Arab J Sci Eng (2012) 37:1451–1458
DOI 10.1007/s13369-012-0247-9

RESEARCH ARTICLE – EARTH SCIENCES

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Comparison of Some Rock Hardness Scales Applied in Drillability Studies

Received: 22 January 2011 / Accepted: 20 April 2011 / Published online: 25 April 2012

Abstract In this paper, the influence of hardness of rock material on drilling rate has been studied. During the research, eight various rock types were subjected to drilling and hardness tests such as; Mohs hardness, Indentation Hardness Index (IHI) and L-type Schmidt hammer. Mean Mohs hardness of each rock was calculated based on the hardness of contained minerals and other two scales are carried out based on ISRM standards. For drilling studies, rock samples have been drilled using actual pneumatics top hammer drilling machine with three inches diameter cross type bit. Regression analyses between mean Mohs hardness and the drilling rate reveal that in soft rocks, with increase in hardness, drilling rate decreases logarithmically but in hard rocks, with increase in hardness, drilling rate decreases linearly. In total, with increase in Mohs hardness, drilling rate decreases exponentially. Also, with increase in Indentation Hardness Index and Schmidt hammer value, drilling rate decreases logarithmically. The regression analyses showed that Indentation Hardness Index has the best and stronger relationship with the rate of percussive drilling.

Keywords Drilling · Percussive drilling · Rock hardness · Mohs hardness · Indentation Hardness Index (IHI) · N-type Schmidt hammer

الخلاصة

تمت ـ في هذه الورقة ـ دراسة تأثير صلابة مواد الصخور على معدل الحفر. وخلال البحث تم إخضاع ثمانية أنواع من الصخور المختلفة لاختبارات الحفر و الصلابة مثل مقياس المواد الصلبة ومؤشر قساوة التسنن (IHI) ومطرقة شميدت نوع (L). وتم حساب متوسط مقياس المواد الصلبة لكل صخرة استناداً إلى صلابة المعادن المحتواة و مقياسين غيرهما تم تنفيذهما بناء على معايير الجمعية الدولية لميكانيكا الصخور. ومن أجل دراسات الحفر تم حفرالعينات الصخرية باستخدام آلة مطرقة ضغط الهواء عالية الفعالية مع نوع قطعة قطرها ثلاث بوصات. وتكشف التحليلات بين متوسط مقياس المواد الصلبة و معدل الحفر أن الصخوراللينة مع زيادة صلابتها فإن معدل الحفر يقل لوغارثيميا في حين أن الصخور الصلبة مع الزيادة في الصلابة فإن معدل الحفر يقل بشكل خطي. وفي المجموع فعند زيادة مقياس المواد الصلبة فإن معدل الحفر ينخفض أضعافاً مضاعفة. أيضا مع زيادة مؤشر قساوة التسنسن وقيمة مطرقة شمديت فان معدل الحفر ينخفض لوغارثيميا. وقد أظهرت تحليلات الإنحدار أن مؤشر قساوة التسنسن يمتلك أفضل وأقوى علاقة مع معدل الحفر الطرقي.

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1 Introduction

Up to now, especially in the previous 15 years, many researchers have studied on rock drilling and many relationships between drilling rate and various mechanical and physical rock properties have been presented. In each of these researches, one or several parameters have been investigated and some major results have been achieved truly. In brief, the researchers concluded that drilling rate decreases with increase in rock density [1–9]. In rocks with dense texture and very fine grains, the drilling rate decreases but it is easy to drill in porous or fragmental rocks [3,4,8,10–12]. When rock's porosity decreases, the structure of rock becomes so weak; therefore the drilling rate increases with increase in rock porosity [4,8,10]. With increase in weathering, the drillability of rock increases [3,4].

Uniaxial compression strength (UCS), tensile strength and elastic modulus are known as the most important strength parameters of rock material. Many researchers emphasized that drilling rate decreases with increase in rock strength parameters [1–4,6,8–15]. With increase in rock abrasiveness, the drilling rate decreases and tool wear increases [3,4,10,11,16,17].

In many drilling texts, the influence of rock hardness on drilling rate has been discussed and emphasized [8,10–12]. Also, application of hardness indexes in testing and analyzing the properties of rocks has been presented in previous researches [18–20].

Among the rock hardness measurement tests, only Schmidt hammer method has been used for drilling studies till now and any mathematical relationship between other rock hardness scales and drilling rate has not been presented yet. In this paper, the effect of rock hardness on penetration rate of pneumatics percussive drills has been studied in laboratory using Mohs hardness, Indentation Hardness Index and L-type Schmidt hammer.

2 Rock Hardness Measurement Methods

Hardness is defined as a mineral or rock's resistance to penetration of tool or permanent indentation. It is important to recognize that hardness is an empirical test and therefore it is not a rock property. This is the main reason for the variation of hardness values between different hardness tests for the same piece of rock. Therefore, hardness is test method dependent.

According to application condition and theoretical background, rock hardness measurement tests which have been presented until now can be classified into three major categories as shown in Table 1.

All presented hardness scales have specific testing conditions which are different from each other. The instrumental methods need special instruments with specific characteristics which are designed for metal testing and their applications in rock engineering are limited to some special cases and rocks. Among these methods, only IHI has been presented particularly for rock testing and it is the newest suggested method for rock hardness testing. Therefore, in this study among the instrumental methods IHI method has been selected for laboratory studies and comparison with two conventional methods; Mohs hardness and Schmidt hammer.

At present, ISRM suggests an indentation hardness test based on a 60° conical tip with a 5 mm radius spherical tip, which gives the indentation hardness index, the IHI value. The IHI value is obtained by dividing the maximum load (kN) with the maximum penetration depth (mm) [21–23]. This index is an indicator of the rock's resistance to elasto-plastic deformation.

Mohs hardness is defined by how well a rock will resist scratching by tool or another rock. This scale is the most famous and applicable method for evaluating and classification of rock hardness because this method is directly based on mineralogical studies and has good ability to analyze of rock hardness. Mean Mohs hardness

Table 1 Classification of rock hardness testing methods

Based on minerals hardness	Instrumental methods	Field applied methods
Mohs hardness	Brinell Rockwell Vickers Shore Knoop Indentation Hardness Index (IHI)	Schmidt hammer

Table 2 Classification of rocks in respect of hardness [2]

Mohs hardness	1–2	2–3	3–4.5	4.5–6	6–7	>7
Description of hardness	Very soft	Soft	Semi-soft	Semi-hard	Hard	Very hard

of each rock was calculated based on the hardness of contained minerals using the following equation:

$$\text{Hardness}_{\text{mean}} = \sum_{i=1}^{n} A_i \times H_i \tag{1}$$

where A is the mineral amount (%), H the Mohs hardness and n is the number of minerals in rock. All rocks can be classified according to the Mohs hardness scale (Table 2).

The Schmidt hammer test is the quickest, simplest and least expensive method for evaluating rock hardness. The simplicity of the test is offset by its limited utility. The hammer is a compact, lightweight instrument that provides a measure of relative rock surface hardness. An experimental procedure has been adopted for testing masonry structures based upon the International Society for Rock Mechanics (ISRM) which has suggested a method for determining Schmidt rebound hardness.

3 Laboratorial Studies

The samples of rocks which have been studied in this research were collected from seven mines and one high way slope in the north-west of Iran. In this research, a typical thin section belonging to each rock type was prepared for petrographical analyses and the determination of rock hardness (Fig. 1). Then, mean hardness of each rock was calculated based on the hardness of contained minerals using Eq. 1.

According to suggested standard method for determination of IHI of all rocks [21,22], the standardized indenter is a conical tip of the same shape and dimensions as a conical platen used to determine the point load strength index. The conical platen has a 60° cone and 5 mm radius spherical tip. The tip transmits the load to the specimen. As a result, a value of the IHI can be calculated by dividing the maximum load, L (in kN), applied to the specimen by the maximum penetration, D (in mm). For the tests showing the chipping phase, the peak load and penetration were taken at the point of the first chipping. For those tests that did not display any chipping phase, the maximum load and penetration values were taken at the load of up to 20 kN or penetration reaching 1 mm. The choice of 1 mm as maximum indentation, of course, was arbitrary but seemed to be satisfactory for hard rocks. It was found that more than half of all tests showed a distinct chipping phase, evidenced as a peak in the load-penetration profile. In this study, five rock types had chipping phase but in two values were taken when the penetration reached 1 mm. The indentation hardness was calculated for each studied rock. The test was carried out on five samples from each rock type.

Schmidt hammer rebound tests were carried out on fresh surfaces of outcrops of rocks using a calibrated L-type Schmidt hammer in field. The result of above tests is presented in Table 3.

4 Drilling Tests

For drilling tests, all samples were fixed in ground using concrete. Concrete will prevent the samples from rotation during the drilling. Therefore, drilling machine can drill the blocks in suitable and stable condition without any movement. A pneumatic top hammer drill machine with 8.5 kN pull down pressure, 2,200 bpm blow frequency, 80 rpm rotational speed with a new $3\frac{1}{2}$ in. diameter insert cross type bit was used in drilling studies. In each sample, five holes of 10 cm depth were drilled and the average of drilling times of those holes was recorded as the drilling rate in each rock type. The penetration rate of each formation as a result of drilling testes is given in Table 4. Figure 2 shows the drilling of sample holes.

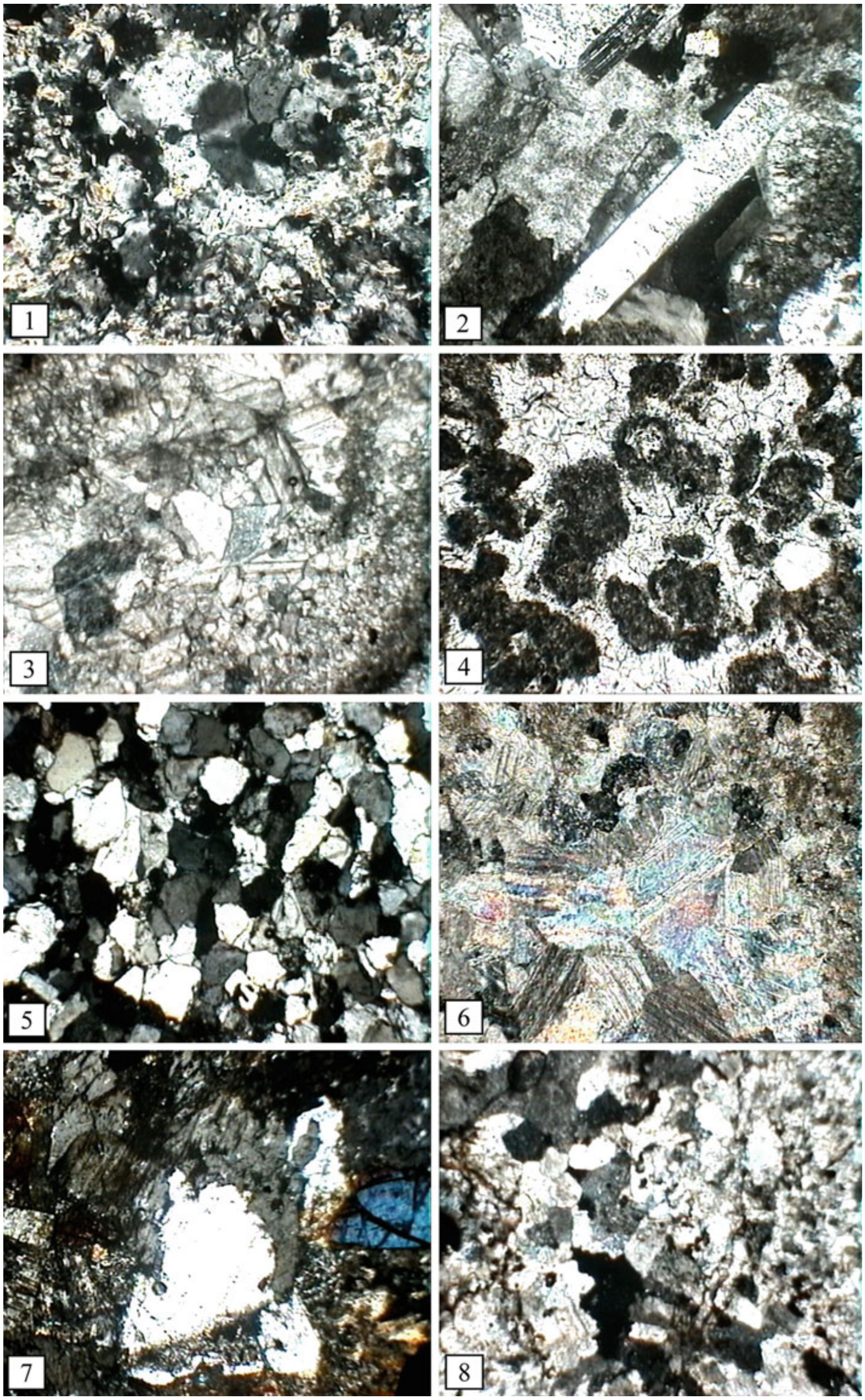

Fig. 1 Samples of studied rocks' thin sections

Table 3 Results of laboratorial test on studied rocks

No.	Location	Rock type	Mean Mohs hardness	IHI value	Schmidt hammer value
1	Sungun Mine	Monzonite	4.75	50.9	14.97
2	Ooch Mazi Mine	Granite	5.42	58.1	28.95
3	Souphiyan Mine	Limestone	3.15	54.1	17.67
4	Khalkhal Mine	Travertine	2.6	54.3	19.18
5	Khajemarjan Mine	Silica	2.7	54	7.43
6	Jooyband Mine	Hematite	6.35	56.15	36.7
7	Razgah Mine	Nepheline cyanite	5.85	57.2	20.93
8	Pasdaran High Way (Tabriz)	Sandstone	2.1	45.5	4.84

Table 4 Results of drilling tests in studied rocks

Rock type	Penetration rate (m/min)
Monzonite	0.52
Granite	0.29
Limestone	0.44
Travertine	0.58
Silica	0.81
Hematite	0.11
Nepheline cyanite	0.22
Sandstone	1.28

5 Regression Analysis

According the data presented in Tables 3 and 4, regression analyses between drilling rate of percussive drilling and three rock hardness scales are done and some mathematical relationships were achieved. The best equation with highest R^2 has been selected as a regression equation for mentioned relationship between drilling rate and hardness of rocks. The plots of drilling rate versus the rock hardness scales are shown in Figs. 3, 4 and 5.

As shown in Fig. 3, with increase in Mohs hardness, drilling rate decreases exponentially. Also, with attention to data points in plot, it is obvious that in soft rocks, with increase in hardness, drilling rate decreases logarithmically but in hard rocks, with increase in hardness, drilling rate decreases linearly. Considering the inclination of the lines in figure, in soft rocks (Mohs hardness <4.5), the sensitivity of drilling rate to rock hardness may be higher than its sensitivity in hard rocks. Therefore in soft rocks, the study of hardness and exact recognition of hardness may be very essential because this factor seriously affects the drilling rate and tool life.

As Fig. 4 shows, with increase in indentation hardness, drilling rate decreases logarithmically. Also in Fig. 5, with increase in Schmidt hammer value, drilling rate decreases logarithmically.

According to R^2 values illustrated in the above figures, it is shown that in total, relationship between drilling rate and indentation hardness of rocks is stronger than the relationship between drilling rate and two other hardness scales. But considering the local relationships for hard and soft rocks in Fig. 3, in hard rocks the relationship between Mohs hardness and drilling rate may be stronger than the relationship between drilling rate and indentation hardness (pay attention to R^2 values). Therefore in drillability studies of hard rocks, the Mohs hardness is more useful than IHI scale but in soft rocks the IHI scale is suggested.

As shown in Fig. 5, Schmidt hammer rebound has weak relationship with drilling rate. It might be related to application condition of this test in field. Therefore, application of this scale is not suggested for hardness and drillability studies of rocks.

6 Conclusion

The results of this study show that with increase in Mohs hardness, drilling rate decreases exponentially. Also, relationship between drilling rate and Mohs hardness is logarithmic in soft rocks and liner in hard rocks. In soft rocks, the sensitivity of drilling rate to rock hardness is higher than its sensitivity in hard rocks. In drillability studies of hard rocks, the Mohs hardness may be more useful than IHI scale but in soft rocks the IHI scale is suggested. Also, with increase in Indentation Hardness Index and Schmidt hammer value, drilling rate decreases logarithmically.

Fig. 2 Drilling the 10 cm sample holes

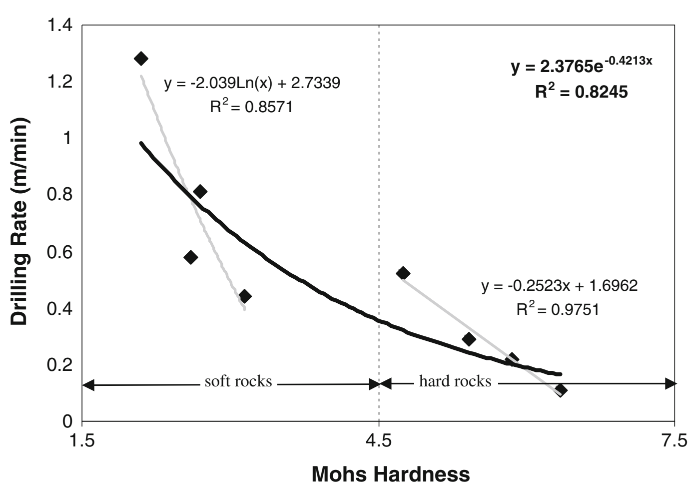

Fig. 3 Relationship between penetration rate of percussive drilling and mean Mohs hardness

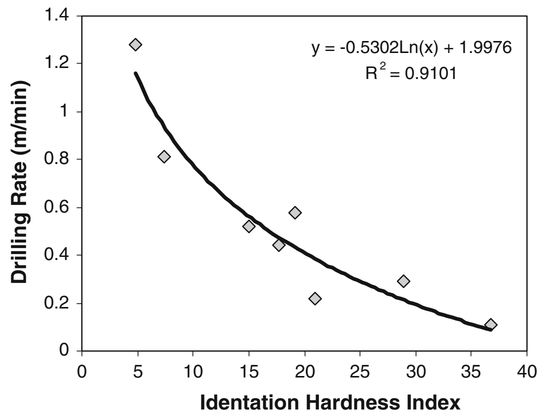

Fig. 4 Relationship between penetration rate of percussive drilling and Indentation Hardness Index

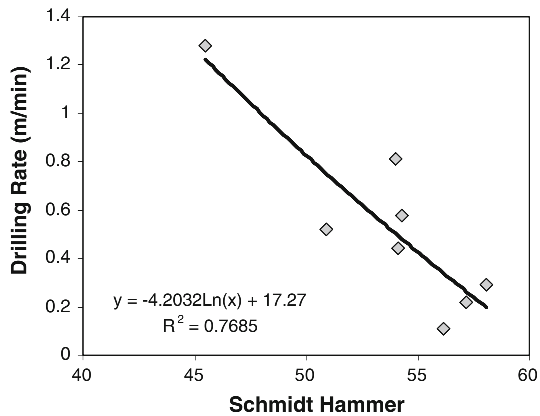

Fig. 5 Relationship between penetration rate of percussive drilling and Schmidt Hammer

Finally, in total, according to obtained results from this study, Indentation Hardness (IHI) scale is better than Mohs Hardness and Schmidt hammer scales for hardness studies in rocks.

Acknowledgments Grateful thanks are recorded to Prof. M. Osanloo, Dr. H. Aghababaie and Mrs. N. S. Rozati. The co-operation of kind miners of studied mines in collection of rock samples is also acknowledged.

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