Review of Rock Properties Based on Drilling Parameters

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ABSTRACT

One of the important factors of concern to the engineers in the general field of rock excavation is to assess the physico-mechanical properties of rock. The International Society of Rock Mechanics (ISRM) has developed standard methods for measuring the rock properties both in the laboratory as well as in the fields. In India also the geotechnical studies in the laboratory are conducted according to IS standards stipulated for each property. However, these direct methods are time consuming and expensive. To obtain realistic results of rock properties, it requires carefully prepared rock samples. The standard cores cannot always be extracted from weak, highly fractured, thinly bedded, foliated and/or block-in-matrix rocks.

An extensive review has been made in this paper to identify different controlling factors in drilling which influence rock properties, to understand the relation between these parameters and to prepare a strategy for developing a system which will help in establishing an alternative method for determination of physico-mechanical properties of rocks using drilling technique.

1 INTRODUCTION

Investigation of rock properties based on drilling performance measurements have been carried out by many researchers. Most of the studies reported that rock samples were collected from drilling locations and the physico-mechanical properties were determined both in the field and the laboratory. During drilling in the site or in the laboratory, various drilling performance parameters were measured. These results were analyzed to develop best-fit correlation between the drilling parameters and rock properties.

An extensive literature survey has been carried out on the studies conducted by

different researchers in the past to establish relations between various physico-mechanical properties of rock and drilling parameters. Some of these works have been summarized in this paper.

2 DRILING INDICES INFLUENCING ROCK PROPERTIES

2.1 Rate of Penetration

The rate of penetration, also termed as penetration rate or drill rate, is the speed at which a drill bit breaks the rock under it to deepen the borehole. It is normally measured in meters per hour or meters per minute or meters per second in SI units. It is calculated as:

$$ROP = \frac{D}{\Delta t} \quad \text{------ (1)}$$

Where, D = Depth of drilling, m

Δt = Time duration, sec or min

Many researchers have investigated drilling performance and correlated the penetration rate of drills with various rock properties. 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. (2000) 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. Kahraman (2002) further found that the penetration rates of rotary and diamond drills exhibit strong correlations with modulus ratio. Significant correlations also exist between the penetration rates of percussive drills and the modulus ratio.

Bilgin and Kahraman (2003) analysed data from tests conducted by rotary blast hole drills in fourteen rock types at eight open pit mines. 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. Then, the penetration rates were correlated with the rock properties and regression equations were developed. The results of this study, as shown in figure 1, clearly indicated that uniaxial compressive strength, point load strength, Schmidt hammer value, Cerchar hardness and impact strength show strong correlations with the penetration rate. The equations derived from Schmidt hammer and impact

strength values are valid for the rocks having uniaxial

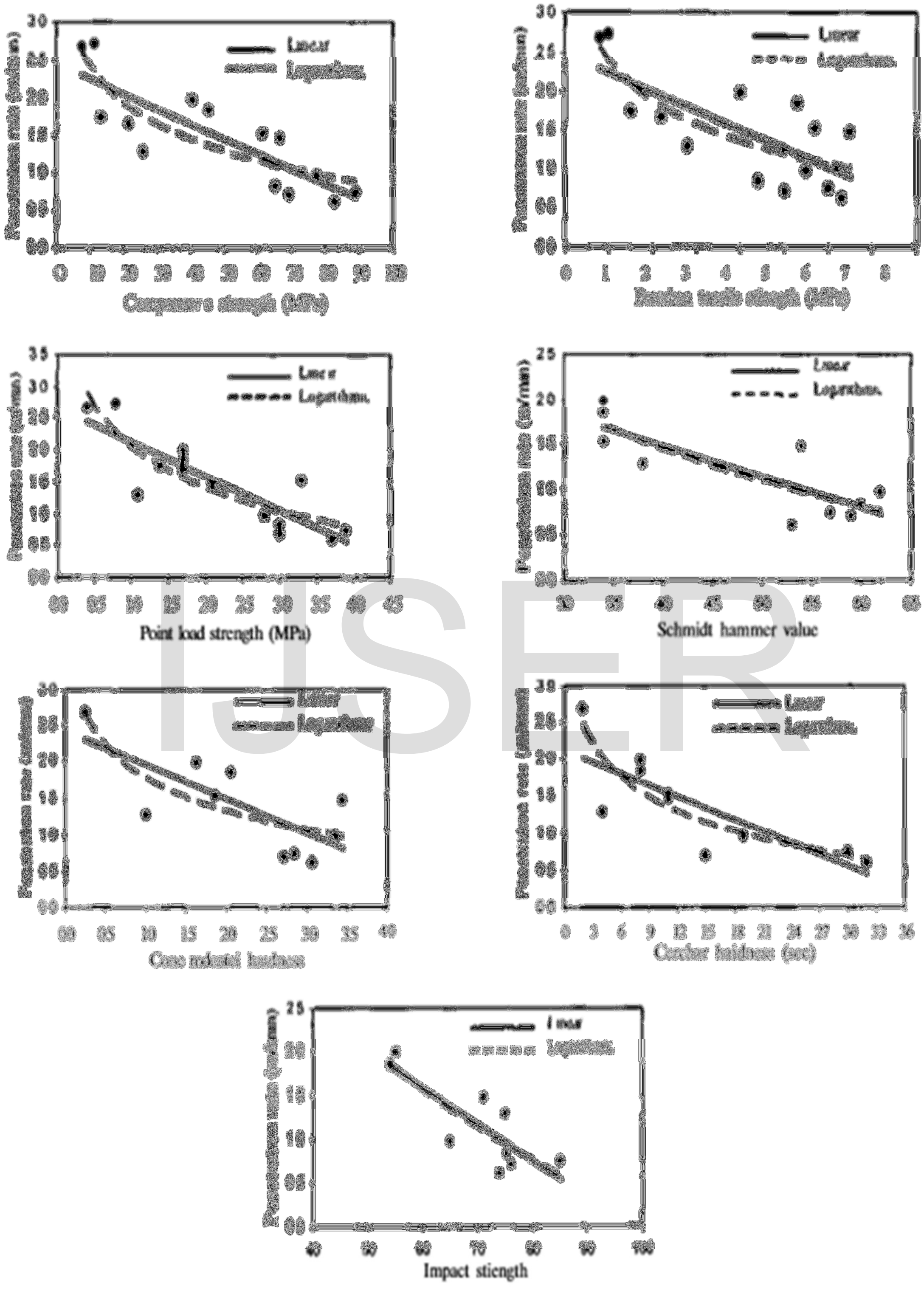


Figure 1: Penetration rate versus physico-mechanical properties of rocks (after Bilgin and Kahraman 2003)

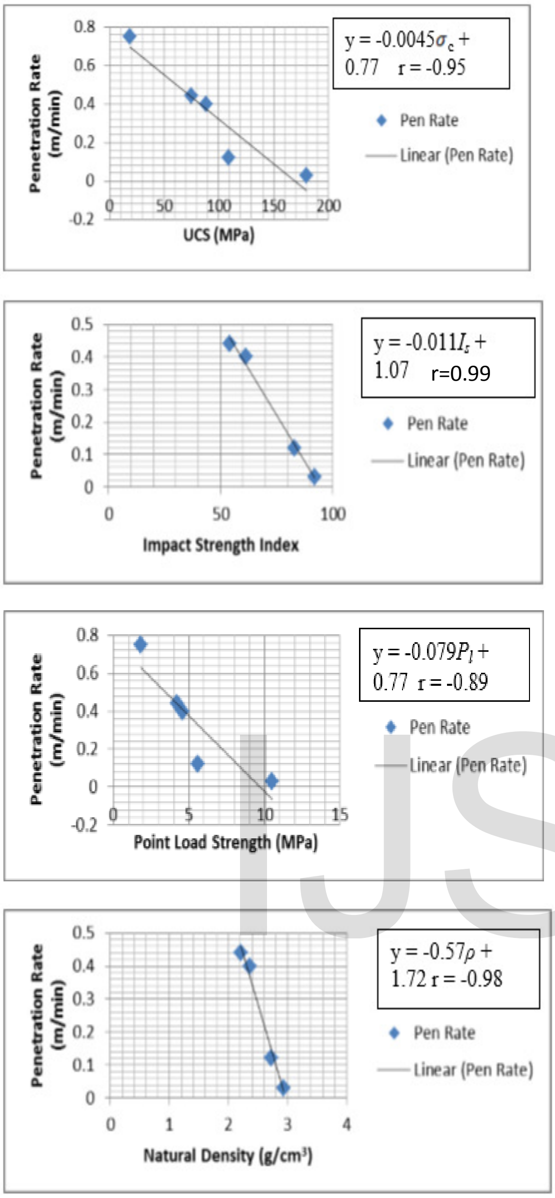


Figure 2: Rate of penetration versus versus physico-mechanical properties of rocks (after Ngerebara and Youdeowei 2014)

Paone et al. (1969) 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 in nine hard and abrasive rocks.

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. Lundberg (1973) carried out detailed investigations on stress wave mechanics of percussive drilling and developed a microcomputer simulation program. Microcomputer simulation studies 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. Hartman (1962) used the volume created in percussive drill as a quantity for estimation of rock drillability. Selmer-Olsen and Blendheim (1970) showed that the rate of percussive drilling has a strong relationship with Drilling Rate Index (DRI) of rocks. Tandanand and Unger (1975) used the coefficient of rock strength in their presented drilling model. Rabia and Brook (1980) 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.

Hoseinie et. al. (2014) reported the results of a testing program to determine the mechanical and physical properties to investigate the dependency of drilling rate of a pneumatic top hammer drill on rock. The important physical rock properties which were taken in this study are tensile strength, compressive strength, dry density, mean hardness of rock, mean grain size, Young's modulus, Schmidt hammer rebound number and Schimazek's F- abrasivity. The rock samples were collected from eight mines and one high way's slope. The results of the tests were correlated with the different physical and mechanical properties of studied rocks as shown in figure 3. The regression analyses showed that tensile strength (Brazilian test), uniaxial compressive strength and Schmidt hammer rebound are the important properties affecting the drilling rate and have relatively an appropriate correlation with the drilling rate. It was also observed that individually even a single parameter was not able to give the proper prediction of drilling rate. Hence the combinations of parameters were more effective. So the regression analysis showed that Brazilian tensile strength, dry density and Schmidt hammer rebound all together affecting the drilling rate and giving relatively best correlation with the drilling rate.

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 during performance studies. Then, net penetration rates have been calculated from the measurements as shown in table 1 and correlation graphs are shown in figure 4. From this study they concluded that among the other rock properties adopted, 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 also found. Any significant correlation between penetration rate and P-wave velocity was not found.

2.2 Specific Energy

The concept of specific energy (*SE*) was proposed by Teale (1965) as a quick means of assessing rock drillability and defined it 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 given by Parthinker and Misra (1976).

Teale developed the concept of the specific energy of rock drilling where the drilling parameters of thrust, torque, penetration rate and rotational speed were correlated to determine the uniaxial compressive strength of rocks.

SE can be measured in KJ/m^3 or GJ/m^3 and can be expressed as follows:

$$SE = \frac{F}{A} + \frac{2\pi NT}{A * ROP} = E_t + E_r \qquad \text{---(2)}$$

where, F = thrust/weight on the bit (kN).
A = hole section (m^2).
N = rotation speed (rps).
T = rotation torque (kN · m).
ROP = rate of penetration (m/s).

The first member of the equation represents the contribution of the thrust (thrust component). It is equivalent to the pressure acting over the cross – sectional area of the hole. The second member is the rotary component of energy.

Table 1: Penetration rates of studied rock

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.

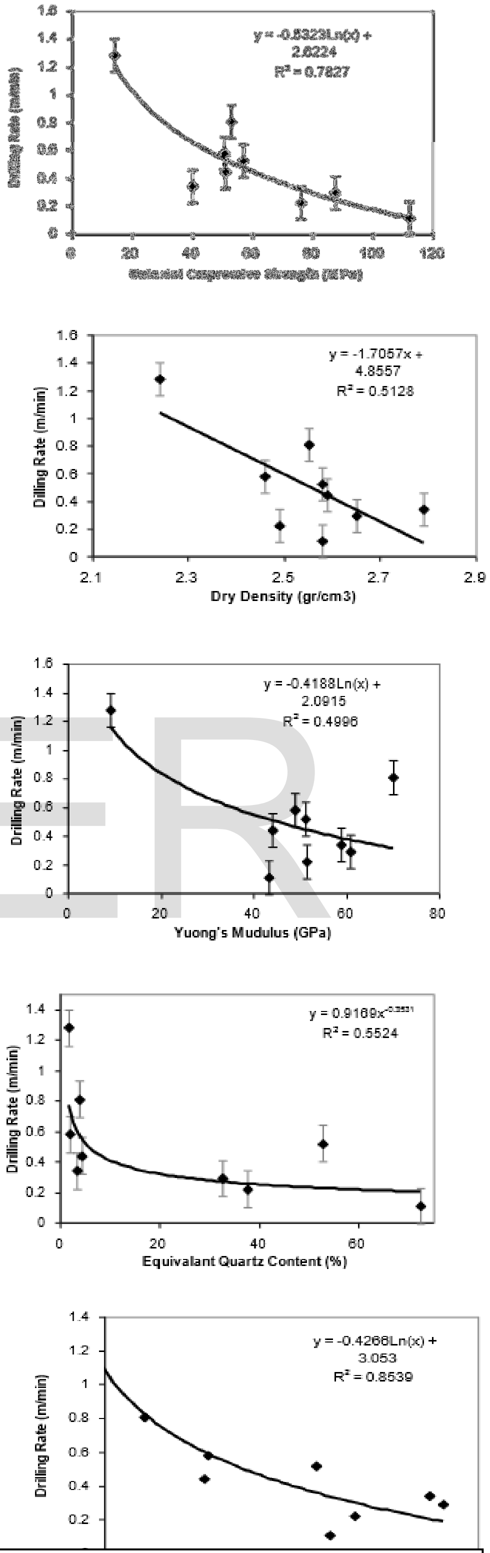
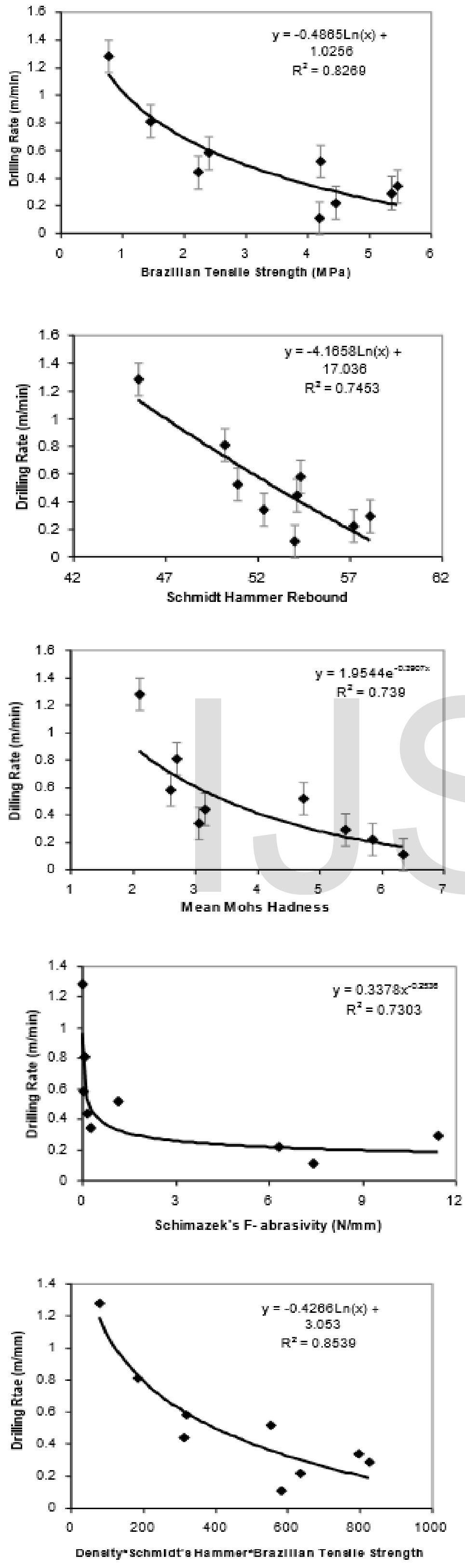


Figure 3: Drill rate versus different physico-mechanical properties of rocks



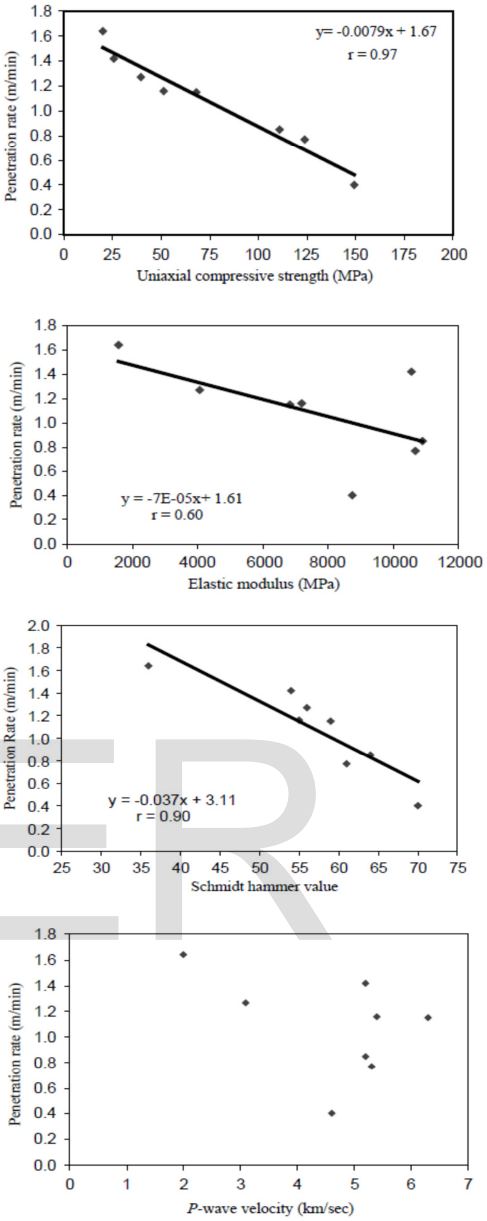
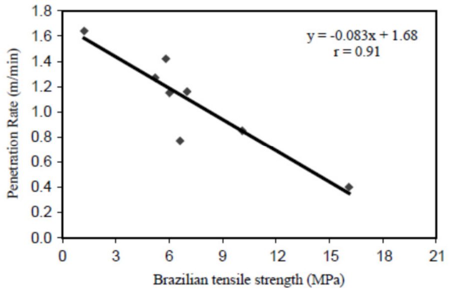
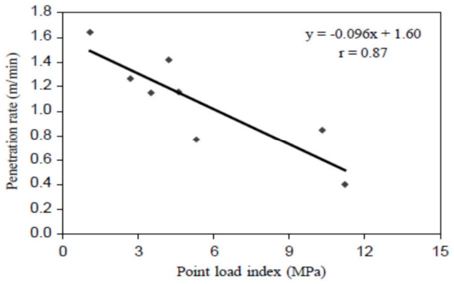
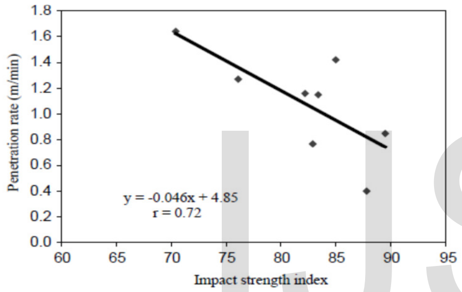


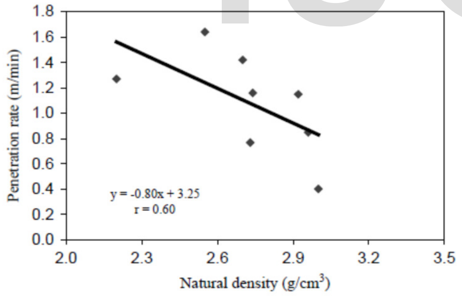
Figure 4: Penetration rate vs. different physico-mechanical properties of rocks

SE is valuable because it helps identify inefficiencies in the drilling process. Drillers should strive to keep SE as low as possible and ROP as high as possible, by varying weight on bit (WOB), rotary speed, and mud flow within normal operating limits. Unexpected changes in SE may indicate changes in rock properties, or drilling inefficiency, or both.









Reddish and Yasar (1996) obtained an index called as “Stall Penetration Rate” from the graph of penetration versus specific energy and this stall penetration rate were correlated with the modulus ratio values.

Celada et. al. (2009) obtained correlations between specific energy and different rock mass parameters using the data from a 80 m long pilot borehole as well as from the data recorded while the excavation of the Guadarrama tunnel that have a length of 28.3 km.

Figure 5 shows the variation in specific energy along the depth of the borehole and its relation with the rock mass properties namely, RMR, RQD and joints per meter length of borehole. Figure 6 shows correlation between the Bieniawski Rock Mass Rating and specific energy of five different rock types, namely, shale, sandstone, schist, coal and massive sulphide. It can be seen that the SE values increase with increase in value of RMR although the correlation coefficients are very low indicating poor relation except for coal.

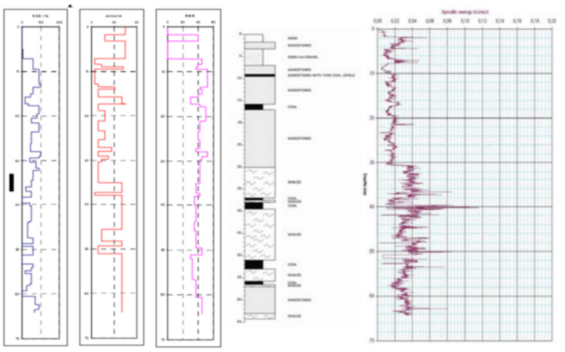
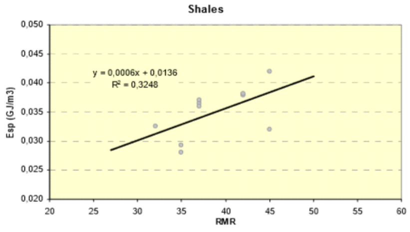
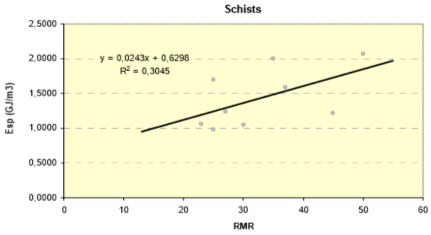


Figure 5: Rock mass parameters and specific energy obtained with depth (after Celada et. al. 2009)

Similarly, figure 7 shows correlation between uniaxial compressive strength and specific energy of three different rock types, namely, sandstone, marls and schist. Here also it can be seen that the SE values increase with increase in value of rock mass compressive strength. The R^2 in case of schist is 0.8162 which shows a strong correlation. Figure 8 shows correlation between specific energy and the rock mass compressive strength (σ_{cm}) of three different rock types, namely, shale, sandstone and schist. Here also it can be seen that the SE values increase with increase in value of rock mass compressive strength. In case of sandstone, $R^2 = 0.7033$ indicates an acceptable correlation between SE and σ_{cm}.





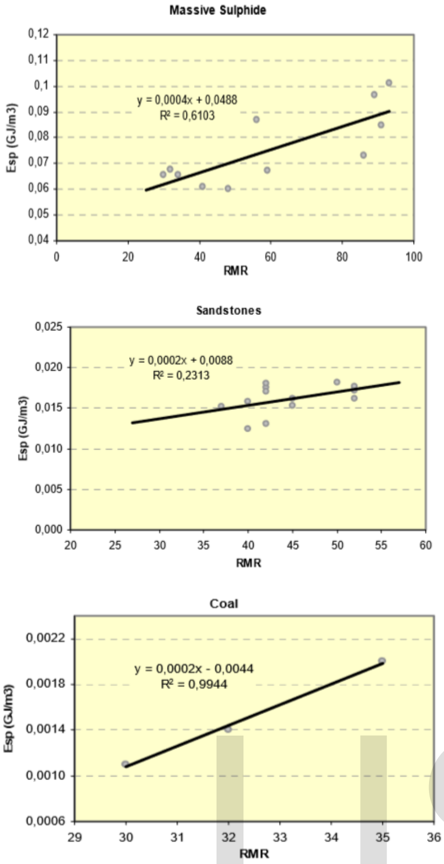
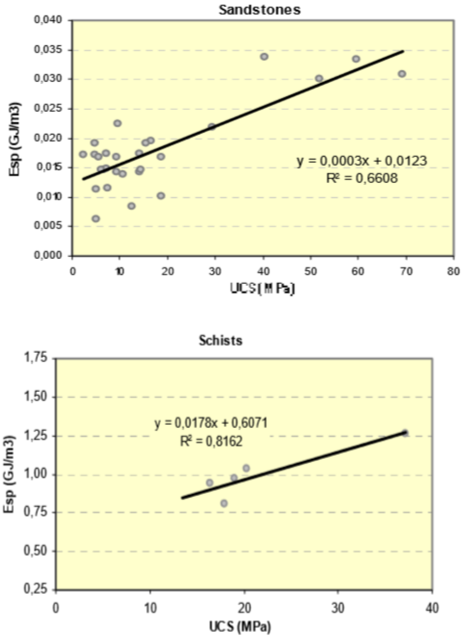


Figure 6: Correlation between specific energy and RMR for different rock type (after Celada et. al. 2009)



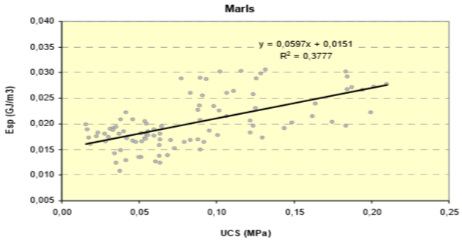


Figure 7 : Correlation between specific energy and uniaxial compressive strength for different rock type (after Celada et. al. 2009)

2.3 Heating Rate

A measure of how warm and cold an object is with respect to some standard related to the random thermal motion of the molecules in a substance. Temperature is the quantity which is directly proportional to the average kinetic energy of the atoms of matter. Temperature variation occurs at the drill bit due to the heat produced while drilling. The heating rate (HR), defined as the rate of change in temperature with respect to time, has been used in the experiment for correlation with rock properties.

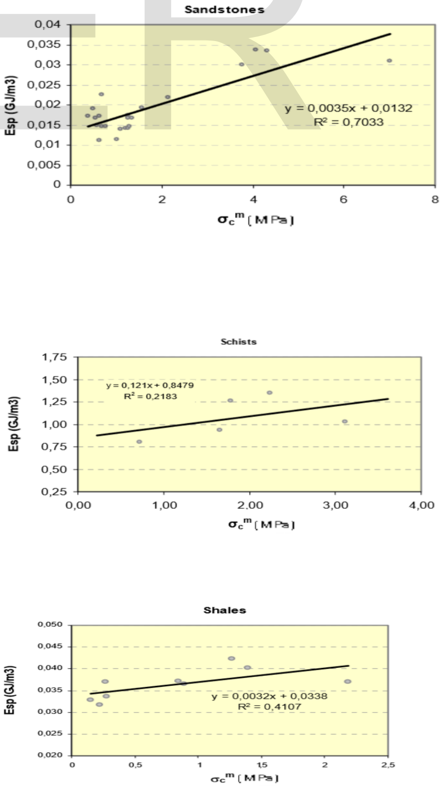


Figure 8: Correlation between specific energy and rock mass compressive strength (after Celada

et. al. 2009)

It can be calculated as:

$$HR = \frac{\Delta T}{\Delta t} \qquad \text{--- (3)}$$

where, HR is the heating rate, ^{o}C/sec

ΔT is the change in temperature, ^{o}C

Δt is the duration of drilling, sec.

The process of drilling invariably increases temperature of either the drill or the job on which it is being operated. The rate of increase in temperature will greatly be influenced by the rock types and their physico-mechanical properties. Hence, this parameter can obviously act as a means to study the rock properties.

However, impact of drilling on temperature has rarely been analyzed for rock. This is probably because most of the studies on rock drilling have been conducted in the field where drilling mud is used to control the rise in temperature. A few studies have been reported in medical field where heat generation is an important issue during bone drilling since, if the heat is not easily conducted away from the drill site, the bone is at significant risk of thermal damage.

In a study by Tu et. al. (2013) an elastic–plastic FE model (FEM) was prepared for simulating the thermal contact behavior between bone and a drill bit during bone drilling. The model allows both the temperature rise and temperature distribution near the drilled hole to be effectively estimated. Utilizing the FEM, a series of simulations were performed to examine the effects of drilling speed on the temperature of the bone during the drilling process. One of the results shown in figure 9 and figure 10 indicate that there is increase in temperature with time during drilling in a bone. The temperature reduces with increase in radial distance. A higher drilling speed leads to an obvious increase in bone temperature.

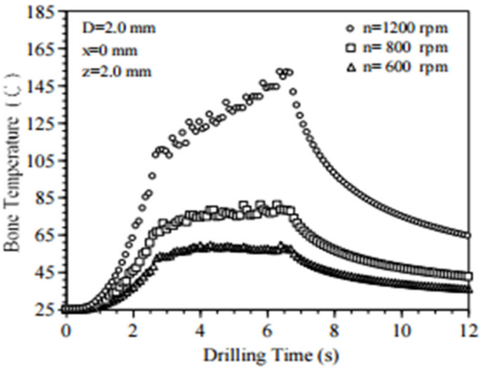


Figure 9: Variation of bone temperature with drilling time for various drilling speeds

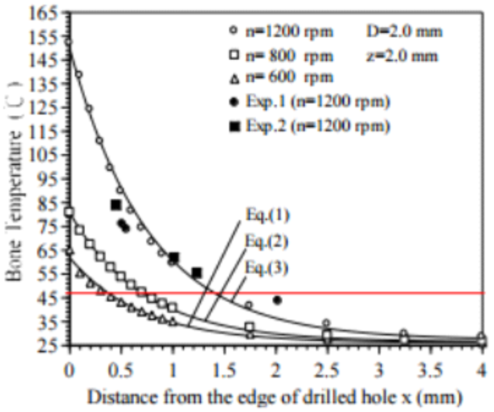


Figure 10: Variation of bone temperature along the radial direction for various speeds

3 SUMMARY

The literature review indicates that there exists specific correlation between the drilling performance parameters and different rock properties. Most of the studies found that the penetration rates of rotary and diamond drills exhibit strong correlations with uniaxial compressive strength, tensile strength, modulus of elasticity, modulus ratio and Poisson's ratio. Some other studies also established a close relation between specific energy and strength values. In various other studies, the strength properties have been very well correlated with the acoustic emissions from the sound and vibration signals generated during drilling. Dusts and temperature generated during drilling can also act as diagnostic tools to investigate rock properties.

A need thus arises to design and develop a drilling prototype which will generate online performance parameters, such as, penetration, drilling speed, current, voltage, load, temperature etc. These parameters would then be correlated with various rock properties determined in the laboratory. Such a system will be a very useful testing installation from which most of the rock properties can be estimated from a single test.

4 ACKNOWLEDGEMENT

The authors would like to thank Director, CSIR-Central Institute of Mining & Fuel Research, Dhanbad for constructive discussions and valuable suggestions.

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