



# Performance analysis of drilling machines using rock modulus ratio

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## Synopsis

The correlations between the modulus ratio and penetration rate of rotary and percussive drills were statistically investigated using the raw data obtained from the experimental works of different researchers. An inverse power law was found between the modulus ratio and the penetration rate of rotary and diamond drills. The penetration rate of rotary drills and diamond drills decrease with an increasing modulus ratio. The penetration rates of percussive drills increase with an increasing modulus ratio. There are significant linear correlations between the penetration rates of percussive drills and the modulus ratio. In one of the cases of percussive drilling, a strong correlation between the penetration rate and the modulus ratio was found for the rocks having a porosity value lower 1.23 %.

It can be concluded that the modulus ratio might be a representative measure of rock drilling efficiency. However, further study is necessary to check the validity of the derived equations for other rock types. The effect of porosity on the correlations between the modulus ratio and penetration rate needs to be further investigated.

## Introduction

Rotary drills, diamond drills and percussive drills have been extensively used in open pits, quarries and construction sites. The prediction of the penetration rate of drilling machines is very important in the cost estimation and the planning of the rock excavation projects.

The rock modulus ratio, which is the ratio of elastic modulus to compressive strength, indicating the deformability, is a very important rock property. However, there is no available published material on the relationship between modulus ratio and drillability. In this study, the correlations between the modulus ratio and drillability were statistically analysed using the raw data obtained from the experimental studies of different researchers. Rock properties and performance data obtained from the works of different researchers were listed in the respective tables.

## Previous drillability studies

### Diamond and rotary drilling

Paone and Madson (1966) carried out drillability studies with impregnated diamond bits

on 7 rock types in the laboratory and on 21 rock types in the field and correlated penetration rates with rock properties. Penetration rates correlated quite well with compressive and tensile strengths. It was also seen that penetration rates do not change significantly for rocks having a compressive strength greater than 173 MPa.

Paone *et al.* (1966) statistically analysed the drilling capability of surface-set and impregnated diamond bits. The results indicated that the most significant parameters affecting penetration rates of surface-set bits were thrust, rotational speed, compressive strength, Shore hardness and quartz content. For impregnated diamond bits, the most significant parameters were thrust, Young's modulus, shear modulus, abrasiveness, quartz content and compressive strength.

Howarth *et al.* (1986) performed drillability studies with a thin walled impregnated bit with water flushing and correlated penetration rates with rock properties. Penetration rates exhibited strong correlations with dry and saturated density, saturated P-wave velocity, saturated compressive strength and apparent porosity. However, the correlations between penetration rate and Schmidt hammer value and dry compressive strength were weak.

Ersoy and Waller (1995) conducted drillability studies in the laboratory with polycrystalline diamond compact (PDC) and impregnated diamond core bits using a fully instrumented drilling rig at different rotational speeds and with a range of weights on bit. They developed predictive models using multiple regression analysis. The results showed that the parameters significantly affecting penetration rate of PDC bit were weight on bit, rotational speed, Cerchar

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abrasivity index and Shore hardness. The model for hybrid bits indicated that the significant parameters were weight on bit, round per minute grain-shape factor and Mohs hardness. The model for impregnated bits comprised two hardness parameters (Mohs hardness and Shore hardness) alone and its correlation coefficient was weak.

Fish (1968) developed a model for rotary drills that penetration rate is directly proportional to thrust and inversely proportional to uniaxial compressive strength. However, Singh (1969) showed that compressive strength is not directly related to the drilling rate of a drag bit. Adamson (1984) showed a close correlation between a quantitative measure of rock texture, the texture coefficient, and penetration rate data of a rotary drilling machine in six rock types.

As result of research carried out at 96 different locations at 16 mines of Turkish Coal Enterprises, Karpuz *et al.* (1990) developed curvilinear regression models for the prediction of penetration rates of rotary blast hole drills. In their study, the uniaxial compressive strength has been determined as the dominant rock property.

Pandey *et al.* (1991) correlated the penetration rate value obtained from a microbit drilling test with compressive strength, tensile strength, shear strength and Protodyakonov Index and found logarithmic relations.

Kahraman (1999) developed a multiple regression model for the prediction of penetration rates of rotary blast hole drills using the data obtained from field observations. The results indicated that the parameters significantly affect penetration rate of rotary blast hole drills were weight on bit, rotational speed, bit diameter and compressive strength. Kahraman *et al.* (2000) defined a new drillability index from force-penetration curves of indentation tests and developed a mathematical penetration rate model for rotary drills using this new drillability index. They also correlated this drillability index with compressive strength, tensile strength, point load index, Schmidt hammer value, impact strength, P-wave velocity, elastic modulus and density and found significant correlations.

Kahraman (2002) statistically investigated the relations between the penetration rate of rotary and diamond drills and three different degrees of brittleness obtained from compressive strength and tensile strength using the raw data obtained from the experimental works of different researchers. The results indicated that there was no correlation between the penetration rate of diamond drills and brittleness values. However, strong correlations were found between the penetrations rate of rotary drills and brittleness values obtained from compressive strength and tensile strength.

Altindag (2002) suggested a new brittleness index obtained from compressive strength and tensile strength and correlated this index with the drillability index for rotary blast hole drills. He found significant correlations between the new brittleness index and drillability index.

Bilgin and Kahraman (2003) observed rotary blast hole drills in fourteen rock types at eight open pit mines and correlated the penetration rates with rock properties. They found that the uniaxial compressive strength, the point load strength, Schmidt hammer value, cerchar hardness and impact strength show strong correlations with the

penetration rate. The Brazilian tensile strength and cone indenter hardness exhibit quiet good correlations with the penetration rate.

### **Percussive drilling**

Protodyakonov (1962) developed drop tests and described the coefficient of rock strength (CRS) used as a measure of the resistance of rock by impact. The Protodyakonov test was then modified by Paone *et al.* (1969), Tandanand and Unger (1975), and Rabia and Brook (1980, 1981). 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 Young's modulus correlated tolerably well with penetration rates of percussive drills in nine hard, abrasive rocks. A much better correlation was obtained by using the CRS. They stated that no single property of a rock was completely satisfactory as a predictor of penetration rate. Tandanand and Unger developed an estimation equation that showed good correlations with actual penetration rates of percussive drills. They concluded that CRS shows its usefulness in predicting penetration rate with higher reliability than other rock properties.

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 down the hole and drifter drills. The equation relating penetration rate to drill operating pressure, Shore hardness and rock impact hardness number was found to give excellent correlation for field data obtained from down the hole and drifter drills.

Selmer-Olsen and Blindheim (1970) 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 (1970) carried out percussive drilling experiments on nine rocks in the laboratory. They correlated the penetration rate for a specific drill rig 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. They stated that the established equations can be used for the prediction of the performance data of percussive drills.

Schmidt (1972) 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.

Pathinkar and Misra (1980) correlated several rock properties with penetration rate in five different rock types as obtained from laboratory drilling and concluded that conventional rock properties such as compressive strength, tensile strength, specific energy, Shore hardness and Mohs hardness do not individually and correlate well with the penetration

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rate of percussive drilling. They developed a good correlation between penetration rate and a set of rock properties, but the relation was complex.

Howarth *et al.* (1986) correlated penetration rate with rock properties and found that bulk density, saturated compressive strength, apparent porosity and saturated P-wave velocity exhibit strong relations with the penetration rate. However, the correlations between penetration rate and Schmidt hammer value and dry compressive strength were not strong. They stated that porosity can influence drillability, since high porosity is likely to assist the formation of fracture paths and networking of such paths.

Howarth and Rowland (1987) developed a quantitative measure of rock texture—the texture coefficient—and found a close relation between the texture coefficient and percussion drill penetration rates. It was seen that a rock with a high texture coefficient has a low drillability and a high compressive strength.

Thuro and Spaun (1996) measured the drilling rates using 20 kW 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 (1999) developed penetration rate models for down the hole and hydraulic top hammer drills using multiple curvilinear regression analysis. The results showed that the parameters significantly affecting the penetration rate of down the hole drills were operating pressure, piston diameter and Schmidt hammer value. For hydraulic top hammer drills, the most significant parameters were blow frequency, compressive strength and quartz content.

Kahraman (2002) statistically investigated the relations between the penetration rate of percussive drills and three different methods of brittleness obtained from compressive strength, tensile strength and percentage of fines formed in Protodyakonov test using the raw data obtained from the experimental works of different researchers. He obtained that there was no correlation between the penetration rate and the brittleness values derived from compressive strength and tensile strength. However, he found a strong correlation between the penetration rate and the brittleness value derived from compressive strength and percentage of fines formed in the Protodyakonov test. He concluded that each method of measuring brittleness has its usage in rock drilling, 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.

Kahraman *et al.* (2003) observed percussive blast hole drills in eight rock types at an open pit mine and three motorway sites and correlated penetration rates with the rock properties. The uniaxial compressive strength, the Brazilian tensile strength, the point load strength, and the Schmidt hammer value exhibited strong correlations with the

penetration rate. Impact strength showed 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.

Many researchers have correlated the penetration rate of drills with a single rock property. Most of them found good correlations, but their studies were mostly for limited rock or drill types. In addition, some studies were carried out under specific laboratory conditions. Rock drilling is a complex phenomenon. A single rock property does not completely define rock drillability for different rock types. Several scientists have developed penetration rate models using multiple regressions. Most of these models include more than one rock property. Modulus ratio combined with rock property indicates both strength and deformability. This rock property may be significant for drillability analysis.

### Modulus ratio

Modulus ratio defined by Deere and Miller (1966) may be represented by the equation:

$$MR = \frac{E}{\sigma_c} \quad [1]$$

where  $MR$  is the modulus ratio,  $E$  is the Young's modulus, and  $\sigma_c$  is the uniaxial compressive strength.

Young's modulus can be expressed by:

$$E = \frac{\sigma}{\varepsilon} \quad [2]$$

where,  $\sigma$  is the stress, and  $\varepsilon$  is the strain or deformation.

Substituting Equation [2] in the Equation [1], the following equation is obtained.

$$MR = k \frac{1}{\varepsilon} \quad [3]$$

where,  $k$  is the proportionality constant, and  $\varepsilon$  is the strain.

Therefore, it can be said that the modulus ratio is inversely proportional to the deformation, i.e. the higher the modulus ratio, the lower the deformation. Modulus ratio is increases with stiffness for a given strength.

### Evaluation of some experimental data

#### Diamond drilling

Howarth (1987) reported the performance characteristics of a diamond-drilling tool in crystalline and sedimentary rock types. The type of diamond drilling tool used was a thin walled impregnated bit with water flushing. The impregnated bit had an outer diameter of 31.9 mm and an internal diameter of 28.1 mm. Drilling data, rock characteristics and calculated modulus ratio values are given in Table I.

The data in Tables I were analysed using the least square regression method. Penetration rates vs. the modulus ratio values are plotted. As it is shown Figure 1, the penetration rate is strongly correlated with the modulus ratio. The relation between the penetration rate and the modulus ratio follows an inverse power function. The equation of the curve is

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Table I

Laboratory test data of impregnated diamond bits from Howarth (1987) and calculated modulus ratio values

Rock type	Penetration rate (cm/min)	Dry uniaxial compressive strength (MPa)	Young's modulus (MPa)	Modulus ratio
Carrara marble	3.93	93.6	49300	526.7
Ulan marble	3.08	49.9	56600	1134.3
Ipswich sandstone	12.64	64.7	20500	316.9
Gosford sandstone	22.74	44.1	12500	283.5
Mt.Crosby sandstone	38.96	36.6	14000	382.5
Helidon sandstone	37.82	35.1	7500	213.7

Thrust: 378 N, rpm: 750, water pressure: 275 kPa, water flow rate: 5 l/min

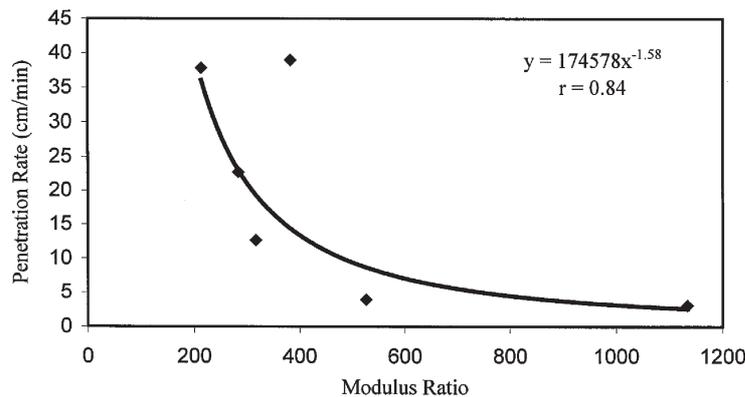


Figure 1—Penetration rate vs. modulus ratio for the diamond drill (the graph was plotted using the data in Table I)

$$PR = 174578MR^{-1.58} \quad r^2 = 0.71; \quad r = 0.84 \quad [4]$$

where,  $PR$  is the penetration rate (cm/min), and  $MR$  is the modulus ratio.

### Rotary drilling

Reddish and Yasar (1996) performed rotary drilling tests in the laboratory using a modified industrial rotary hammer drill. The drill uses a 10 mm masonry bit sharpened to 118 degrees. The drill was used in a drill stand for the majority of tests and in a hand-held mode for some of larger blocks of material. All tests were conducted with the same basic operating mode and drill bit geometry. Reddish and Yasar (1996) obtained an index called as 'stall penetration rate' from the graphs of penetration rate versus specific energy. Drilling data, rock characteristics and calculated modulus ratio values are given in Table II. The stall penetration rates were correlated with the modulus ratio values. A very strong correlation between the stall penetration rate and the modulus ratio was found (Figure 2). The equation of the curve is

$$PR = 4 \times 10^9 MR^{-2.85} \quad r^2 = 0.90; \quad r = 0.95 \quad [5]$$

where,  $PR$  is the stall penetration rate and  $MR$  is the modulus ratio.

### Percussive drilling

Selim and Bruce (1970) reported the penetration data of percussive drills determined from nine rocks drilled in the laboratory. Two drills were used in the experiments. The drill included in the current study was a 6.67 cm-bore jackleg

type. The drill was a backstroke rifle-bar-rotation machine and bit diameter was confined to 3.81 cm cross bits. Penetration rates, rock properties and calculated modulus ratio values are given in Table III.

Schmidt (1972) 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. Penetration rates, rock properties and calculated modulus ratio values are given in Table IV.

Howarth (1987) carried out percussion drilling tests on 10 sedimentary and crystalline rocks. The percussion drilling tool was a simple 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. Penetration rates, rock properties and calculated modulus ratio values are given in Table V.

The data in Table III were evaluated using regression analysis. As it is seen in Figure 3, there is a linear relationship between the penetration rate and the modulus ratio. For percussive drills, penetration rate increases with increasing modulus ratio. The equation of the line is

$$PR = 0.14MR + 3.25 \quad r^2 = 0.48; \quad r = 0.69 \quad [6]$$

where,  $PR$  is the penetration rate (cm/min), and  $MR$  is the modulus ratio.

Using the data in Table IV, penetration rates were correlated with modulus ratio values. The plot indicating the correlation is shown in Figure 4. It is seen that there is no

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Table II

Laboratory test data of rotary drill from Reddish and Yasar (1996) and calculated modulus ratio values

Rock type	Stall penetration rate	Uniaxial compressive strength (MPa)	Young's modulus (MPa)	Modulus ratio
Slate	11082	148.0	15500	104.7
Sandstone	3018	72.0	10490	145.7
Siltstone	2496	70.0	9040	129.1
Mudstone	168	19.0	6600	347.4
Limestone	5100	63.2	7310	115.7
Gypsum	1110	16.5	4290	260.0

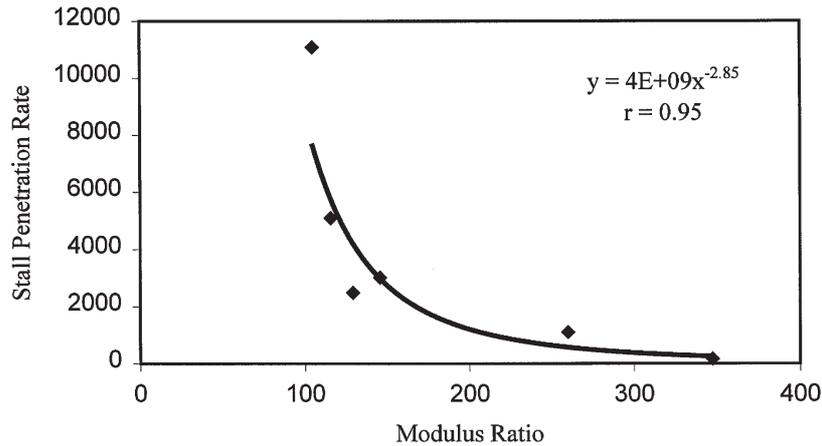


Figure 2— Stall penetration rate vs. modulus ratio for the rotary drill (the graph was plotted using the data in Table II)

Table III

Laboratory test data of percussive drill from Selim and Bruce (1970) and calculated modulus ratio values

Rock type	Penetration rate (cm/min)	Uniaxial compressive strength (MPa)	Young's modulus (MPa)	Modulus ratio
Mankato stone	82.6	54.1	28823	532.8
Kasota stone	90.4	103.7	36556	352.5
Rockville granite	52.2	144.1	63973	443.9
Rainbow granite	44.9	198.2	73112	368.9
Charcoal granite	41.0	234.2	68894	294.2
Dresser basalt	20.6	312.8	85766	274.2
Jasper quartzite	40.0	396.5	71003	179.1
AuroraTaconite A	37.1	451.3	105450	233.7
Babbitt Taconite B	25.6	473.5	94202	198.9

Operating pressure: 632.7 kPa, feed pressure: 492 kPa

significant correlation because the value of Mankato stone is an anomalous position. When the value of Mankato stone is omitted from the graph, a linear relationship between the penetration rate and the modulus ratio is obtained (Figure 4). The equation of the dotted regression line is

$$PR = 0.041MR + 11.97 \quad r^2 = 0.48; \quad r = 0.69 \quad [7]$$

where,  $PR$  is the penetration rate (cm/min), and  $MR$  is the modulus ratio.

The data in Table V were evaluated using regression analysis. A significant correlation between the penetration rate and the modulus ratio was not found (Figure 5). When the cause of the lack of the correlation was investigated, it was seen that the porosity values of sandstones and

microsyenite were much higher than that of the other rocks. Excluding the rocks having higher porosity values resulted in a strong correlation (Figure 5). The equation of the line is

$$PR = 0.0084MR + 14.40 \quad r^2 = 0.79; \quad r = 0.89 \quad [8]$$

where,  $PR$  is the penetration rate (cm/min),  $MR$  is the modulus ratio.

## Discussion

The penetration rates of diamond and rotary drills decrease with increasing modulus ratio. However, the penetration rates of percussive drills increase with increasing modulus ratio. As it was explained before, the deformability of the

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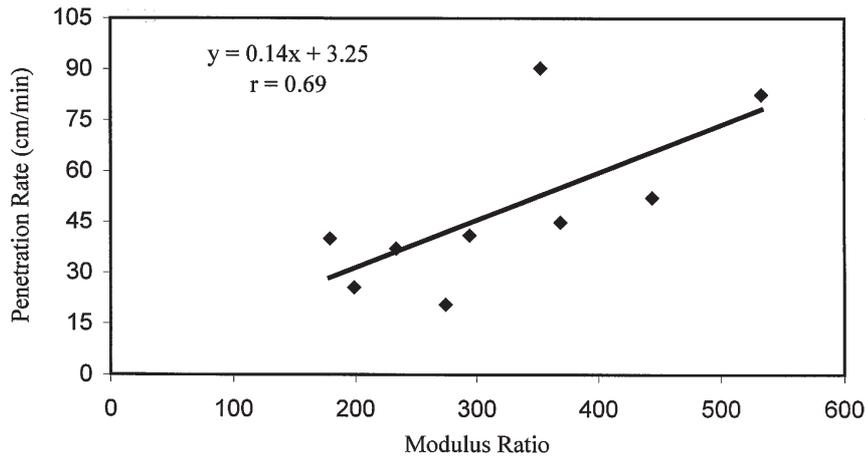


Figure 3—Penetration rate vs. modulus ratio for the percussive drill (the graph was plotted using the data in Table III)

Table IV  
Field test data of percussive drill from Schmidt (1972) and calculated modulus ratio values

Rock type	Penetration rate (cm/min)	Uniaxial compressive strength (MPa)	Young's modulus (MPa)	Modulus ratio
Humboldt iron silicate	13.3	418.6	78033	186.4
Hornblende schist	20.8	208.1	102638	493.2
Granite pegmatite	34.3	89.6	41477	462.7
Wausau quartzite	34.8	222.5	73815	331.8
Wausau argillite	18.3	220.7	53428	242.0
Mankato stone	91.4	125.1	52022	415.7
New Ulm quartzite	32.5	156.4	40774	260.7
Jasper quartzite	21.8	307.2	66082	215.1
Rockville granite	26.4	154.7	67488	436.4
Charcoal granite	22.9	203.5	68894	338.5
Diamond gray granite	31.5	171.2	65379	381.9
Dresser basalt	17.0	286.8	92093	321.1
Shiely limestone	48.3	99.8	43586	436.6
Mt. Iron taconite	21.3	361.0	110371	305.7
Aurora taconite	15.5	368.4	93499	253.8
Babbitt taconite	14.0	364.5	91390	250.7
Babbitt diabase	21.3	374.7	82251	219.5
Ely gabbro	27.7	208.1	90687	435.8
Trap rock	46.2	68.9	59755	867.3
Anorthosite	40.6	131.5	85766	652.4
Duluth basalt	33.8	186.3	64676	347.2
Marble	38.1	127.6	81548	639.1
Primax gabbro	28.4	176.1	104044	590.8
Iron ore	32.5	225.3	70300	312.0

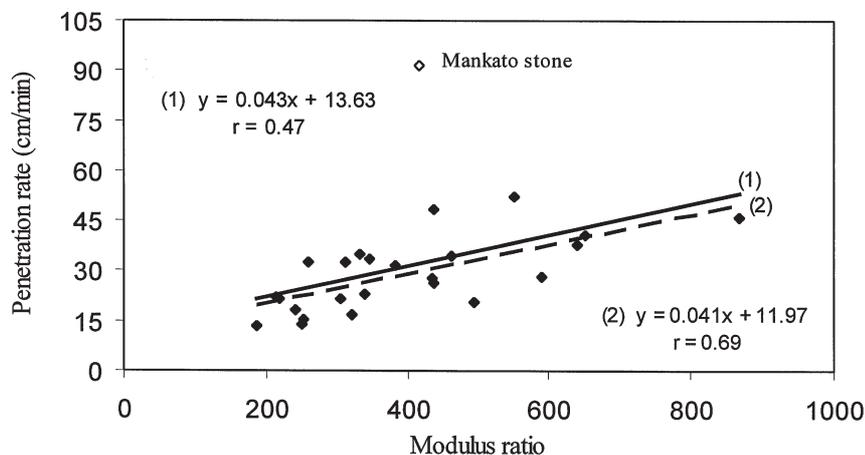


Figure 4—Penetration rate vs. modulus ratio for the percussive drill (the graph was plotted using the data in Table IV. The dotted regression line was obtained after the value of Mankato Stone was omitted)

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Table V

Laboratory test data of percussive drill from Howarth (1987) and calculated modulus ratio values.

Rock type	Penetration rate (cm/min)	Dry uniaxial compressive strength (MPa)	Porosity	Young's modulus (MPa)	Modulus ratio
Ashgrove granite	18.6	234.0	0.33	66500	284.2
Beenleigh hornfels	19.2	100.5	0.99	67100	667.7
Moogerah microsyenite	20.2	137.1	5.24	40600	296.1
Caboolture Trachyte	15.9	202.4	1.23	46400	229.2
Mt. Morrow basalt	15.4	219.8	0.65	80600	366.7
Carrara marble	20.2	93.6	0.69	49300	526.7
Ulan marble	24.1	49.9	0.35	56600	1134.3
Gosford sandstone	32.4	44.1	12.70	12500	283.4
Mt. Crosby sandstone	38.5	36.6	18.30	14000	382.5
Helidon sandstone	54.0	35.1	17.80	7500	213.7

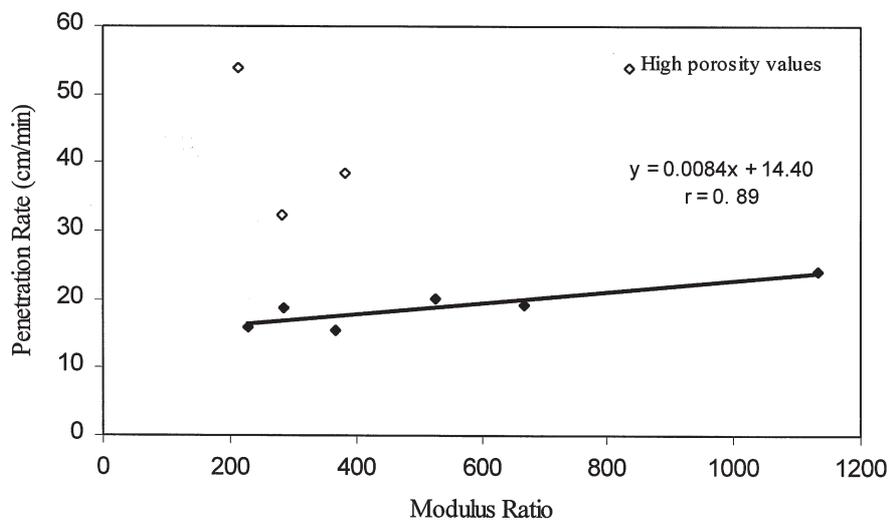


Figure 5—Penetration rate vs. modulus ratio for the percussive drill (the graph was plotted using the data in Table V)

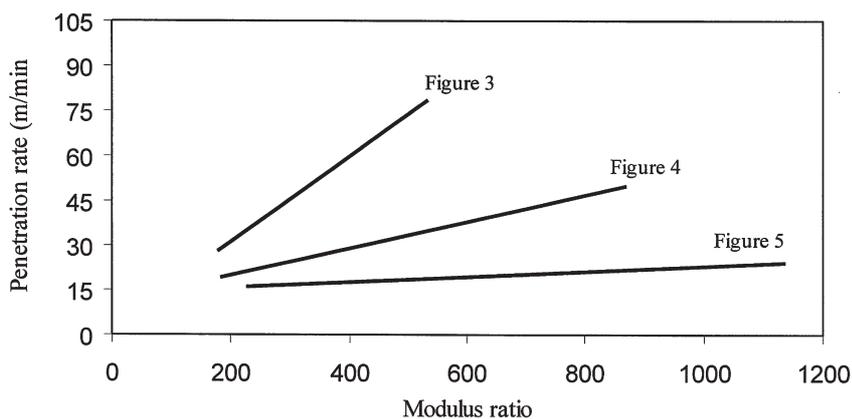


Figure 6—The combination of figures 3, 4 and 5

rock decreases with increasing modulus ratio. Because thrust and rotation are the dominant factors in rotary drilling, under the same thrust and rotation, the higher the modulus ratio, the lower the deformation, and so penetration rate decreases. However, percussion is the dominant factor in percussive drilling. It was known that the percussive drilling of the hard or stiffer rocks is much easier than that of the rotary drilling.

The rocks having a high modulus ratio or stiffer rocks can easily be deformed under the percussion, and so penetration rate increases.

The correlations between the penetration rate and modulus ratio for percussive drills are generally not strong. It is interesting that a strong correlation between the penetration rate and modulus ratio was found in one of the

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cases of the percussive drilling for the rocks having the porosity value lower 1.23 %. In a drillability study, if the rocks have largely different porosity values, a strong or significant correlation between the penetration rate and modulus ratio for percussive drills might not be found.

Figures 3, 4 and 5 belonging to percussive drills, were combined in a graph (Figure 6) and it was seen that each regression line shows a different trend. This is not an abnormal situation since drilling rigs and drilling conditions in each test are different from each other.

## Conclusions

The penetration rates of rotary and diamond drills exhibit strong correlations with modulus ratio. Significant correlations exist between the penetration rates of percussive drills and the modulus ratio. However, in one of the cases of percussive drilling, a strong correlation between the penetration rate and the modulus ratio was only found when the rocks having the porosity value greater than 1.23 % were excluded.

It can be concluded that modulus ratio might be a typical measure of rock drilling. But, further study is necessary to check the validity of the derived equations for other rock and drill types. In addition, the effect of porosity on the correlations between modulus ratio and penetration rate needs to be investigated.

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