 rock types. The drill included in this study was a standard drifter having a bore diameter of 6.67 cm. Bit type was H—thread carbide and bit diameter was 5.08 cm. Schmidt correlated the penetration rate with compressive strength, tensile strength, Shore hardness, density, static and dynamic Young's modulus, shear modulus, longitudinal velocity, shear velocity and Poisson's ratio. He found that only compressive strength and those properties highly correlated with it, such as tensile strength and Young's modulus, exhibited good correlations with penetration rate.

Lundberg [21,22] carried out detailed investigations on stress wave mechanics of percussive drilling and developed a microcomputer simulation program [23]. Microcomputer simulation studies [24] of a percussive drill (Atlas Copco COP 1038 HD) have shown that predicted values of a drill stresses, efficiency, coefficient of restitution of the hammer and forces acting on the rock compare well with exact theoretical results. Pathinkar and Misra [25] concluded that conventional rock properties such as compressive strength, tensile strength, specific energy, Shore hardness, Mohs hardness do not individually give good correlation with the penetration rate of percussive drilling. Miranda and Mello-Mendes [26] 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.

Howarth et al. [27] carried out percussion drilling tests on 10 sedimentary and crystalline rocks. The percussion drilling tool was a 37.7 mm wedge indenter (tungsten carbide insert) located on the end of a drill steel that was driven by an Atlas Copco RH571 compressed air powered percussion drill with water flushing. They correlated penetration rate with rock properties and found that bulk density, compressive strength, apparent porosity, P-wave velocity and Schmidt hammer value exhibit strong relationships with the penetration rate. Howarth and Rowland [28] also developed a quantitative measure of rock texture—the texture coefficient. They found a close relation between the texture coefficient and percussion drill penetration rates.

Wijk [29] defined the stamp strength index which may be used for the rock drilling efficiency and demonstrated the validity of this index by drop hammer experiments. Karlsson et al. [30] experimentally studied the efficiency of a percussive process for fragmentation of rock and similar materials. They simulated each test using a previously developed one-dimensional model. The results of simulations and experimental tests were found to agree well.

Pandey et al. [31] carried out drilling tests in the laboratory with microbit drilling machine, full scale drag-bit rotary drilling arrangement and percussive drilling arrangement. They investigated the performance of different drilling methods in some Indian rocks and correlated the penetration rate with rock properties. Thuro and Spaun [32] measured the drilling rates using 20 and 15 kW borehammers (Atlas Copco COP 1440 and COP 1238 ME) along with the geological documentation of the tunnel face. They correlated specific rock properties with the penetration rates of percussive drills and concluded that penetration rate exhibits strong logarithmic relations with compressive and tensile strength. They also introduced a new rock property called 'destruction work' for toughness referring to drillability and found a highly significant correlation between the destruction work and drillability.

Kahraman [33] developed penetration rate models for rotary, down the hole and hydraulic top hammer drills using multiple curvilinear regression analysis. Kahraman [34] statistically investigated the relationships between three different methods of brittleness and both drillability and borability using the raw data obtained from the experimental works of different researchers. He concluded that each method of measuring brittleness has its usage in rock excavation depending on practical utility, i.e. one method of measuring brittleness shows good correlation with the penetration rate of percussive drills, while the other method does not.

The effect of geological discontinuities on the efficiency of mechanical rock destruction is an important point, which is partly neglected in the research programmes. One of the main conclusion made by Thuro [35] was that, rock strength, the power of the drill rig, the shape of the drill bit (ballistic or spherical), geological discontinuities and bit wear were significant factors effecting the penetration rate in percussive drilling. He noticed that drilling rate increase 25% when joint spacing decreases from 20 to 1 cm and increases up to double when joint spacing is getting closer specially in fault zones. This has also similarities with rock cutting processes. Fowell and McFeat-Smith [36] showed that in undercutting with Dosco 2A roadheader in open jointed mudstone, the cutting rate of the machine increased from 20 to 30 m^3/h for joint spacing decreasing from 50 to 25 cm. Other research work carried out on full scale laboratory cutting tests showed that the effect of RQD on instantaneous cutting rates of roadheaders is the most dominant between the values of RQD 0–50% [37].

3. Theoretical and practical considerations

Percussive drilling can be divided by the energy transmission medium used by the location of the drill hammers into hydraulic top hammers, pneumatic top hammers and down the hole drilling methods. Hydraulic used in drilling offers specific advantages in the transmission of the forces and energy and the penetration rates of hydraulic top hammers are generally considered to be 50–300% higher than those of competing drilling methods [38].

There are four main components in percussive rock drilling, feed, rotation, percussion and flushing. The feed is used to keep the drill bit in contact with rock. The purpose of the rotation is to rotate the drill bit inserts in order to operate on new surface at the hole bottom at each blow and thus achieving a larger volume of crater per impact blown. Subsequent craters are purposely formed within a critical distance of existing craters, which is called indexing. Operational variables of a top hammer are defined in Fig. 1 [39]. Hartman [9] emphasized that in indexing, the blow forces and impact energy applied to the rock by the tool are focused by the boundary conditions; the stress field they create induces rock failure predominantly in the direction of a previous crater, promoting chipping and producing more crater volume per force or energy level.

The pioneering work on theoretical and experimental study of the percussive drilling of rock was done by Hustrulid and Fairhust [14–17]. They investigated in detail, energy transfer in percussive drilling, drill steel–piston interface, thrust force requirements and some comments were done for the design of percussive drilling systems. They formulated the following expression for penetration rate:

$$PR = \frac{E_i f\, T_r}{A\, SE}, \tag{1}$$

where E_i is the energy per blow (N m), f is the blow frequency (blow/min), T_r is the energy transfer rate, A is the drill hole area (m^2), and SE is the specific energy (N m/m^3).

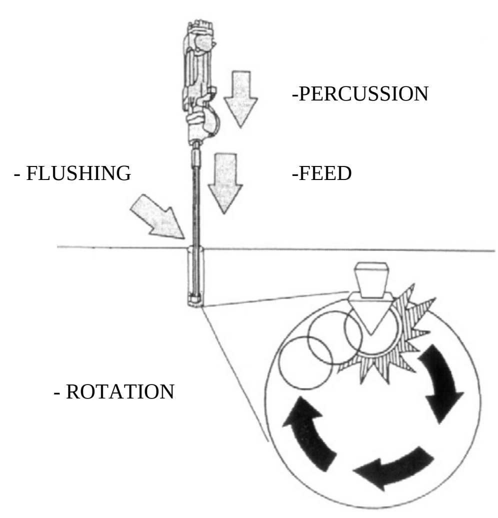

Fig. 1. Top hammer drilling [14].

The above equation shows that the penetration rate is proportional to both blow energy and blow frequency, as well as being inversely proportional to SE. For hydraulic hammers, the number of blows/min vary from 1000 to 12 000 while corresponding blow energy is in the range of 30–70 kg m.

McCarty [40] and Workman and Szumanski [41] concluded that (although specific energy is a difficult parameter to define) the above mentioned expression (Eq. (1)) is a reliable equation for estimating the prediction of penetration rates of top hammers. McCarty emphasized that specific energy has units of $\mathrm{N\,m/m^3}$ and reduces to $\mathrm{N/m^2}$, which is in the same order as uniaxial compressive strength. Therefore, by using the uniaxial compressive strength in place of specific energy in the penetration rate equation, an accurate estimate of drill hole penetration rates can be calculated. This is an important point since, although the drilling mechanics are complex, one should be able to consider from first principles what rock properties govern failure and hence what properties will effect the drilling rate.

The concept of specific energy was proposed by Teale [42] as a quick means of assessing rock drillability. Teale defined specific energy as the energy required to remove a unit volume of rock. However, another definition of specific energy as the energy required to create a new surface area was done by Pathinkar and Misra [43]. Rabia [44,45] concluded that specific energy in terms of either unit volume or new surface area is not a fundamental intrinsic property of rock, breakage parameters or operational parameters control numerical value of specific energy. Wayment and Grantmyre [46] and Mahyera et al. [47] studying high-energy hydraulic impactors concluded that, for a given rock type specific energy is proportional to the inverse root of the blow energy. Destruction of rocks, either by drilling, cutting breaking and sawing has some mechanical similarities. Specific energy is a common concept of rock destruction governing the efficiency of any rock excavation process. It is well known from previously published works of Roxborough [48] and Fowell [49] that specific energy in rock cutting is effected significantly by tool geometry, cutter spacing, tool penetration and rock properties. These verify the above arguments mentioned by Rabia [44]. Brook in his recently published paper [50] concluded that currently used tests for rock strength do not indicate energy consumption, but the Shore and Brinell tests are relevant. However, the consumed energy is better predictable from a new index of rock strength, called Brook hardness. Nevertheless if some operational parameters are kept constant with the same cutting tool for optimum condition of tool spacing/depth of cut ratio, it is evident that specific energy will be a direct function of rock parameters as shown previously by Copur et al. [51].

The main point of the above argument comes to how to formulate specific energy Hughes [52] and Mellor [53] demonstrated that specific energy may be formulated as follow:

$$SE = \frac{\sigma_c^2}{2E}, \tag{2}$$

where SE is the specific energy, E is the secant modulus from zero to load to failure and σ_c is the rock compressive strength.

Farmer and Garritly [54] and Pool [55] using the same concepts as explained above, showed that for a given power of roadheader, excavation rate in $\mathrm{m^3/h}$ may be predicted significantly using specific energy values as given in Eq. (2). It is interesting to note that Krupa and Sekula and co-workers [56–59] noticed that for given power, advance rate of a full face tunnel boring machine, is directly related to specific energy values as formulated in Eq. (2).

There are some models in percussive drilling or rotary cutting assuming that thrust force is a product of rock compressive strength and tool projectile area, given good agreement between predicted and actual advance rate values [60,61]. This fact emphasizes that rock compressive strength should be considered as one of the major properties in a model for estimating drilling rates. However, in rotary drilling or in rock cutting using drag tools, tensile strength, compressive strength and shear strength are the dominant rock properties as explained by Evans and Pomeroy [62] and Nishimatsu [63].

Sinkala [64] emphasized that reduction of hole deviation is vital in order to minimize operational costs and stated that among the controllable factors with a major effect on hole trajectory deviation, are thrust, torque and operator. The main function of the thrust is to maintain bit-rock contact and to keep the drill string joints closed before the pulses arrive so that the energy losses are minimized. The torque is applied mainly to move bit inserts to new surfaces and simultaneously to tighten drill string joints before the arrival of stern waves [65]. Sinkala derived the following theoretical expression for minimum torque necessary to maintain constant bit rotation. He found good agreement between actual and theoretical values.

$$\tau = \frac{F\,D}{3}\sqrt{\frac{R}{15 f\,\theta}}, \tag{3}$$

where τ is the bit rotation torque, F is the thrust on bit, R is the penetration rate, f is the piston impact frequency, D is the bit diameter, and θ is the button diameter.

The above consideration showed that automatic control of drilling parameters may be realized as rock condition change. Sinkala concluded that his study enabled the sub-level intervals from LKAB-Kirum mine

Table 1
The sites in which performance studies were carried out

Site type	Location	Firm	Rock type
Motorway Site	Pozanti	Dogus Constr. and Trade Co.	Limestone
Motorway Site	Osmaniye/Bahce	Tekfen Constr. and Institution Co.	Altered sandstone, sandstone, dolomite
Motorway Site	Gaziantep/Erikli	Tekfen Constr. and Institution Co.	Limestone, diabase, marl
Open Pit	Yahyali	Ozkoyuncu Mining Co.	Metasandstone

to be increased from 22 to 27 m, thereby increasing the scale of mining and minimizing drifting costs [64].

4. Performance studies

The drilling performance was measured on hydraulic top hammer drill rigs that drill blastholes on eight rock types in four different worksites including three motorway sites and an open pit (Table 1). Drill type, bit type and diameter, hole length, feed pressure, rotation pressure, blow pressure, air pressure, net drilling time, etc. were recorded in the performance forms (Table 2) during performance studies. Then, net penetration rates have been calculated from the measurements. The penetration rates for all observations are given in Table 3.

5. Experimental studies

5.1. Uniaxial compressive strength test

Uniaxial compression tests were performed on trimmed core samples, which had a diameter of 33 mm and a length-to-diameter ratio of 2. The stress rate was applied within the limits of 0.5–1.0 MPa/s.

5.2. Brazilian tensile strength test

Brazilian tensile strength tests were conducted on core samples having a diameter of 33 mm and a height to diameter ratio of 1. The tensile load on the specimen was applied continuously at a constant stress rate such that failure will occur within 5 min of loading.

5.3. Elastic modulus

Tangent Young's modulus was measured at a stress level equal to 50% of the ultimate uniaxial compressive strength.

5.4. Point load test

The diametral point load test was carried out on the cores having a diameter of 33 mm and a length of 66 mm. The results were corrected to a specimen diameter of 50 mm.

Table 2
The performance form for observation number 8[a]

Hole number	Rod number	Net penetration rate (m/min)	Average net penetration rate (m/min)
1	1	1.50	
	2	1.80	1.58
	3	1.44	
2	1	1.55	
	2	1.70	1.55
	3	1.40	
3	1	1.25	
	2	1.30	1.18
	3	1.00	
4	1	1.35	
	2	1.30	1.28
	3	1.20	
5	1	1.50	
	2	1.75	1.53
	3	1.35	
			Average: 1.42 ± 0.18

[a] Location: Yahyalı; rock type: metasandstone; drill type: Tamrock DHA 600 S; blow freq.: 3200 bpm; puldown pressure: 60 bar; blow pressure: 90 bar; rotational pressure: 60 bar; air pressure: 6 bar; bit diameter: 89 mm; bit type: button bit.

Table 3
Penetration rates for all observation[a]

Observation number	Location	Rock type	Net penetration rate (m/min)
1	Pozanti	Limestone	0.77
2	Osmaniye/Bahce	Altered Sandstone	1.64
3	Osmaniye/Bahce	Sandstone	0.4
4	Osmaniye/Bahce	Dolomite	1.15
5	Gaziantep/Erikli	Limestone	1.16
6	Gaziantep/Erikli	Diabase	0.85
7	Gaziantep/Erikli	Marl	1.27
8	Yahyali	MetaSandstone	1.42

[a] Bit diameter: 76–89 mm; rock drill power: 14–17.5 kW; bpm: 3000–3600; puldown pressure: 60–80 bar; blow pressure: 100–120 bar; rotational pressure: 60–70 bar.

5.5. Schmidt hammer test

N-type Schmidt hammer tests were conducted in the field. The Schmidt hammer was held on downward position and 10 impacts were carried out at each point, and the peak rebound value was recorded. The test was repeated at least three times on any rock type and average value was recorded as rebound number.

5.6. Impact strength test

The device designed by Evans and Pomeroy [62] was used in the impact strength test. A 100 g sample of rock in the size range 3.175–9.525 mm is placed inside a cylinder of 42.86 mm diameter and a 1.8 kg weight is dropped 20 times from a height of 30.48 cm on to the rock sample. The amount of rock remaining in the initial size range after the test is termed as the impact strength index.

5.7. Sound velocity test

P-wave velocities were measured on the rock blocks having an approximate dimension of $13 \times 20 \times 12\,cm^3$. In the tests, the PUNDIT instrument and two transducers (a transmitter and a receiver) having a frequency of 54 kHz were used.

5.8. Density

Trimmed core samples were used in the determination of natural density. The specimen volume was calculated from an average of several calliper readings. The weight of the specimen was determined by a balance, capable of weighing to an accuracy of 0.01 of the sample weight. The natural density values were obtained from the ratio of the specimen weight to the specimen volume.

The average results of the all tests are listed in Tables 4–11.

6. Statistical analysis

6.1. Coefficients of variation

The coefficients of variation (CoV) were calculated to evaluate the variability of test results for each test and each rock type (Tables 4–11). The average values fo CoV are listed in Table 12. The CoV is obtained by dividing the standard deviation by the population mean and expressing it as a percentage. The higher the CoV, the more variable are the results of a given test.

The UCS values range from 20.1 MPa for the Osmaniye/Bahce altered sandstone to 149.2 MPa for the Osmaniye/Bahce sandstone. The CoV ranges from 1.02% for the Osmaniye/Bahce sandstone to 8.91% for the Osmaniye/Bahce dolomite with an overall average of 4.26%.

The Brazilian tensile strength values range from 1.2 MPa for the Osmaniye/Bahce altered sandstone to

Table 4
Results of the uniaxial compression test

Location	Rock type	Compressive strength (MPa)	Standard deviation	Coefficient of variation (%)
Pozanti	Limestone	123.8	3.81	3.10
Osmaniye/Bahce	Altered sandstone	20.1	0.92	4.62
Osmaniye/Bahce	Sandstone	149.2	1.52	1.02
Osmaniye/Bahce	Dolomite	68.0	6.01	8.91
Gaziantep/Erikli	Limestone	51.3	3.03	5.90
Gaziantep/Erikli	Diabase	110.9	6.04	5.41
Gaziantep/Erikli	Marl	39.5	0.75	1.73
Yahyali	Metasandstone	25.7	0.90	3.41
				Average: 4.26

Table 5
Results of the Brazilian tensile test

Location	Rock type	Brazilian tensile strength (MPa)	Standard deviation	Coefficient of variation (%)
Pozanti	Limestone	6.6	1.21	18.33
Osmaniye/Bahce	Altered sandstone	1.2	0.46	38.33
Osmaniye/Bahce	Sandstone	16.1	0.84	5.23
Osmaniye/Bahce	Dolomite	6.0	1.23	20.50
Gaziantep/Erikli	Limestone	7.0	1.36	19.43
Gaziantep/Erikli	Diabase	10.1	0.91	9.01
Gaziantep/Erikli	Marl	5.2	0.25	4.81
Yahyali	Metasandstone	5.8	0.92	15.86
				Average: 16.44

Table 6
Elastic modulus values for the rocks tested

Location/Panel	Rock type	Elastic modulus (MPa)	Standard deviation	Coefficient of variation (%)
Pozanti	Limestone	10682	1190	11.14
Osmaniye/Bahce	Altered sandstone	1566	210	13.41
Osmaniye/Bahce	Sandstone	8746	1060	12.12
Osmaniye/Bahce	Dolomite	6830	1360	19.90
Gaziantep/Erikli	Limestone	7193	1110	15.43
Gaziantep/Erikli	Diabase	10901	1100	10.09
Gaziantep/Erikli	Marl	4060	680	16.75
Yahyali	Metasandstone	10562	830	7.86
				Average:13.34

Table 7
Results of the point load test

Location	Rock type	Point load strength (MPa)	Standard deviation	Coefficient of variation (%)
Pozanti	Limestone	5.3	1.02	19.24
Osmaniye/Bahce	Altered sandstone	1.1	0.31	28.18
Osmaniye/Bahce	Sandstone	11.2	0.73	6.52
Osmaniye/Bahce	Dolomite	3.5	0.68	19.42
Gaziantep/Erikli	Limestone	4.6	0.59	12.83
Gaziantep/Erikli	Diabase	10.3	0.85	8.25
Gaziantep/Erikli	Marl	2.7	0.45	16.67
Yahyali	Metasandstone	4.2	0.54	12.86
				Average: 15.50

Table 8
Results of the Schmidt hammer test

Location/Panel	Rock type	N-type Schmidt hammer value	Standard deviation	Coefficient of variation (%)
Pozanti	Limestone	61	1.00	1.64
Osmaniye/Bahce	Altered sandstone	36	0.58	1.62
Osmaniye/Bahce	Sandstone	70	0.58	0.82
Osmaniye/Bahce	Dolomite	59	2.08	3.51
Gaziantep/Erikli	Limestone	55	0.58	1.06
Gaziantep/Erikli	Diabase	64	1.00	1.56
Gaziantep/Erikli	Marl	56	1.73	3.09
Yahyali	Metasandstone	54	4.32	8.00
				Average: 2.66

Table 9
Results of the impact strength test

Location/Panel	Rock type	Impact strength	Standard deviation	Coefficient of variation (%)
Pozanti	Limestone	82.9	0.17	0.21
Osmaniye/Bahce	Altered sandstone	70.4	0.72	1.03
Osmaniye/Bahce	Sandstone	87.8	0.32	0.37
Osmaniye/Bahce	Dolomite	83.4	0.66	0.79
Gaziantep/Erikli	Limestone	82.2	0.11	0.14
Gaziantep/Erikli	Diabase	89.5	0.60	0.67
Gaziantep/Erikli	Marl	76.1	0.79	1.04
Yahyali	Metasandstone	85.0	0.43	0.51
				Average: 0.60

Table 10
Results of the seismic velocity test

Location/Panel	Rock type	P-wave velocity (km/s)	Standard deviation	Coefficient of variation (%)
Pozanti	Limestone	5.3	0.29	5.48
Osmaniye/Bahce	Altered sandstone	2.0	0.20	10.00
Osmaniye/Bahce	Sandstone	4.6	0.21	4.49
Osmaniye/Bahce	Dolomite	6.3	0.21	3.29
Gaziantep/Erikli	Limestone	5.4	0.38	6.97
Gaziantep/Erikli	Diabase	5.2	0.11	2.21
Gaziantep/Erikli	Marl	3.1	0.06	1.84
Yahyali	Metasandstone	5.2	0.49	9.42
				Average: 5.46

Table 11
Natural density values for the rock tested

Location/Panel	Rock type	Density (g/cm^3)	Standard deviation	Coefficient of variation (%)
Pozanti	Limestone	2.73	0.07	2.56
Osmaniye/Bahce	Altered sandstone	2.55	0.10	3.92
Osmaniye/Bahce	Sandstone	3.00	0.16	5.33
Osmaniye/Bahce	Dolomite	2.92	0.11	3.77
Gaziantep/Erikli	Limestone	2.74	0.06	2.19
Gaziantep/Erikli	Diabase	2.96	0.16	5.41
Gaziantep/Erikli	Marl	2.20	0.12	5.45
Yahyali	Metasandstone	2.73	0.09	3.30
				Average: 3.99

Table 12
The average coefficient of variation values for each test method

Test method	Average coefficient of variation (%)
Uniaxial compressive strength	4.26
Brazilian tensile strength	16.44
Elastic modulus	13.34
Point load test	15.50
Schmidt hammer test	2.66
Impact strength test	0.60
Seismic velocity test	5.46
Natural density	3.99

16.1 MPa for the Osmaniye/Bahce sandstone. The CoV ranges from 4.81% for the Gaziantep/Erikli marl to 38.33% for the Osmaniye/Bahce altered sandstone with an overall average of 16.44%.

The elastic modulus values range from 1566 MPa for the Osmaniye/Bahce altered sandstone to 10 901 MPa for the Gaziantep/Erikli diabase. The CoV ranges from 7.86% for the Yahyali metasandstone to 19.90% for the Osmaniye/Bahce dolomite with an overall average of 13.34%.

The point load strength index values range from 1.1 MPa for the Osmaniye/Bahce altered sandstone to 11.2 MPa for the Osmaniye/Bahce sandstone. The CoV ranges from 6.52% for the Osmaniye/Bahce sandstone to 28.18% for the Osmaniye/Bahce altered sandstone with an overall average of 15.50%.

The average Schmidt hammer rebound number ranges from 36 for the Osmaniye/Bahce altered sandstone to 70 for the Osmaniye/Bahce sandstone. The CoV ranges from 0.82% for the Osmaniye/Bahce sandstone to 8.00% for the Yahyali metasandstone with an overall average of 2.66%.

The impact strength index range from 70.4 for the Osmaniye/Bahce altered sandstone to 89.5 for the Gaziantep/Erikli diabase. The CoV ranges from 0.14% for the Gaziantep/Erikli limestone to 1.04% for the Gaziantep/Erikli marl with an overall average of 0.60%.

The P-wave velocity values range from 2.0 km/s for the Osmaniye/Bahce altered sandstone to 6.3 km/s for the Osmaniye/Bahce dolomite. The CoV ranges from 1.84% for the Gaziantep/Erikli marl to 10.00% for the Osmaniye/Bahce altered sandstone with an overall average of 5.46%.

The natural density values range from 2.20 g/cm^3 for the Gaziantep/Erikli marl to 3.00 g/cm^3 for the Osmaniye/Bahce sandstone. The CoV ranges from 2.19% for the Gaziantep/Erikli limestone to 5.45% for the Gaziantep/Erikli marl with an overall average of 3.99%.

6.2. Regression analysis

Penetration rates were correlated with the rock properties using the method of least-squares regression. The equation of the best-fit line, the 95% confidence limits, and the correlation coefficient (*r*) were determined for each regression.

Although the drilling mechanics are complex, one should be able to consider from first principles what rock properties govern failure, even in this complex dynamic case, what properties will govern drilling. Theoretical and practical considerations discussed in Section 3, showed that, one would expect the drilling rate to be correlated with compressive strength, for a given drill rig or in similar operational variables and with specific energy values as explained in Eq. (1).

Fig. 2 gives the relation between penetration rates of top hammers studied with specific energy values as calculated from Eq. (2). As seen from this figure there is close relation between two variables, supporting the theoretical and practical consideration given in Section 3.

Some theoretical models in percussive drilling and rotary cutting assume that thrust force and penetration rate is related to the product of rock compressive strength and tool projectile area. The linear relationship between penetration rates and the UCS values shown in Fig. 3 verifies these theoretical considerations. As it is shown, there is an inverse relation between penetration rates and the UCS values. The equation of the line is

$$PR = -0.0079\sigma_c + 1.67, \quad r = 0.97, \tag{4}$$

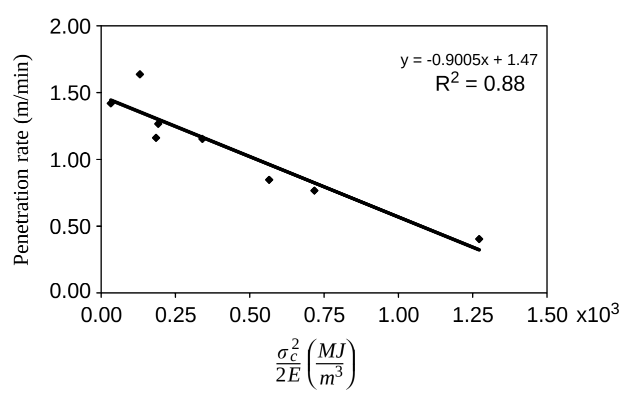

Fig. 2. Penetration rate versus theoretical specific energy. (For the top hammer having power of drill 14–17.5 kW, blow frequency, 3000–6000 blows/min, bit diameter, 76–89 mm).

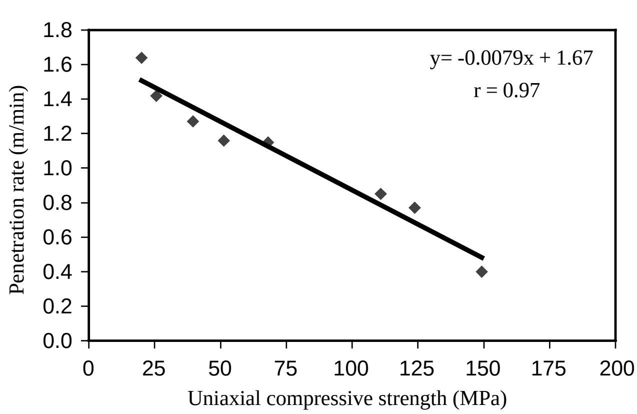

Fig. 3. Penetration rate versus uniaxial compressive strength.

where PR is the penetration rate (m/min), and σ_c is the UCS (MPa).

Fig. 4 shows the plot of penetration rate versus the Brazilian tensile strength value. Penetration rate exhibits an inverse relation with the tensile strength value. As it is shown, there is an inverse relation between penetration rates and the UCS values. The equation of the line is

$$PR = -0.083\sigma_t + 1.67, \quad r = 0.91 \tag{5}$$

where PR is the penetration rate (m/min), and σ_t is the Brazilian tensile strength (MPa).

The plot of penetration rates as a function of the elastic modulus is shown in Fig. 5. The relation between penetration rate and elastic modulus follows a linear function. The equation of the line is

$$PR = -7 \times 10^{-5}E + 1.61, \quad r = 0.60, \tag{6}$$

where PR is the penetration rate (m/min), and E is the elastic modulus (MPa).

As shown in Fig. 6, there is a linear relationship between penetration rate and the point load index. The equation of the line is

$$PR = -0.096I_s + 1.60, \quad r = 0.87, \tag{7}$$

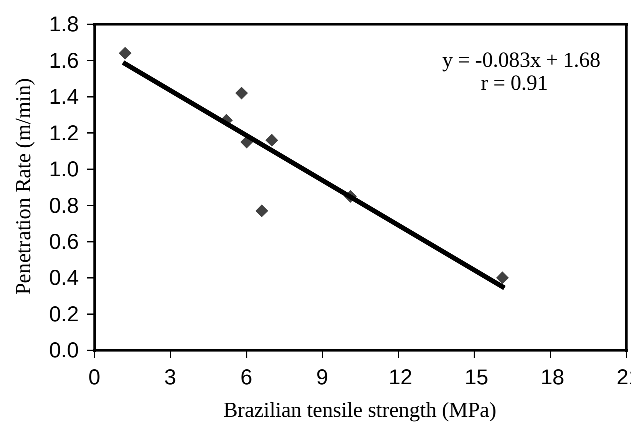

Fig. 4. Penetration rate versus Brazilian tensile strength.

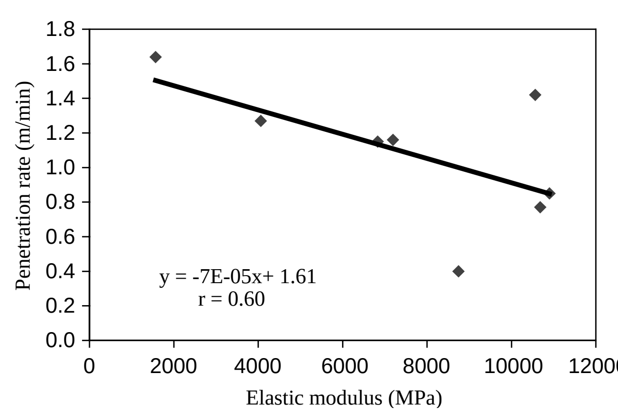

Fig. 5. Penetration rate versus elastic modulus.

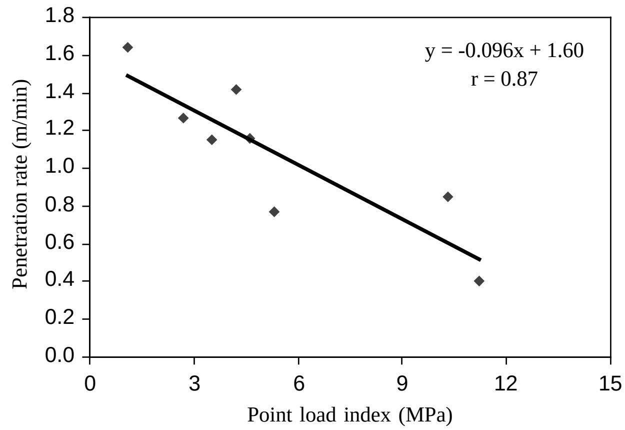

Fig. 6. Penetration rate versus point load index.

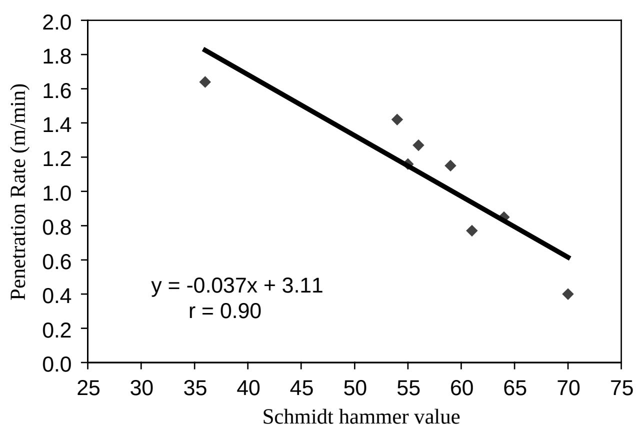

Fig. 7. Penetration rate versus Schmidt hammer value.

where PR is the penetration rate (m/min), and I_s is the point load index (MPa).

The relation between penetration rate and Schmidt hammer value is shown in Fig. 7. The equation of the linear relation is

$$PR = -0.037R_N + 1.60, \quad r = 0.90, \tag{8}$$

where PR is the penetration rate (m/min), and R_N is the Schmidt hammer value.

The plot of penetration rate as a function of the impact strength index is shown in Fig. 8. There is a linear relation between penetration rate and the impact strength index. The equation of the line is

$$PR = -0.046ISI + 4.85, \quad r = 0.72, \tag{9}$$

where PR is the penetration rate (m/min), and ISI is the impact strength index.

Fig. 9 shows the plot of penetration rate versus P-wave velocity. As it is seen, there is no significant correlation between penetration rate and P-wave velocity.

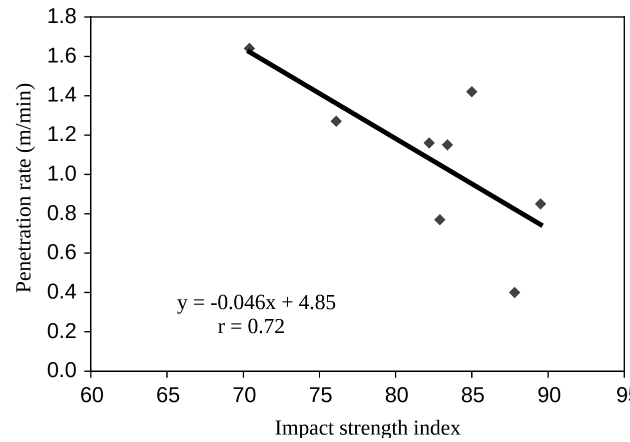

Fig. 8. Penetration rate versus impact strength index.

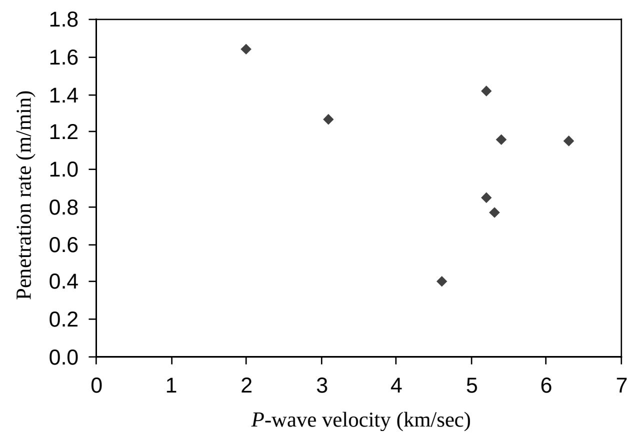

Fig. 9. Penetration rate versus P-wave velocity.

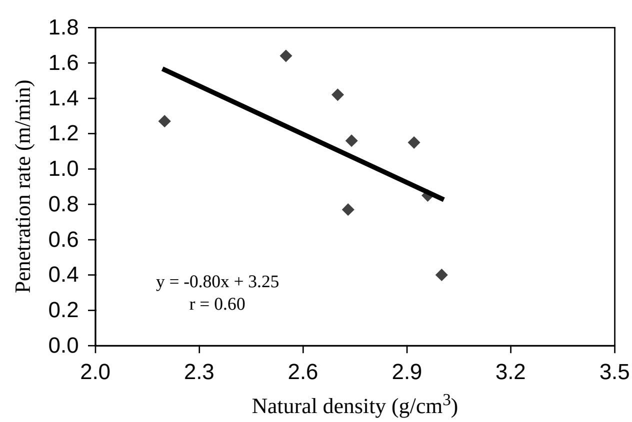

Fig. 10. Penetration rate versus natural density.

A linear relation between penetration rate and natural density was found (Fig. 10). The equation of the line is

$$PR = -0.80\rho + 3.25, \quad r = 0.60, \tag{10}$$

where PR is the penetration rate (m/min), and ρ is the natural density.

7. Discussion

The average coefficient of variation values of each test method are summarised in Table 12.

The impact strength test yields most consistent result of the eight methods. The coefficient of variation for both the sound velocity tests and natural density are rather close that of the UCS test. The Brazilian tensile test, elastic modulus and the point load test have relatively high average values of coefficient of variation, but the variability of their results is still within acceptable limits for most engineering purposes.

Theoretical considerations given in the paper show that penetration rates of percussive drills are directly proportional to blow energy, blow frequency, energy transfer rate and inversely proportional to hole diameter and specific energy values. However specific energy is not a fundamental intrinsic rock property and operational parameters such as blow energy controls the numerical values of specific energy. It is concluded that for a given power of drill rig specific energy is direct function of rock parameters and may be formulated as given in Eq. (2). There are some models in percussive or rotary drilling assuming that thrust force for unit length of advance is a product of compressive strength and tool projectile area. These two realities explain the highly statistical relations between penetration rates, compressive strength and elastic modulus values.

Among the other rock properties adopted in this study, the Brazilian tensile strength, the point load strength and the Schmidt hammer value exhibit strong correlations with the penetration rate. Impact strength shows a tolerably good correlation with penetration rate. Weak correlation between penetration rate and natural density was found. Any significant correlation between penetration rate and P-wave velocity was not found. The specific energy, the uniaxial compressive strength, the Brazilian tensile strength, the point load strength and the Schmidt hammer value were selected as the most significant rock properties effecting the penetration rate of percussive drills. From the four most significant rock properties, the point load strength and the Schmidt hammer value can easily be obtained according to uniaxial compression and tensile test. The testing equipment of these properties is portable, and so they can be used easily in the field.

The derived equations are valid for 76–89 mm bit diameter, 14–17.5 kW rock drill power, 3000–3600 blow frequency, 60–80 bar pull down pressure, 100–120 bar blow pressure and 60–70 bar rotational pressure. The theoretical relation given by Hustrulid and Fairhurst [14–17] and experimental findings of Thuro [35] support Maurer's considerations [8]. Maurer, based on the work of wells, indicated that the percussive drilling rate is directly related to the power of the drills. These permit to generalize the statistical relation given in this paper for other drill rigs having different powers.

8. Conclusions

Predicting 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. One of the important parameters effecting the drillability is the rock properties. The penetration rate of percussive drills was correlated with theoretical specific energy values and eight rock properties. Among the rock properties adopted in this study, the uniaxial compressive strength, the Brazilian tensile strength, the point load strength and the Schmidt hammer value are found as the dominant rock properties effecting the penetration rate of percussive drills. The point load strength and the Schmidt hammer value can easily be measured in the field and used for the rapid estimation of the percussive drill penetration rate. Theoretical considerations given permits to generalize the prediction equations formulated in this paper.

Further study is required to check the validity of the derived equation for the other rock types.

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