International Journal of Rock Mechanics & Mining Sciences 83 (2016) 248–251

Contents lists available at ScienceDirect

International Journal of Rock Mechanics & Mining Sciences

journal homepage: www.elsevier.com/locate/ijrmms

Technical Note

Effects of rock properties and temperature differential in laboratory experiments on underbalanced drilling

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ARTICLE INFO

Article history:
Received 11 April 2013
Received in revised form
2 August 2014
Accepted 11 August 2014
Available online 27 September 2014

1. Introduction

A number of technical documents have addressed the effects of confining stress and fluid pressure on rock failure in overbalanced drilling (OBD) conditions [1–3]. It is commonly recognized that reducing bottom hole pressure to achieve UBD conditions can significantly increase the rate of penetration [4–6]. It is also believed that the performance of UBD is highly dependent on rock type which can be characterized by rock's mechanical properties. However, it is not clear what property of rock is a dominating factor affecting UBD performance. No literature has been found to address the effect of rock properties on rock failure in UBD conditions.

Temperature differential at bottom hole may also affect UBD performance. A lower-than-formation temperature condition exists at bottom hole during well drilling geothermal and oil and gas well. The low temperature is due to the fact that the drilling fluid is colder than the formation rock being drilled. The magnitude of bottom hole temperature was mathematically investigated by Tragesser and Crawfordm [7], Hasan and Kabir [8] and Kabir and Kouba [9]. The bottom hole temperature is significantly lower than rock temperature due to Joule–Thomson cooling effect at drill bit orifices in gas UBD. Under sonic flow conditions the Joule–Thomson cooling effect causes the absolute temperature of gas to drop by about 84% [10]. This is translated to a reduction of gas temperature from 110 °C to 48 °C. The effect of temperature on rock's deformation was reported by Griggs et al. [11]. Moore [12] listed bottom hole temperature as one of the major factors affecting drilling rate. Guo and Liu [13] pointed out several detrimental effects of low-bottom hole temperature, including hole enlargement, hole inclination, and bit ice-balling. The first two effects are believed to be caused by the reduced rock strength under temperature differential. Zhang et al. [14] performed an analytical and numerical modeling to study the rock failure mechanism due to pressure and temperature differentials in UBD. The effect of temperature differential on UBD performance has never been verified and needs to be experimentally investigated.

Theoretically, temperature may affect UBD performance in two ways: (1) change in temperature alters rock property and weakens rock strength, and (2) change in temperature induces thermal stress and promotes rock failure. The former is a complex process because temperature may alter rock tensile strength and compressive strength differently in different conditions. Investigation of temperature on rock properties was beyond the scope of this study. The latter, thermal stress, has been investigated analytically and numerically in [14], considering temperature gradient. The theory was tested in this study.

Sandstone samples of different permeabilities were first tested for compressive and tensile strengths in this study. The samples were then drilled with a state-of-the-art apparatus to obtain rate of penetration (ROP) data under various UBD pressure differentials. It was found that the ROP data correlates well to rock permeability and the compressive to tensile strength ratio. The temperature differential effect was further investigated under ambient pressure conditions. It was found that the ROP increased by 22.4% on average as the temperature differential changed from 30 °C to 180 °C.

2. Effect of rock properties on rate of penetration

2.1. Test design

The rock core samples used in the experiments are sandstones with permeability levels of 0.158 md, 8.23 md, and 57.3 md. Two

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http://dx.doi.org/10.1016/j.ijrmms.2014.08.004
1365-1609/

types of tests were designed and run to investigate the effect of rock properties on ROP. Type-a tests were run to investigate the effect of rock permeability on ROP at various pressure-differentials. Type-b tests were run to investigate the effect of rock strength on ROP at two levels of pressure-differentials. Properties of the core samples are presented in Table 1.

2.2. Experimental apparatus

The rock drillability tester used in the experiments is very similar to the one used in [15]. It consists of a core holder, a drill bit, a drive box, pumps for pore pressure, confining pressure, bottom hole pressure, and axial stress, and a central control and the data acquisition system. The drill bit is a 31.75 mm diameter roller type bit. The contact force at the drill bit can be controlled within an error of less than 20 N. The rotary speed of the drill bit can be controlled with an error of less than 1 rpm.

2.3. Experimental procedure

The test procedure involves preparing core samples and drilling the core samples with fluid injection to the surface of rock. The test sample's boundary condition was established during the test by applying confining pressure and pore pressure. The following procedure was used in the experiments: cut core sample to 45 mm long and polish its test surface. Install the core sample in the core holder. Apply a confining pressure of 30 MPa. Apply a designed pore pressure of 25 MPa. Apply a bottom hole pressure to achieve a desired pressure differential value. Set a fluid flow rate of 10 cm^3/min. Set rotary speed to 55 rpm. Drill the core sample for a depth of 2.4 mm with a force on rock of 890 N. Record the actual depth of penetration and drilling time.

2.4. Result and discussion

The resultant data from the experiments were analyzed using the normalized ROP defined by

$$\beta = \frac{ROP_{\Delta p}}{ROP_{\Delta p=0}} \tag{1}$$

where β is the normalized ROP [dimensionless], $ROP_{\Delta p}$ is the rate of penetration at pressure differential Δp [mm/min], and $ROP_{\Delta p=0}$ is the rate of penetration at pressure differential $\Delta p = 0$ [mm/min]. The pressure differential is defined as the borehole pressure minus formation pore pressure.

Type-a tests were run on 10 samples for each permeability-level of rocks. The normalized ROP data is plotted against the pressure differential in Fig. 1. It is indicated that the normalized ROP increases as the pressure differential drops. However, this effect is more pronounced for low-permeability rocks than for high-permeability rocks. This means that UBD is more efficient in drilling low-permeability rocks.

Type-b tests were run on eight core samples of given strengths at pressure differentials of 0 and 10 MPa. When the normalized ROP data were plotted against the compressive and tensile strengths, no correlation was found. Then, a normalized rock strength was defined as

$$\alpha = \frac{\sigma_c}{\sigma_t} \tag{2}$$

where α is the normalized rock strength [dimensionless], σ_c is the compressive strength of the rock [MPa], and σ_t is the tensile strength [MPa].

The normalized rate of penetration, β, is plotted against the normalized rock strength in Fig. 2. A linear correlation between the two parameters is indicated. Since the compressive strength to tensile strength ratio reflects rock's degree of compaction, it is concluded that UBD is more efficient in drilling highly compacted rocks. This is consistent with the observation from the Type-a tests because highly compacted rocks have low permeabilities.

3. Effect of temperature differential on ROP

3.1. Test design

Tests were designed to drill dry core samples with air at ambient pressure and varying temperature-differentials. The sandstone cores used in the experiments were taken from the Chagan group, Tamuchage Basin, Mongolia. Core sections were cut to obtain 60 samples for testing.

3.2. Experimental apparatus

The micro-bit drilling tests were conducted using an experimental setup consisting of a core holder, a drill bit, a drive box, and an air injection line. The drill bit is a 31.75 mm diameter roller type bit. The hydraulic cylinder in the drive box can provide maximum 40 MPa pressure, which acts on the piston and generates up to 16 metric tons of force to the rock core. The force transducer is accurate to 0.5%. The displacement transducer is accurate to 0.25%. The computerized drive box provides an automated control of

Table 1
Properties of rock samples for drillability testing.

Sample no.	Rock type	Permeability (md)	Porosity (%)	Compressive strength (MPa)	Tensile strength (MPa)	Core diameter (mm)	Core length (mm)
1	Sandstone	0.155	8.3	96.70	6.39	75.3	46.0
2	Sandstone	0.159	8.9	86.90	6.96	75.2	45.7
3	Sandstone	0.163	8.7	97.30	7.03	74.9	45.2
4	Sandstone	8.360	9.7	127.30	12.90	75.1	44.9
5	Sandstone	8.130	10.9	117.90	13.40	74.6	45.9
6	Sandstone	8.250	10.5	121.70	12.70	74.8	45.8
7	Sandstone	58.900	11.0	194.20	11.60	75.1	45.7
8	Sandstone	57.500	11.7	192.60	12.90	75.0	45.7
9	Sandstone	55.900	10.2	198.60	12.60	75.3	46.0
10	Sandstone	15.600	15.6	28.50	3.60	75.2	45.7
11	Sandstone	0.270	11.0	42.10	4.50	74.9	45.2
12	Sandstone	0.250	10.9	75.80	5.40	75.1	44.9
13	Sandstone	0.180	9.4	96.20	5.60	74.6	45.9
14	Sandstone	0.290	11.0	126.80	12.70	75.0	45.8
15	Sandstone	0.240	10.8	192.70	13.90	75.1	45.7
16	Sandstone	0.210	10.3	91.70	7.84	74.6	45.7
17	Sandstone	0.190	9.6	64.39	7.46	74.8	45.9