

Effects of microfabric on drillability of rocks

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Abstract Quantifying the rock microfabric is one of the most important research interests and challenges in the field of rock drilling and excavation. In this study, the relationship between quantitative parameters of the rock microfabric and the rate of top-hammer drilling was studied. For this purpose, a drilling operation was performed on five soft rock samples and three hard rock samples and drilling rates were recorded. Thin sections from the rock samples were prepared and micrographs of the sections were reviewed using AutoCAD software and digital boundaries of the grains were clarified and drawn. After preparation and filtering of the digitized thin sections, four basic properties of each grain, including maximum diameter, minimum diameter, area and perimeter, were calculated with the help of the software. These parameters were then analyzed statistically and used to obtain six indexes including equivalent diameter, grain compactness, shape factor, aspect ratio, interlocking index and grain size homogeneity index. Finally, the microfabric and drilling rate data were subjected to regression analysis and the significance of the relationships between the grain parameter values and drilling rate were

explored. Drilling rate was found to increase with increasing equivalent diameter and shape factor. In contrast, drilling rate decreased with increasing grain compactness, aspect ratio, grain size homogeneity and grain interlocking index. Grain compactness showed the most significant relationship ($R^2 = 0.8$) with drilling rate among the studied parameters.

Keywords Drillability · Microfabric · Thin section · Grain compactness

Introduction

Drilling as the initial unit operation in open pit mining plays an important role in production assurance and deliverability of a whole production process. However, it is associated with different costs, some of which are considerable. Considering the cost of all elements including labor, fuel and electricity, drilling tools and supplies, maintenance labor and parts, supervision, administration and equipment ownership, the total drilling cost can exceed US\$300 per meter per operating hour (Atlas Copco 2005). Therefore, any improvement in this operation would potentially increase the production rate and extend the life of the machine and tools.

Drillability is a term used in mining and construction to describe the influence of a number of parameters on the drilling rate and drilling rig tool wear (Thuro 1997). Determination of the drillability of a rock mass is crucial for planning drilling techniques and operations. Drillability is mainly influenced by two categories of geotechnical factors: the rock material and the characteristics of the rock mass. A wide range of studies have been done during the past 60 years in the field of drillability and on techniques for its determination. Detailed discussions and reviews are available, for example: Howarth and

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Table 1 Basic microfabric rock measurement parameters (adapted from Prikryl 2006)

Parameter	Symbol	Computation	Meaning of parameter
Area	A_i		Cross-section area
Perimeter	L_p		Length of grain boundary
Major axis length	D_{max}		
Minor axis length	D_{min}		
Equivalent diameter	D_{equi}	$D_{equi} = \sqrt{\frac{4A_i}{\pi}}$	Grain size
Compactness	C	$C = \frac{L_p^2}{A_i}$	Shape of grain cross-section
Shape (habit) factor	SF	$SF = \frac{4\pi A_i}{L_p^2}$	Circularity of grain cross-section
Aspect ratio	AR	$AR = \frac{D_{max}}{D_{min}}$	Grain ellipticity
Index of interlocking	g	$g = \frac{1}{n} \cdot \sum \frac{1}{n}$	Complexity of grain–grain relationships
Index of grain size homogeneity	t	$t = \frac{A_{avg}}{\sqrt{\sum (A_i - A_{avg})^2}}$	Grain size distribution

Rowlands (1986, 1987), Kahraman (1999), Kahramana et al. (2003) and Hoseinie et al. (2008, 2009).

In previous investigations, some researchers have studied, or at least have emphasized, the importance of rock

microfabric in drillability. Howarth and Rowlands (1987) concluded that microfabric features, including grain shape, grain size, degree of grain interlocking, porosity/microcracking, grain orientation and the nature of the

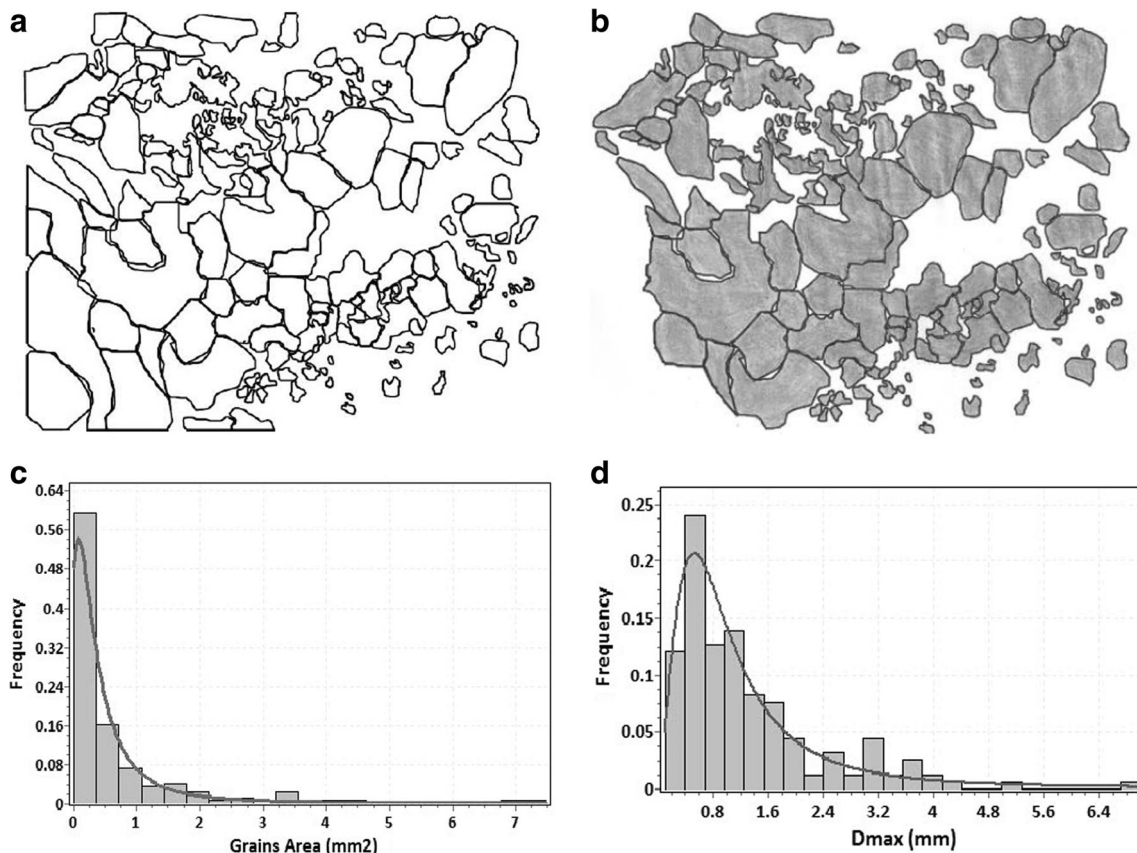


Fig. 1. Digitized images from AutoCAD and their statistical analysis. **a** Digitized raw photograph of a thin section. **b** Thin section after removal

of incomplete grains (grains shown in gray), **c** Histogram of grain areas. **d** Histogram of grain D_{max} values

Table 2 Values of the basic microstructural parameters of the studied rocks

Rock ID	Rock type	Grain area (mm ²)	Equivalent diameter, D_{equ} (mm ²)	Compactness, C	Shape factor, SF	Aspect ratio, AR	Index of interlocking, g	Grain size homogeneity, t
SI	Silica	0.89	1.06	20.77	0.6	1.79	5.01	0.098
NC	Nepheline syenite	1.83	1.52	14.88	0.84	1.83	5.18	0.08
GR	Granite	3.17	2.01	15.57	0.8	1.63	4.58	0.1
WL	Limestone	0.48	0.78	17.18	0.73	1.77	4.96	0.097
BL	Limestone	0.44	0.75	13.3	0.94	1.54	4.28	0.047
MO	Monzonite	0.43	0.8	10.76	0.93	1.63	4.48	0.047
TR	Travertine	0.65	1.01	10.97	0.92	1.47	4.23	0.046
TR2	Travertine	0.96	0.91	13.67	0.92	1.53	4.26	0.067

grain boundaries, affect the mechanical properties and drillability of rocks. Ersoy and Waller (1995a) classified the microfabric characteristics as one of the four main rock drillability parameters. They defined microfabric characteristics as consisting of: grain size, grain shape, degree of grain orientation, packing density, relative proportion of grains, texture coefficient (TC), mineral content, matrix material and type, cement type and degree of cementation, porosity, grain boundary and grain contact relationship. In another study, Ersoy and Waller (1995b) used grain size and grain shape as representative of microfabric characteristics for predicting the drilling rate in the laboratory. Ozturk et al. (2004, 2014) correlated the rock TC with physical and mechanical properties. They found some reliable relationships (e.g. with specific energy and porosity) and some weak relationships (e.g. between TC and uniaxial tension stress).

All previous studies have emphasized some microfabric factors and some studies have shown no significant relationships. In addition, TC as a general rock texture index is difficult and time-consuming to calculate and apply. Therefore, its application as a main rock texture measure has been limited and have been developed well.

In this study we attempted to correlate all basic and fundamental rock microfabric measures with rock drillability. The main aim was to identify the easiest, simplest and most significant quantitative parameter to represent the rock microfabric condition from the view point of its drillability.

Microfabric characteristics of rocks

Rock microfabric is defined as the “degree of crystallinity, grain size or granularity and fabric or geometrical relationship

Fig. 2 Drilling test on the intact rock block samples

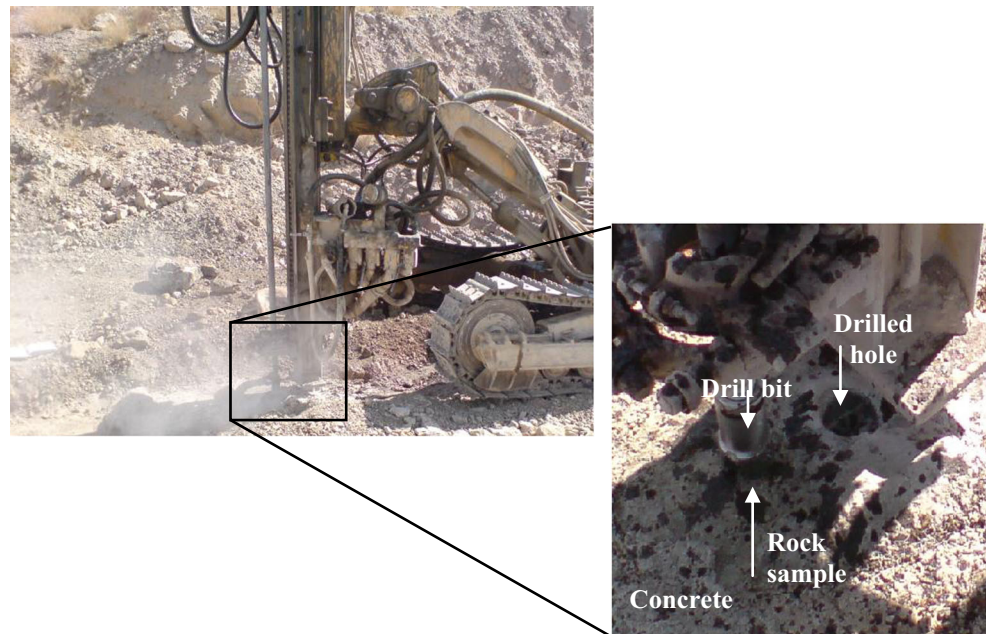


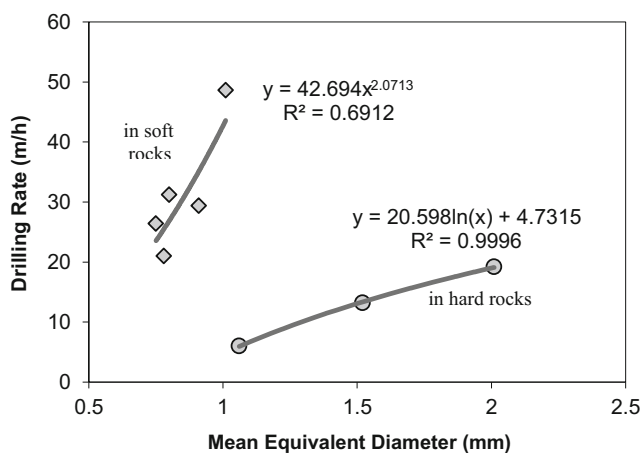
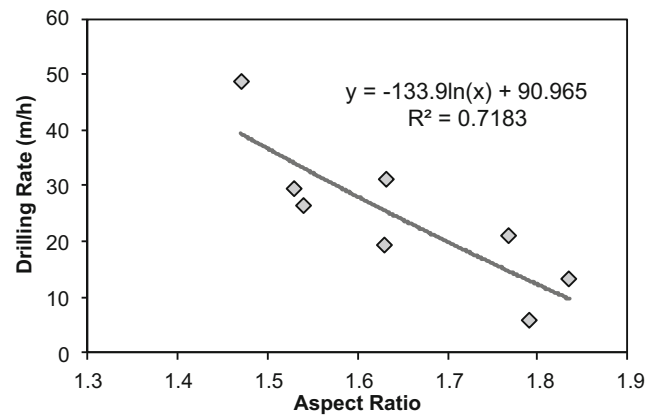
Table 3 Rate of drilling in each rock sample in the drilling tests (Hoseinie et al. 2009)

Rock ID	Drilling rate (m/h)
SI	6
NC	13.2
GR	19.2
WL	21
BL	26.4
MO	31.2
TR	48.6
TR2	29.4

between the constitutions of a rock” (Ersoy and Waller 1995a, b). Microfabric is one of the dominant features of rock material that affects its penetrability and tool wear. The required cracking and drilling energy are directly related to the rock microfabric (Howarth and Rowlands 1987). From a practical point of view, microfabric is the most challenging parameter to determine in rock drillability studies, and its relationship with penetration rate of drilling systems has not been comprehensively studied and defined because there are a large number of methods for quantifying the rock microfabric that lead to different outputs.

In geology and rock mechanics, there are some well-established microfabric parameters and indexes that are classified into three main families (Ozturk et al. 2004):

1. Commonly measured parameters including grain area and size, length of major and minor axes and their orientation
2. Quantitative parameters including aspect ratio, grain boundary smoothness
3. Fabric coefficients including micropetrographic quality index (K) (Mendes et al. 1966), grain roughness (Ehrlich and Weinberg 1970), index of interlocking (t), grain size homogeneity (g) (Dreyer 1973) and TC (Howarth and Rowlands 1986)

**Fig. 3** Drilling rate versus mean equivalent diameter**Fig. 4** Drilling rate versus grain aspect ratio

These parameters are used for the definition and quantitative analysis of the rock microfabric and are directly measured and calculated by analysis of thin section images. Common and simple to use parameters are presented in Table 1.

As is apparent in Table 1, during the quantitative analysis of thin sections, most of the parameters are defined on the basis of grain area, perimeter and length. However, each parameter represents a special feature related to mechanical, geometrical or structural condition of the rock microfabric. In this study, all the parameters shown in Table 1 were evaluated in regression analysis and drillability studies. However, many other parameters such as TC are available for similar analysis but because of the complexity and time-consuming nature of the methods, they were not included in the regression analysis.

Laboratory studies

Mineralogical and microfabric properties

All studies and tests in this study were done on rock samples collected from eight mines in the northwest of Iran. Two perpendicular thin sections were prepared from each rock type for determination of the microfabric characteristics. A microphotograph of a representative area of each thin section was then obtained. The photographs were reviewed using AutoCAD software and digital boundaries of the grains were clarified and drawn (Fig. 1a). Incomplete grains in the boundary area of the photographs were excluded from the analysis (Fig. 1b). After preparation and filtering of the digitized thin section images, the four basic properties of each grain (maximum diameter, minimum diameter, area and perimeter) were calculated by the software. Statistical analysis of the parameters was performed using EasyFit software (MathWave Technologies, <http://www.mathwave.com/products/easyfit.html>). Histograms of the grain parameters from a representative digitized thin section are shown in Fig. 1.

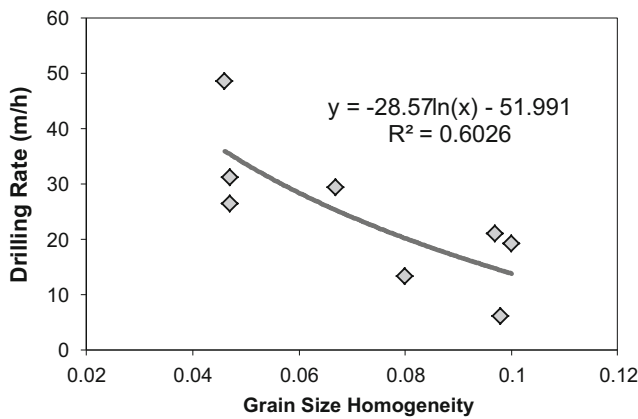


Fig. 5 Drilling rate versus grain size homogeneity

After analyzing the four above parameters, all other basic microfabric parameters of the rocks were calculated based on the equations presented in Table 1. The values of these parameters of the studied rocks are presented in Table 2.

Drilling tests

This paper is part of a research project whose partial results have already been published. The drilling data discussed in this paper are the same as those used by Hoseinie et al. (2009). For the drilling tests, one massive sample of intact rock with average dimensions of 30 cm width, 50 cm length and 30 cm height was collected from each site. All samples were embedded in shallow concrete (Fig. 2). A pneumatic top hammer drill machine with a 35 bar pull-down pressure, 2,200 bpm blow frequency, 40 bar rotational pressure and a new three-inch diameter insert cross-type bit was used in the drilling studies (Hoseinie et al. 2009). In each sample, five holes 15 cm deep were drilled and

the average drilling time calculated. The drilling rates in the studied samples are presented in Table 3.

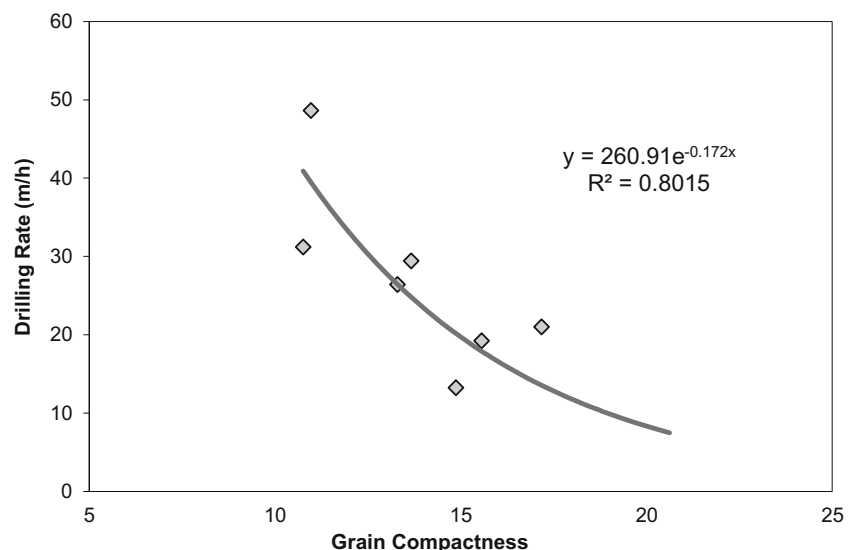
Statistical analysis

To evaluate the relationships between drilling rate and the microfabric properties of the rocks, regression analysis was done using the laboratory and field data. For this purpose, the correlations between drilling speed and the six mentioned microfabric indexes were determined. Linear, logarithmic, exponential and power curve fitting approximations were tried and the equation providing the best approximation with the highest correlation coefficient (R^2) was selected. Regression analysis of the available data from the laboratory tests showed that except grain shape factor, the microfabric parameters of the rocks were negatively associated with drilling rate (Figs. 3, 4, 5, 6, 7 and 8).

As shown in Fig. 3, the studied rocks showed two different drillability behaviors in relation to the mean equivalent diameter. The relationships followed power and logarithmic functions. Further analysis showed that the upper equation related to the soft rock samples (travertine and limestone) and the other equation related to the hard rock samples (granite, silica and nepheline syenite). The slopes of the curves showed that the drilling rate in soft rocks was more sensitive to the mean equivalent diameter than in hard rocks. In the hard rocks, the drilling rate appeared to be affected more by rock hardness than by grain size. We consider that because of the lack of sufficient data in this study, to determine more reliable relationships, a wider study is needed.

As shown in Fig. 4, the drilling rate decreased with increasing grain aspect ratio. The aspect ratio represents the grain ellipticity (Přikryl 2006). The aspect ratio of the rock grains

Fig. 6 Drilling rate versus grain compactness



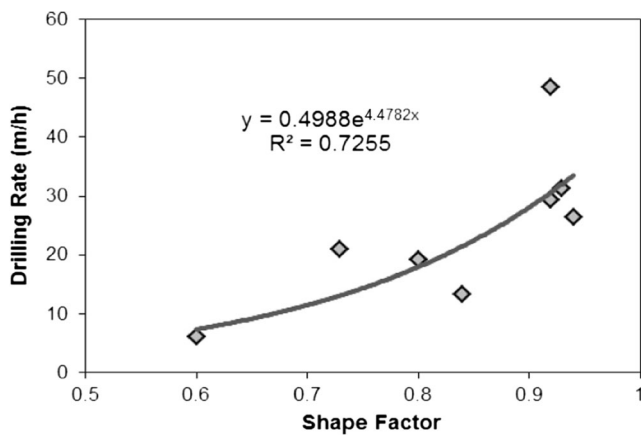


Fig. 7 Drilling rate versus grain shape factor

increased with increasing grain interlocking. Since the macroscopic mechanical behavior of rock as a granular material is governed by the interaction forces between grains (Jongchansitto et al. 2017), rock strength increases with increasing grain interlocking and is associated with a decrease in drilling rate.

Increasing grain homogeneity results in increasing homogeneity of the whole structure of the rock material. Rock heterogeneity is one of the most important factors affecting the fracture and breakage process of rocks (Wang 2015). High homogeneity is associated with higher strength and resistance to penetration. To allow better interpretation of this relationship, a laboratory test was done on the studied rock types. With increasing of grain homogeneity, the uniaxial compressive strength of the studied rocks increased linearly (Fig. 9). Therefore, the drilling rate decreased with increasing grain homogeneity. However, as can be seen in Fig. 5, grain homogeneity showed the weakest relationship with drilling rate of all the microfabric properties of the rocks. This indicates that grain homogeneity is of less value in studying the drillability of rocks than the other parameters.

The analysis showed that drilling rate decreased with increasing of grain compactness (Fig. 6). This result was predictable because high drilling energy was required to crack the

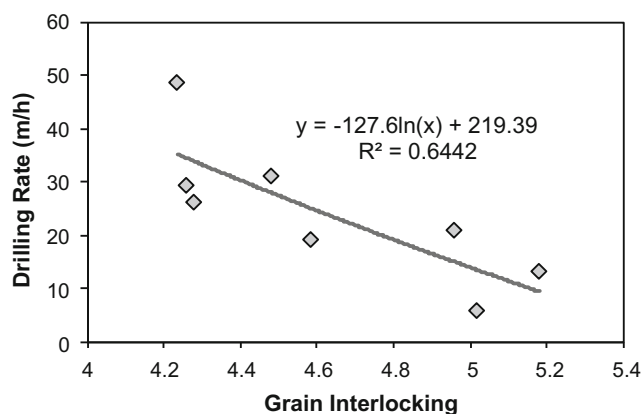


Fig. 8 Drilling rate versus grain interlocking

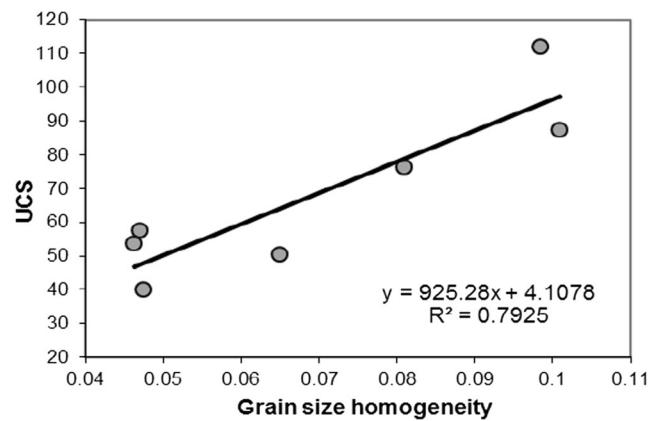


Fig. 9 Grain size homogeneity versus uniaxial compressive strength (UCS) in the studied rock types

rock microfabric because of the high grain compactness, and therefore the drilling rate was reduced. The shape factor shows the circularity of grain cross-section (Přikryl 2006). In general, grain interlocking and microfabric compactness decrease with increasing shape factor. Therefore, as shown in Fig. 7, the drilling rate increased with increasing shape factor. However, this relationship was not very strong ($R^2 = 0.73$), but the regression analysis showed a reasonable increasing trend. As shown in Fig. 8, the correlation between drilling rate and the grain interlocking index was weak and followed a power function. The drilling rate decreased with increasing grain interlocking. With increasing grain interlocking, the grain network becomes increasingly complex and dense, and therefore the drilling bit requires more power to overcome the grain–grain interactions of the dense network, and thus the drilling rate decreases.

Conclusion

This study focused on the relationships between rock microfabric characteristics and rock drillability. Six indexes were used and calculated to describe the rock microfabric characteristics: equivalent diameter, compactness, shape factor, aspect ratio, interlocking index and grain size homogeneity. Regression and statistical analyses showed that mean grain size showed the strongest relationship with drilling rate in hard rocks. In general, grain compactness showed the most reliable relationship (relationships with a coefficient of determination, R^2 , higher than 0.8) with drilling rate among the parameters. Grain size homogeneity showed the weakest relationship with drilling rate. The drilling rate increased with increasing equivalent diameter and shape factor. However, the drilling rate decreased with increasing grain compactness, aspect ratio, grain size homogeneity and grain interlocking.

The results appear to indicate that in soft rocks, the drilling rate is more sensitive to grain size than in hard rocks. In hard

rocks, hardness and strength may affect the drilling rate more than grain size. The results indicate that for deep drillability studies or drillability classifications, the simple quantitative microfabric parameters of rock can be applied with high significance and can help provide a good overview of the characteristics of rocks encountered in practice. All parameters mentioned in this study could also be applied to drill-bit wear analysis and prediction, and we suggest this as the subject of future work.

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References

- Atlas Copco (2005) Total Drilling Cost; AC BHMT's Value Proposition. Indiana Society of Mining and Reclamation, 19th Annual Technology Transfer Seminar, Jasper, Indiana, USA, 5–6 December 2005. <http://www.in.gov/dnr/reclamation/3740.htm>
- Dreyer W (1973) The science of rock mechanics. Part I. The strength properties of rocks, 2nd ed. Series on rock and soil mechanics, vol. 1 (1971/73), No. 2. Trans Tech Publications, Clausthal, 500 p
- Ehrlich R, Weinberg B (1970) An exact method for characterization of grain shape. *J Sediment Petrol* 40(1):205–212
- Ersoy A, Waller MD (1995a) Prediction of drill-bit performance using multivariable linear regression analysis. *Trans Inst Mining Metall Trans A* 104:101–114
- Ersoy A, Waller MD (1995b) Textural characterization of rocks. *J Eng Geol* 39(3–4):123–136
- Hoseinie SH, Aghababaei H, Pourrahimian Y (2008) Development of a new classification system for assessing of rock mass drillability index (RD_i). *Int J Rock Mech Min Sci* 45:1–10
- Hoseinie SH, Ataei M, Osanloo M (2009) A new classification for evaluating of rock penetrability. *Int J Rock Mech Min Sci* 46:1329–1340
- Howarth DF, Rowlands JC (1986) Development of an index to quantify rock texture for qualitative assessment to intact rock specimens. *Geotech Test J* 9(4):169–179
- Howarth DF, Rowlands JC (1987) Quantitative assessment of rock texture and correlation with drillability and strength properties. *Rock Mech Rock Eng* 20:57–85
- Jongchansitto P, Preechawuttipong I, Balandraud X, Grédiac M (2017) Numerical investigation of the influence of particle size and particle number ratios on texture and force transmission in binary granular composites. *Powder Technol* 308:324–333
- Kahramana S, Bilgin N, Feridunoglu C (2003) Dominant rock properties affecting the penetration rate of percussive drills. *Int J Rock Mech Min Sci* 40:711–723
- Kahraman S (1999) Rotary and percussive drilling prediction using regression analysis. *Int J Rock Mech Min Sci* 36(7):981–989
- Mendes FM, Aires-Barros L, Rodrigues FP (1966) The use of modal analysis in the mechanical characterization of rock masses. Proceedings of the First Congress of the International Society of Rock Mechanics. Lisbon, Portugal, 25 September – 1 October 1966, vol. I, theme 2, pp. 217–223
- Ozturk CA, Nasuf E, Bilgin N (2004) The assessment of rock cutability, and physical and mechanical rock properties from a texture coefficient. *J South Afr Inst Min Metall* 7(August):1–6
- Ozturk CA, Nasuf E, Kahraman S (2014) Estimation of rock strength from quantitative assessment of rock texture. *J South Afr Inst Min Metall* 114:471–480
- Přikryl P (2006) Assessment of rock geomechanical quality by quantitative rock fabric coefficients: limitations and possible source of misinterpretations. *Eng Geo* 87:149–162
- Thuro K (1997) Drillability prediction – geological influences in hard rock drill and blast tunneling. *Geol Rundsch* 86:426–438
- Wang Y (2015) Numerical modelling of heterogeneous rock breakage behavior based on texture images. *Miner Eng* 74:130–141