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The assessment of correlation between rock drillability and mechanical properties in the laboratory and in the field under different pressure conditions

Gao Li [a], Mou Yang [a,*], Yingfeng Meng [a], Houbin Liu [a,**], Lin Han [a], Feng Zhou [b], Hua Zhang [b]

[a] State Key Laboratory of Oil and Gas Geology and Exploration, Southwest Petroleum University, 610500, Chengdu, PR China
[b] Southern Gas District, Petrochina Southwest Oil and Gas Field Company, 646000, Luzhou, PR China

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ABSTRACT

Drillability, used for evaluating penetration rate and in selecting suitable bit types, is greatly influenced by the mechanical properties of rock. To investigate the correlation between drillability and rock mechanical properties, compressive strength, elastic modulus and Poisson's ratio were measured separately under uniaxial, 30 MPa and 60 MPa confined pressure conditions. Drillability numbers were obtained using Rollow's microbit method. Regression analysis results demonstrated the correlation between drillability grade and rock mechanical properties. The correlation improved with increased confining pressure. Additionally, the best correlation was shown between drillability grade (DG) and compressive strength under varying confined pressure conditions, as opposed to the correlation between DG and the elastic modulus or DG and Poisson's ratio under uniaxial conditions. The calculation results of rock compressive strength and DG under varying confined pressure conditions illustrated that the rock effective porosity, wellbore fluid pressure and formation pore pressure played an important role in determining the confined pressure at bottom hole. This further affects DG and compressive strength distribution along the wellbore during field drilling process. These preliminary studies could contribute significantly to understanding the effect of rock mechanical properties on confining pressure and thus on safety and efficiency of drilling in the field.

1. Introduction

The oil and gas industry faces enormous challenges in deep well drilling. Porosity of rock generally decreases with depth. This is demonstrated by increased rock compressive strength and drillability grade (DG). Drilling of these deeply buried tight rocks tends to slow the rate of penetration (ROP), resulting in a reduction in bit life and an overall increase in drilling time. Rock drillability is the basis for the drilling plan and drilling operation. It assists in choosing the drilling method, selection of the rock-breaking tools, predicting the ROP and optimizing the drilling parameters. Appropriate bit selection and drilling parameters optimized for the rock drillability of specific geological formations hastens the drilling process while reducing interruptions for bit changing.

Rock drillability is defined as the relative penetration rate of a drill bit into the rock and is essential data for bit selection (Yarali and Kahraman, 2011). Unfortunately, the drillability assessment of rock is limited by many factors, which can be divided into two categories. The first category is related to the inherent uncontrollable properties of rock, such as mineral composition, cementation type and porosity, which affect the mechanical and strength properties of rock. The second category includes controllable technical specifications such as the drilling rig and drilling method used, the bit type and weight on bit (WOB), as well as the rotational speed of the bit. The evaluation and analysis of rock drillability can improve the penetration rate by influencing the selection of the most effective bit types (Yarali and Soyer, 2013).

Past studies have focused on studying and analyzing the factors that affect rock drillability. These showed that the drillability was a function of rock mechanical properties (Howarth and Rowlands,

* Corresponding author.
** Corresponding author.
E-mail addresses: yangmou@swpu.edu.cn (M. Yang), ym528919@126.com (H. Liu).

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1987; Rasoul et al., 2014), such as compressive strength, hardness, elastic modulus and brittleness. Several empirical methods have been developed for evaluating fundamental rock properties. The analysis models of drillability and rock mechanical properties were established under unconfined pressure conditions (Kahraman et al., 2003; Akün and Karpuz, 2005; Atici and Ersoy, 2009). Some studies demonstrated that during the field drilling process, rock mechanical properties increased with an increase in confining pressure, especially for deep well drilling, due to drilling fluid pressure rather than overburden stress (Skempton, 1954; Maurer, 1965; Yang and Gray, 1967; Bourgoyne et al., 1986). For example, rock compressive strength and DG increase with an increase in well depth as rocks become compacted. Direct drilling on rock is the most reliable test for drillability; however, obtaining additional rock property data is also very important for the evaluation of data in real field drilling operations.

In this study, rock drillability was evaluated on the basis of DG which is a parameter for determining the maximum resistance of rock to drilling. Although DG is not a direct indicator of the drilling rate in the field, it is a relative measure of penetration rate. The objective of this work was to study the correlation between DG and mechanical properties of rock under a variety of confining pressure conditions. The mechanical properties, including compressive strength, elastic modulus and Poisson's ratio, under different confining pressures were investigated. In addition, Mathematical models of compressive strength and DG under confining pressure conditions were also developed and solved, in conjunction with well logging data. The results provided understanding of the relationship between rock mechanical properties and DG under field conditions, and they also served as guidelines for selecting appropriate bit types.

2. Materials and methods

2.1. Materials

Twenty-four test rock blocks were prepared from eight samples in this study (3 test samples per block). The eight samples consisted of five sandstone and three mudstone samples, collected from five exploration wells in the Sichuan Basin of southwest China. Sample depths ranged from 3250 m to 4006 m and were taken from the Triassic strata, which consisted of reddish, greyish and brownish mudstone and fine-grained sandstone with varying content of calcite. Each block sample was inspected for macroscopic defects in order to provide test specimens free from fractures or alteration zones. Locations and names of the rock samples are given in Table 1.

2.2. Laboratory testing methods

2.2.1. Drillability test

Rock drillability tests were performed on trimmed cylindrical core samples with diameters of 40–100 mm and lengths of 30–80 mm. The specifications of Rollow's method were given as follows: The time intervals necessary to drill to a depth of 2.4 mm in each rock sample were measured using a bit diameter of 31.75 mm. Rotational speed was 55 revolutions per minute and the weight on bit was 890 N (Rollow, 1963). Under these conditions, drilling time in seconds was measured, which was then converted to drillability grade. Taken the logarithm of drilling time t to base 2 as the formation drilling grade expressed, and the drillability grade can be classified into 10 categories which were satisfied with drillability assessment for all kinds of rock types. The equation can be expressed as follows (Yin, 1986; Zhang et al., 2011).

$$D_r = \log_2 t \tag{1}$$

Where D_r is the drillability grade; t is the time in seconds to drill to a depth of 2.381 mm.

2.2.2. Rock properties tests

Rock mechanical parameters, including compressive strength, elastic modulus and Poisson's ratio, were tested by RTR-1000 (Rapid Triaxial Rock Testing System, Geotechnical Consulting and Testing Systems, USA) under different confining pressure conditions. The confined pressure limit of the equipment was 140 MPa; the capacity of axial loading was 1000 kN; the radial and axial displacement limits were −2.5 mm and 2.5 mm respectively, and the pressure accuracy was 0.01 MPa. The specifications of mechanical properties are illustrated as follows:

- Strain was applied within the limits of 1.5×10^{-5} to perform confined compressive strength (CCS) tests under 30 MPa and 60 MPa confining pressure conditions.
- Tangent Young's modulus was measured at a stress level equal to 50% of the ultimate compressive strength.
- Poisson's ratio was calculated at a stress level equal to 50% of the ultimate compressive strength.

The core samples had a diameter of 25 mm and a length-to-diameter ratio of 2. The same trimmed core samples were used in the determination of natural density. The bulk density value was obtained by dividing the weight by sample volume.

3. Results and discussion

3.1. The morphology of rocks

The morphology of sandstone and mudstone were observed using a scanning electron microscope (SEM). As shown in Fig. 1(A), some micro cracks and pores (inside the box) were observed in the sandstone and mudstone. The failure pattern photographs of the sandstone and mudstone samples under different confining pressures are presented in Fig. 1(B). Some distinct brittle tensile planes with open fracture planes were observed under uniaxial conditions, whereas there were only minor signs of developing a shear plane under confining pressure conditions. Additionally, the mudstone sample bulged, becoming shorter vertically and wider horizontally, when the confining pressure was up to 60 MPa. Based on the failure modes of the samples, it was found that samples tested at a low confining pressure exhibited a brittle response, while ductile response was present at a high confining pressure.

There are two possible reasons why the small deformation of rock was formed under higher confining pressures. 1. The micro cracks and porosity of the rocks were gradually closed as the confining pressure increased. 2. The brittle-ductile transition of sandstone and mudstone were dependent on grain size, cementing material and clay content, which played an important role in

Table 1
Summary of rock types used in laboratory testing.

Rock code	Well no.	Core sampling depth (m)	Rock type	Density (g/cm^3)
1	A	3250–3254	mudstone	2.70
2	A	3338–3340	sandstone	2.70
3	B	3796–3797	sandstone	2.57
4	C	3558–3559	sandstone	2.61
5	C	3626–3627	mudstone	2.72
6	D	3610–3611	mudstone	2.68
7	D	4005–4006	sandstone	2.72
8	E	3298–3299	sandstone	2.62