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Experimental evaluation of hardness models by drillability tests for carbonate rocks

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ABSTRACT

Drillability, specific energy, resistance to drilling alteration index and several other indices have been proposed to estimate the rock capability to fail (inversely proportional to hardness). Specific energy, resistance to drilling and alteration index are the indices that apply Rate of Penetration (ROP) and operational variables (weight on bit and rotary speed) to quantify the rock hardness. Using a laboratory drilling setup, values of these indices were calculated for six different carbonate rocks in more than 20 different operational conditions. Experiments showed that specific energy has the highest consistency with ROP measurements and is the best parameter to quantify hardness of carbonate rocks. In addition, Drilling Rate index (DRI) was measured for the available samples as an indirect indicator of drilling rate. Specific energy and resistance to drilling reveal a linear correlation with DRI, while alteration index has a polynomial correlation with DRI. Specific energy, resistance to drilling and alteration index can be calculated for carbonate rocks using these correlations with DRI measurements (without performing ROP tests). In addition, ROP shows a polynomial correlation with DRI when weight on bit and rotary speed are constant.

1. Introduction

In the past several decades, because of the importance of rock drilling in petroleum engineering applications, a number of studies have addressed the drilling properties of rocks. Considering high operational costs, full recognition of the parameters involved in drilling would be desirable.

Drillability is the anti-crushing capacity of the formation rock under a certain bit size, bit type and well drilling technology condition. Drillability of rock depends on operational variables (controllable parameters) and rock properties (uncontrollable parameters). Operational variables can include bit type and diameter, weight on bit, rotatory speed and flushing. On the other hand, the parameters such as rock properties and geological conditions are the uncontrollable parameters. Drillability of rock is defined as the Rate of Penetration (ROP) of a drill bit into the rock. Yasar et al. (2010) studied the interplay between the various operational variables and the physico-mechanical properties of cement mortar, analogue for natural rock.

Prasad (2009) described drillability in terms of eight simple physical, mechanical, and micro-structural properties. The relevant rock properties are density, porosity, compressional and shear wave velocities, Unconfined Compressive Strength (UCS), Mohr friction angle, mineralogy and grain sizes.

Several empirical methods have been developed for predicting drilling performance in different rocks. Drilling Rate Index (DRI) was originally developed for the prediction of ROP for percussive drills. The DRI is not a direct indicator of drilling rate in the field, but a relative measure of ROP therefore it is not an absolute value of the drilling rate in the site. It may also be pointed as a parameter for the maximum resistance of the rock to drilling. DRI is calculated based on two tests, the Brittleness Test and the Sievers Miniature Drill Test. The Brittleness Test gives a measure of the ability of the rock to resist crushing from repeated impacts. The volume of test material corresponds to 500 g with 2.65 g/cm^3 specific gravity of the fraction 11.2–16 mm. The Brittleness Value (S_{20}) equals the percentage of material passing the 11.2 mm mesh after the aggregate has been crushed in the mortar, taken as the mean value of 3–4 parallel tests. Sievers′ Miniature Drill Test gives a measure of the surface hardness (or the resistance to indention) of the rock. The test is performed on a precut rock sample. Sievers′ J-value (SJ) is the depth of the drilled hole after 200° rotation, measured in 1/10 mm, taken as the mean value of 4–8 drill holes. The SJ-value measured parallel to the foliation is used to calculate the DRI. Fig. 1 is used to calculate the DRI. The DRI may be

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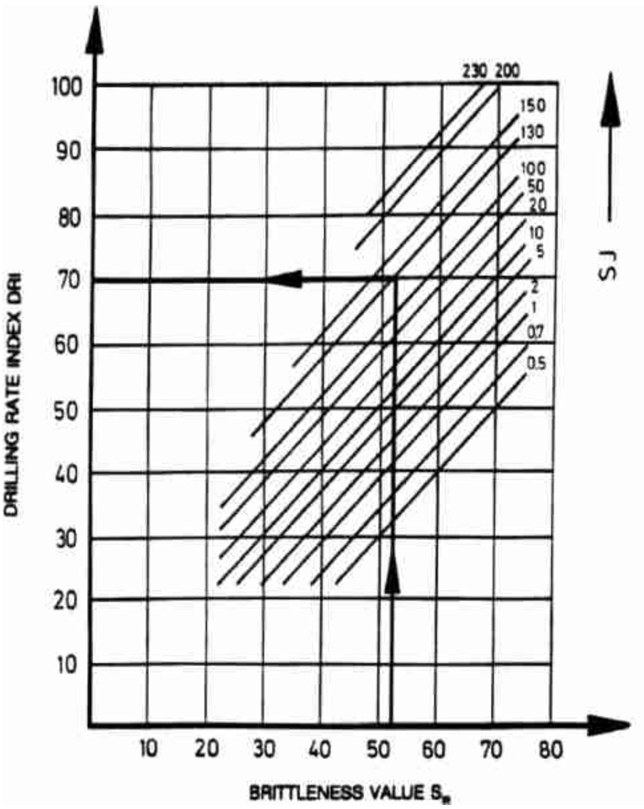

Fig. 1. Calculation of DRI.

Fig. 2. Photo of laboratory setup for the drilling experiments.

described as the Brittleness Value adjusted for the SJ value. For SJ = 10, which is common for granite or syenite, the DRI equals the S_{20} value (Bruland and Nilsen, 1995).

Teale (1965) proposed the concept of specific energy as a simple means of assessing rock drillability. Specific energy is defined as the energy required excavating a unit volume of rock in the drilling process. It is used as a means of evaluating efficiency in the drilling process. There are many ways to measure specific energy for the drilling process, but Rabia (1984) proposed Eq. (1).

$$\mathrm{SE} = 2.35\left(\frac{\mathrm{WOB}N}{d\mathrm{PR}}\right), \tag{1}$$

SE	measured specific energy ($\mathrm{MJ/m^3}$)
N	rotary speed (rpm)
WOB	weight on bit (kN)
d	borehole diameter (m)
PR	ROP (m/s)

Somerton (1959) proposed Resistance to Drilling to quantify the rock hardness (Eq. 2).

$$S_{\mathrm{d}} = \mathrm{WOB}\sqrt{\frac{N}{\mathrm{PR}}} \tag{2}$$

S_{d}	Resistance to drilling (Pa)
WOB	weight on bit (kN)
N	rotation speed (rps)
PR	ROP (m/s)

Pfister (1985) proposed alteration index as an indicative of relative hardness (Eq. 3).

$$\mathrm{AI} = 1 + \left(\frac{W}{W_{\max}}\right) - \left(\frac{V}{V_{\max}}\right) \tag{3}$$

AI	alteration index (dimensionless)
W	weight on bit (thrust − retention force + weights of rods and bit) (kN).
$W_{\max}$	it is the theoretical maximum value of W (kN).
V	it is the instantaneous ROP (with maximum value $V_{\max}$) (m/s)

In this paper, using a laboratory drilling setup, ROP was measured in more than 20 operational conditions for six types of carbonate rocks. The hardness indices and their correlation with ROP results were studied. In addition to performing DRI tests, the empirical correlations were proposed among hardness indices and DRI for tested samples. Finally, the relationship between ROP and DRI in different operational conditions was studied.

2. Experimental work

A specially designed drilling rig with 50 cm core barrel (Fig. 2) was employed to measure various drilling parameters including WOB, rotary speed and ROP in a simulation of the rock drilling process. The properties of drilling setup are mentioned in Table 1.

Using the available drilling rig, ROP was measured for different carbonate rocks in different WOBs and rotary speeds. During drilling, water was applied as a drilling fluid with a rate of 15 l/min to have a complete hole cleaning. Six types of carbonate rocks from different Iranian formations were selected. Ilam, Mila, Lashkarak, Sarvak, Qom and Shemshak were the selected carbonate formations.

In addition, DRI was measured by S_{20} and SJ tests for the selected samples. Devices shown in Figs. 3 and 4 performed S_{20} and SJ tests.

Table 1
Drilling rig properties.

Drilling rig properties	
Maximum power output of the motor	4 kw
Maximum bit weight	2000 lb
Maximum rotary speed	144 rpm
Pump power output	15 kw
Bit diameter	2.125 in.

Fig. 3. S_{20} test setup.

Fig. 4. SJ test setup.

3. Results and discussions

ROP was measured for almost 20 operational conditions for each sample. Specific energy (SE), Resistance to drilling (S_d) and alteration index (AI) were calculated for each operational condition. As an example, hardness indices are correlated with ROP for Sarvak formation (Fig. 5).

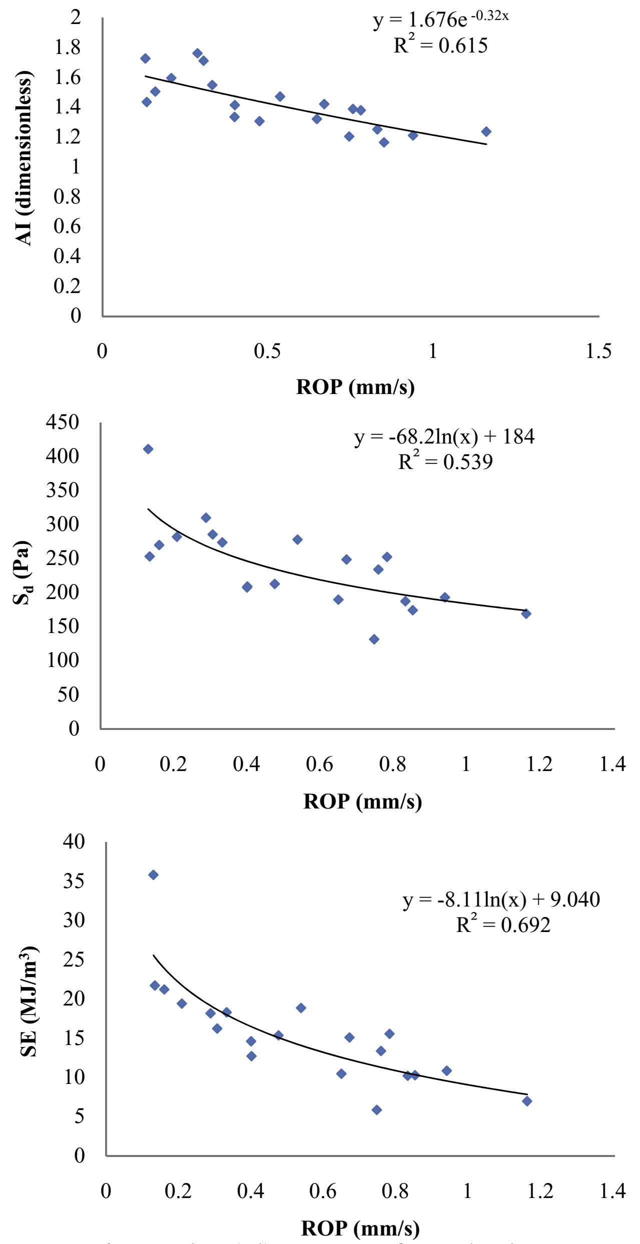

Fig. 5. Hardness indices versus ROP for Sarvak rock type.

Table 2
Calculated values of R^2 for hardness parameters versus ROP for five types of carbonate rocks.

	AI	S_d (Pa)	SE (MJ/m^3)
Ilam	0.1260	0.0410	0.7652
Mila	0.1376	0.0712	0.7322
Lashkarak	0.0035	0.0025	0.7117
Qom	0.0717	0.0612	0.6974
Shemshak	0.0986	0.0435	0.7492

Table 3
Measured values of DRI for six carbonate rocks.

Rock Type	DRI
Ilam	34
Mila	38
Lashkarak	42
Sarvak	46
Qom	48
Shemshak	52

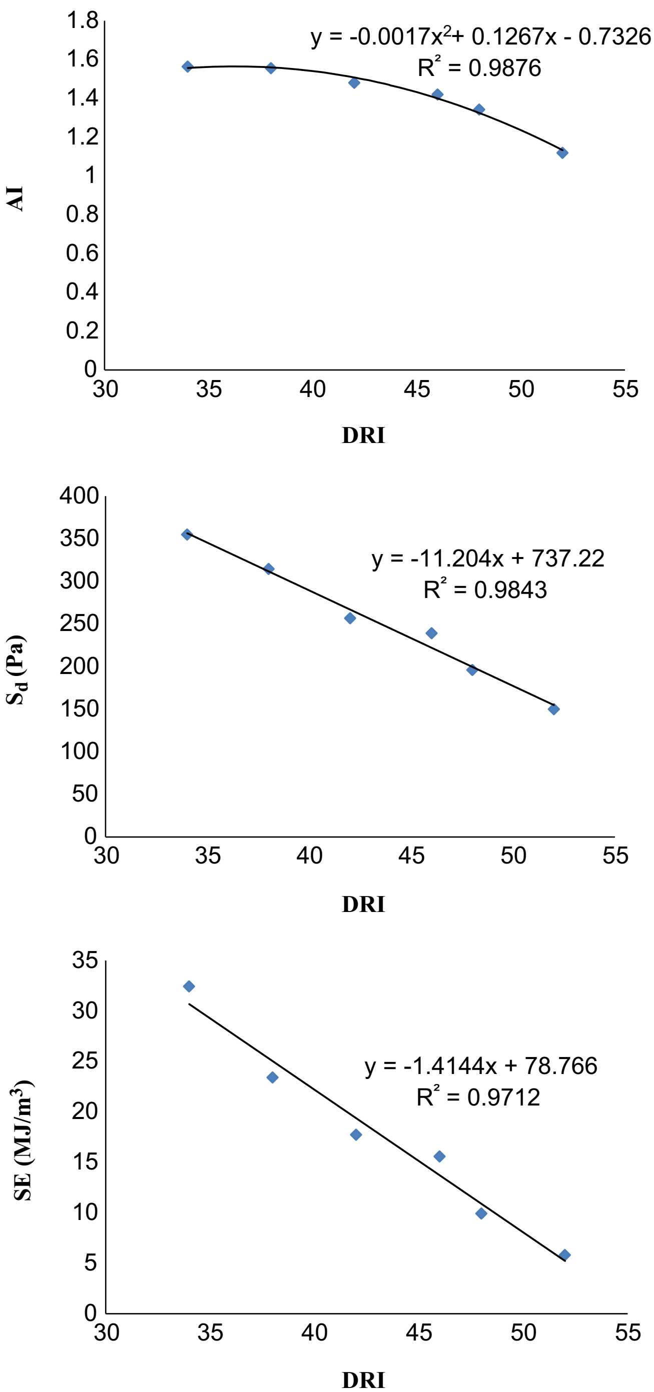

Fig. 6. Hardness indices versus DRI for six carbonate rocks.

The equations of hardness indices of Sarvak formation were calculated using the method of least square regression. Specific energy has the highest value of R^2 among the hardness indices. This procedure was performed for the other five samples and specific energy had the highest value of R^2 among the other hardness indices, too. Table 2 refers to the obtained values of R^2 for different samples. It can be concluded that specific energy is the best parameter, indicating drillability for the tested carbonate rocks and has better correlation with ROP measurements.

In the next step, DRI tests were performed. DRI values for each of the rock types are reported in Table 3. If the average values of different hardness indices in different operational conditions are calculated and plotted versus DRI, a number of interesting correlations will be obtained (Fig. 6). Using Eqs. (4), (5) and (6), values of alteration index (AI), resistivity to drilling (S_d) and specific energy (SE) are expressed as a function of DRI and there is no need to perform ROP tests.

$$S_d = -11.20(\mathrm{DRI}) + 737.2, \quad R^2 = 0.984, \tag{4}$$

$$\mathrm{SE} = -1.414(\mathrm{DRI}) + 78.76, \quad R^2 = 0.971, \tag{5}$$

$$\mathrm{AI} = -0.001(\mathrm{DRI})^2 + 0.126(\mathrm{DRI}) - 0.732, \quad R^2 = 0.987, \tag{6}$$

These correlations are valid only for carbonate rocks and their accuracy should be evaluated for the other types of rocks. Finally, the relationship between ROP and DRI was studied in different operational conditions. If ROP is plotted versus DRI in different weights on bit (when rotary speed is constant) for the carbonate samples, the obtained correlation is a polynomial function. For example, using the DRI, ROP can be calculated in $N=96$ rpm and WOB=390 kg for any carbonate rock using Eq. (7) as in Fig. 7.

$$\mathrm{ROP} = 0.003(\mathrm{DRI})^2 - 0.245(\mathrm{DRI}) + 4.650, \quad R^2 = 0.976, \tag{7}$$

In case of constant weight on bit, ROP versus DRI shows a polynomial correlation (Fig. 8). Applying the DRI, ROP can be calculated in $N=96$ rpm and WOB=390 kg for any carbonate rock using Eq. (8).

$$\mathrm{ROP} = 0.006(\mathrm{DRI})^2 - 0.454(\mathrm{DRI}) + 8.729, \quad R^2 = 0.902, \tag{8}$$

4. Conclusions

An experimental study was carried out on carbonate rock samples to evaluate the existing hardness models. In addition, a

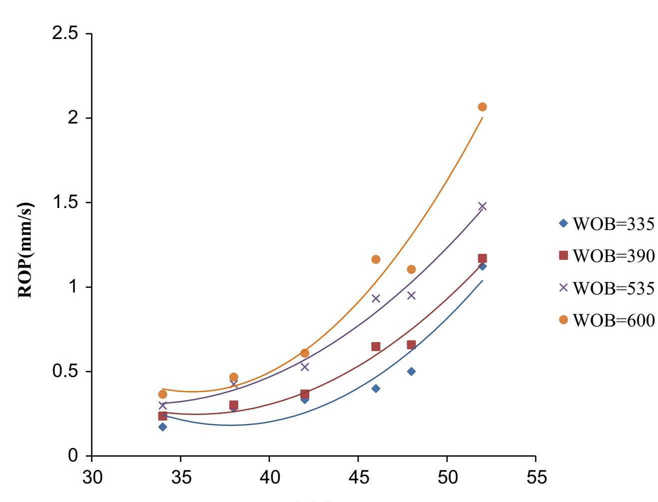

Fig. 7. ROP versus DRI in different weights on bit when $N=96$ rpm, for different tested rocks.

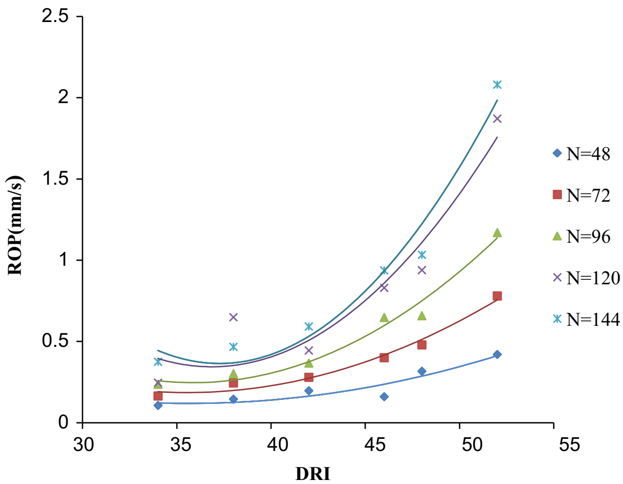

Fig. 8. ROP versus DRI, in different rotary speeds when WOB = 390 kg, for the tested rocks.

new approach was proposed to obtain hardness indices with DRI tests (without ROP measurements, which are very expensive and time consuming). Analysing the obtained results yielded the following conclusions:

(1) Studying the different hardness models shows that specific energy has the highest consistency with ROP measurements and is the best parameter for drillability classification of carbonate rocks.
(2) Specific energy and resistance to drilling have linear correlation with DRI while alteration index has polynomial correlation with DRI in carbonate rocks,
(3) ROP has a polynomial correlation with DRI in different rotary speeds when weight on bit is constant.
(4) ROP has a polynomial correlation with DRI in different weights on bit when rotary speed is constant.

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