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

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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.

Keywords: drillability; drillability grade; mechanical properties; confining pressure.

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, 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).

$$D_r = \log_2 t \quad (1)$$

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 determining the mechanical properties as the confining pressure varied (Åkesson et al., 2001; Li et al., 2014; Zhang et al., 2014). The failure patterns of sandstone and mudstone were quite different under different confining pressure conditions. The features of breaking craters for the sandstone and mudstone samples drilled using Rollow's test method are also presented in Fig 1(C).

3.2 Mechanical properties of rocks

Fifteen sandstone and nine mudstone samples were obtained from different depths from five exploration wells, and the tests were repeated three times for each sample, under 0 MPa, 30 MPa and 60 MPa conditions. The mechanical parameters of rocks measured under different confining pressures are shown in Tables 2-4. When the measured condition was under unconfined compressive pressure, the unconfined compressive strength (UCS) ranged from 49.34 MPa to 170.46 MPa, the elastic modulus values varied from 17340 MPa to 26861 MPa, and Poisson's ratio values varied between 0.163 and 0.263. The coefficients of variation (CoV) expressed by the average value of standard deviation and described in percentages were determined to evaluate the variability of UCS, elastic modulus and Poisson's ratio values for each rock type. Results demonstrated that higher CoV, resulted in a larger variable range of tested results. As shown in Table 2, the UCS, elastic modulus and Poisson's ratio of overall average CoV values were 7.45%, 8.86% and 9.53% respectively, and were within acceptable limits for most engineering purposes.

The mechanical properties measured under 30 MPa confining pressure are shown in Table 3. Confined

compressive strength (CCS) ranged from 130.24 MPa to 286.43 MPa, and the elastic modulus values were in the range of 18,958 MPa to 27,502 MPa. Likewise, Poisson's ratio varied from 0.193 to 0.281. It was clearly noted that compressive strength and elastic modulus of rocks under 30 MPa confining pressure were much larger than those under uniaxial conditions, whereas Poisson's ratio slightly increased. A possible interpretation for the tested data change is that dilation in rock samples at lower pressures was certainly due to both fracturing along grain boundaries and microfracturing of grains, as well as being due to relative movements of grains and their fragments. Compaction during ductile deformation in tested samples presumably consisted of a collapse of pore space and a subsequent readjustment of grains into a denser packing, which obviously explained the significant strain hardening effect under confining pressure conditions. A similar observation was made by other researchers (Renshaw and Shulson, 2001). The overall average CoV values of CCS, elastic modulus and Poisson's ratio were 6.30%, 10.23% and 9.12% respectively.

Similarly, the CCS, elastic modulus and Poisson's ratio tested under 60 MPa confining pressure are shown in Table 4. It was observed that CCS values ranged from 171.70 MPa to 393.71 MPa. CoV values were in the range of 4.39 % to 8.81 % and the overall average value was 6.80%. Elastic modulus values varied from 22,241 MPa to 32,290 MPa, and its CoVs ranged between 6.10 % and 11.31 %, with an overall average value of 7.61 %. Poisson's ratio ranged from 0.207 to 0.289, with an overall average value of 9.14 %. The variation range of mechanical properties as the confining pressure increased from 30 MPa to 60 MPa was higher than that from 0 MPa to 30 MPa. A possible explanation for this phenomenon was that microfracturing of rock samples was a precursory deformation process to the development of macroscopic shear faults in intact porous rock at low confining pressures. At higher confining pressures, multiple shear fractures developed with progressively less dilation. The transition from brittle to ductile deformation took

place and resulted in progressive compaction and homogeneous shear throughout the rock specimen (Gowd and Rummel, 1980; Ismail and Murrell, 1990).

3.3 Drillability grade of rocks

As shown in Table 5, the drilling time of a microbit varied in the range of 20.39-138.14 sec and its CoV values varied between 7.10% and 11.44%, with an average value of 7.94%. In addition, the drilling time of a microbit was converted to drillability grade in the range of 4.35 to 7.11, and the categories ranged between medium and high. On the basis of Table 2 and Table 5, the permeability and porosity of the rock samples have an important influenced on the drillability. In normal conditions, the larger permeability and porosity of the rock is, the higher drillability is. Under field drilling conditions, for the permeable formation, drilling fluid filtrate could fast enter into rock porosity through the pore throats when the formation was drilled, which also decreased the effect of borehole fluid pressure on rock mechanical properties so as to lower the drillability. For the impermeable formation, the rock expanded slightly at the bottom hole and pore pressure slightly decreased, which resulted in borehole fluid pressure had a great effect on the drillability. Generally speaking, to the same lithology of formation, the drillability value is smaller for the permeable rock, whereas it is larger for the impermeable rock

3.4 Regression analysis of drillability grade and mechanical parameters

The relationship between DG and mechanical properties was analyzed by using the linear regression method. The equation of the best-fit line and the correlation coefficient (R) were determined for each case.

It is well known that rock mechanical properties have an effect on DG. However, it is necessary to evaluate which parameter plays the key role in determining rock DG. As shown in Fig 3, the best correlation (0.831) between DG and UCS among the mechanical properties (UCS, elastic modulus and Poisson's ratio) under uniaxial conditions is presented, while the worst correlation coefficient (0.537)

1 between DG and Poisson's ratio is noted among them. The phenomenon was similar to that reported (Yarali
2 and Kahraman, 2011) by those who used Dahl's assessment method, defined as the mean value of the
3 measured drill-hole depths in 1/10 mm, after 200 revolutions of the 8.5 mm miniature drill bit, to study the
4 correlation of mechanical properties and DG. The reason for this phenomenon was that DG was mainly
5 used for evaluating rock failure properties rather than elastic properties (elastic modulus, Poisson's ratio).
6 Although the operation parameters of Dahl's and Rollow's methods are quite different, the test principles
7 are the same, and both focused on assessing DG, as well. Therefore, Rollow's method was also considered
8 as a valid means of evaluating DG.

9 As the confining pressure increased, the correlation coefficients between DG and the mechanical
10 parameters gradually improved, as shown in Figure 2. In particular, there was a higher correlation
11 coefficient between DG and CCS compared to that of elastic modulus and Poisson's ratio, whereas there
12 was a lower correlation coefficient between DG and Poisson's ratio. These phenomena can be explained by
13 the transition of the porous sandstone from brittle to ductile deformation. As fracturing of sandstone along
14 grain boundaries and microfracturing of grains during confining pressure varied, this resulted in an abrupt
15 change from dilational behavior at low pressure to compaction during inelastic axial strain at high
16 confining pressures (Gowd and Rummel, 1980; Ismail and Murrell, 1990). However, the mudstone, mainly
17 composed of clay, was easier to deform under confining pressure conditions and the grain size,
18 permeability and porosity of the mudstone were lower than those of sandstone, as shown in Table 2. This
19 can lead to ductile deformation of mudstone under confining pressure conditions, as shown in Figure 2 (B).

20 To investigate the interactive effects between DG and rock properties, coupled with the tested data in
21 Table 2-5, the regression analysis between DG and rock properties is developed in Table.6. Where σ is the
22 compressive strength; μ is Poisson's ratio; ϵ is the elasticity modulus. As shown in Table 6, the significance
23 levels (F) were all less than 0.05, and multiple R were greater than 0.92, which demonstrates a good

relationship among the tested data. To study the weight function of each parameter in each model, the standard deviation and P-value were also investigated. The range of those parameters was described as follows: As the standard deviation decreases, the regression level improves. P-value needs to be less than 0.05. However, combined with the analysis results with an independent variable, the standard deviation of μ is much larger than that of σ and ε ; thus, the regression level of μ in the model is lowest among the parameters under different confined pressure conditions. In addition, the P-value of μ and ε were much larger than 0.05 with a confined pressure of 30 MPa and 60 MPa; thus, the regression coefficients for these parameters were not significant. The results of a comprehensive analysis showed that the correlation between the dependent variable (K_d) and the independent variable (μ and ε) was poor. Thus, the parameters of μ and ε could be neglected in the multiple regression models and merely required to develop the relational model between compressive strength and DG under confined pressure conditions.

Based on the experimental results above, it was obvious that the confining pressure played a critical role in evaluating the rock mechanical properties, and that compressive strength has a great effect on rock DG. Therefore, it was critical to develop analytical models relating compressive strength and DG under confining pressure to select appropriate drill bits for a given drilling formation.

3.5 The field application

Although the above rock mechanical laboratory testing on preserved core samples was the most accurate method for calculating rock mechanical parameters and DG, well-preserved core samples for conducting laboratory measurements were rarely available, and the testing procedure was tedious. It was very useful to obtain continuous profiles of rock mechanical parameters using log data to make a decision on bit selection prior to drilling. Therefore, integration of core measurements and well log data (density, gamma ray and sonic logs, et.al) in conjunction with some analytical models (Appendix A-B) were preferred to calculate the rock compressive strength and DG along wellbore.

3.5.1 Mathematical model between CCS and DG

Based on the results of Figure 3, the correlation coefficient between DG and compressive strength was higher than that of elastic modulus and Poisson's ratio, under various confining pressure conditions,

indicating a better correlation between DG and compressive strength. Based on the above results, the confining pressure values calculated by formulas 2 to 4 were 17.28 MPa and 8.58 MPa respectively at a depth of 3252 m and 3339 m for well A. The compressive strength of field conditions and DG were tested, as shown by data points in Figure 4.

Then, the relationship between DG and CCS for well A was given by Equations (13).

$$D_{r-cp} = -0.572 + 2.4178e^{0.0085\sigma_{ccs-mix}} \quad (13)$$

Where D_{r-cp} is the DG; $\sigma_{ccs-mix}$ is the CCS, MPa.

3.5.2 The analysis of field application

Figure 4 illustrates an actual field application of the models developed by compressive strength and DG, in conjunction with well logging, from a well in Southwest China. The formation consisted of sandstone and mudstone, and the well depth used in routine overbalanced drilling ranged from 3150 m to 3646 m. Additionally, mud densities were 1.3 g/cm³ (3150 m-3350 m) and 1.32 g/cm³ (3351 m-3646 m), respectively. The tracks containing some of the calculated data were used to determine rock properties, including effective porosity, pore pressure, compressive strength and DG. The tracks also contained other well data, such as borehole fluid pressure and rate of penetration (ROP).

As shown in Figure 4, the rock strength under confining pressure conditions was stronger than that of unconfined pressure conditions due to overbalanced drilling. The UCS varied from 10 MPa to 145 MPa, and the CCS ranged between 20 MPa and 240 MPa. The DG (unconfined) changed from 1 to 6 and the DG (confined) varied from 3 to 7.5. The typical variation trend of the mechanical properties with an increase of confining pressure was consistent with the experimental results (Tables 2-4, and Figure 2). The calculated results were approximately in accordance with test data under unconfined pressure, as shown in Fig 4. It was noted that the calculation data of UCS and DG at a depth of 3252 m were 114 MPa and 5.36

respectively, and the tested data of UCS and DG were 110 MPa and 5.51 respectively. The calculation error of the model was within acceptable limits for most engineering purposes. The drilling of a specific interval was composed of tight sandstone and mudstone, in which the ROP was low (approximately 2.2 m/h) with roller cone bits drilling as illustrated in the right track of Fig.4. But, higher ROP exhibited at a depth of 3340 m as larger effective porosity lead to a decrease of compressive strength and DG. Therefore, rock porosity as an important parameter could influence confining pressure distribution at the bottom hole, resulting in the variation of rock mechanical properties and drillability along the wellbore, and finally ROP was varied.

4 Conclusions

A new database consisting of different rock types was obtained to estimate the correlation of DG and mechanical properties under different confining pressure conditions. The correlation coefficients of DG were affected by the variation of compressive strength, elastic modulus and Poisson's ratio. The analysis results were expressed as follows:

(1)Compressive strength had a strong correlation with DG values under various confined pressures.

The correlation between DG and elastic modulus and Poisson's ratio were poor under uniaxial condition, but there was a reasonably good linear correlation between DG and elastic modulus or Poisson's ratio as the confining pressure varied from 30 MPa to 60 MPa.

(2)The calculated results obtained by mathematical models showed that effective porosity, borehole fluid pressure and formation pore pressure had significant influence on the rock DG and CCS distributions along the wellbore.

(3)The DG and CCS of confining pressure were also higher than those of unconfined pressure under overbalanced drilling conditions, and the variation trend of calculated results was in accordance with the

laboratory test data.

In summary, these results can provide more specific theoretical data to obtain the mechanical properties of confining pressure and assist with suitable bit type selection and drilling method.

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Appendix A. Calculation method of confining pressure

It was demonstrated that failure volume was significantly reduced when the borehole fluid pressure increased above the pore pressure. Failure volume varied little when the difference between borehole fluid pressure and pore pressure was held constant and the horizontal stresses parallel to the rock surface were increased (Maurer, 1965; Yang and Gray, 1967). Therefore, the rock mechanical properties were mainly controlled by the least principal stress rather than the high stress that parallel to the bottom of the hole from the impact tests results. Under field drilling conditions, when the rock removed from the borehole during drilling was replaced by drilling fluid, the rock expanded slightly at the bottom hole due to reduction of stress (lower pressure from drilling fluid than that exerted by overburdened rock) (Hector et al., 2005). This caused a pore volume increase, which can significantly reduce the formation pore pressure of impermeable rocks, such as mudstone or tight sandstone, but does not affect the pore pressure of permeable rocks, as illustrated in Fig A-1.

If the rock is permeable, the confining pressure at bottom hole is the difference between the borehole fluid pressure and formation pore pressure, which can be calculated by Equation A-1, assuming perfect mud cake.

$$\sigma_{dp} = P_h - P_p \quad (\text{A-1})$$

Where, σ_{dp} is the difference between the borehole fluid pressure and formation pore pressure for permeable rock, MPa; P_h is the borehole fluid pressure, MPa; P_p is the formation pore pressure, MPa.

In impermeable rock, a relationship described by Skempton was applied as a means to calculate the formation pore pressure for the expanded rock in the depth of the cut zone. The confining pressure at bottom hole is the difference between the borehole fluid pressure and Skempton pore pressure (Skempton,

1954). The results are written as follows:

$$\sigma_{dp-sk} = P_h - P_{p-sk} \quad (A-2)$$

$$P_{p-sk} = P_p - (\sigma_o - P_h)/3 \quad (A-3)$$

Where, P_{p-sk} is the Skempton pore pressure, MPa; σ_o is the formation overburden stress, MPa.

Appendix B. Solution for confining compressive strength

Mohr-Coulomb criteria were utilized in calculating rock CCS. The model was developed as follows:

$$\sigma_{ccs} = 2C \frac{\cos \theta}{1 - \sin \theta} + \sigma_{dp} \frac{1 + \sin \theta}{1 - \sin \theta} \quad (B-1)$$

If σ_{dp} was equal to 0, the equation (5) was expressed as:

$$\sigma_{ucs} = 2C \frac{\cos \theta}{1 - \sin \theta} \quad (B-2)$$

Equation (B-2) is a general expression of the unconfined compressive strength (UCS). It is well known that UCS is influenced by many factors, including rock density, sonic velocities and gamma ray values. The mathematic model was corrected by the laboratory experiment data, which was expressed as follows (Akgun, 2002):

$$\sigma_{ucs} = \frac{0.745 \cos \theta}{1 - \sin \theta} \left(\frac{\rho_b}{\Delta t_c^2} - \frac{4\rho_b}{3\Delta t_s^2} \right) (3.5V_{cl} + 4.5) \left[\frac{2.68 \times 10^{10} \rho_b (1 - \nu)}{\Delta t_s^2} \right] \quad (B-3)$$

Where, σ_{ccs} is the CCS, MPa; σ_{ucs} is the UCS, MPa; C is the internal cohesion, MPa; θ is the friction angle, °; ρ_b is the formation bulk density, g/cm³; Δt_c is the shear sonic velocity, m/s; Δt_s is the compressional sonic velocity, m/s; V_{cl} is the percent clay volume; ν is the rock Poisson's ratio.

Based on Equations (A-1) and (B-1), the model of CCS for permeable rock could be defined as in Equation (B-4).

$$\sigma_{ccs-dp} = \sigma_{ucs} + \sigma_{dp} + 2\sigma_{dp} \sin \theta / (1 - \sin \theta) \quad (B-4)$$

In the same way, the model of CCS for impermeable rock is also given in Equation (B-5):

$$\sigma_{ccs-sk} = \sigma_{ucs} + \sigma_{dp-sk} + 2\sigma_{dp-sk} \sin \theta / (1 - \sin \theta) \quad (B-5)$$

Where, σ_{ccs-dp} is the CCS of permeable rock, MPa; σ_{ccs-sk} is the CCS of impermeable rock, MPa.

The previous equations are based on the assumption that the rock would behave as permeable if effective porosity was greater than or equal to 0.20, and as impermeable if effective porosity was less than or equal to 0.05, and the effective porosity between the two endpoints was devised to address the intermediate permeability between essentially impermeable rock and highly permeable rock. Therefore, the CCS of rock along the wellbore was employed as follows:

$$\sigma_{ccs-mix} = \sigma_{ccs-dp} \quad \phi \geq 0.2 \quad (B-6)$$

$$\sigma_{ccs-mix} = \sigma_{ccs-sk} \quad \phi \leq 0.05 \quad (B-7)$$

$$\sigma_{ccs-mix} = \sigma_{ccs-dp} (\phi - 0.05) / 0.15 + \sigma_{ccs-sk} (0.2 - \phi) / 0.15 \quad 0.05 < \phi < 0.2 \quad (B-8)$$

Where, $\sigma_{ccs-mix}$ is the CCS of rock along the wellbore, MPa; ϕ is the effective porosity.

Table and Figure Captions

- Table 1.** Summary of rock types used in laboratory testing
- Table 2.** The rock mechanical properties measured under uniaxial test conditions.
- Table 3.** The rock mechanical properties measured at 30 MPa confining pressure.
- Table 4.** The rock mechanical properties measured at 60 MPa confining pressure.
- Table 5.** Summaries of drillability grade properties of rocks.
- Table 6.** The regression results between DG and rock mechanical properties under different confining pressure conditions
- Fig 1.** (A) The morphologies of (A) SEM, (B) failure patterns under different confining pressure conditions, (C) drillability test features for (a) sandstone; (b) mudstone
- Fig 2.** The regression results of (A) DG and compressive strength, (B) DG and elastic modulus, (C) DG and Poisson's ratio under different confining pressure conditions.
- Fig 3.** The regression results of DG and compressive strength
- Fig 4.** Rock properties and drilling performance logs from a well in the Southwest China
- Fig A-1.** The environment of a well in permeable rock at bottom hole

Fig 1. (A) The morphologies of (A) SEM, (B) failure patterns under different confining pressure conditions, (C) drillability test features for (a) sandstone; (b) mudstone

(A)

(B)

(C)

Fig 2. The regression results of (A) DG and compressive strength, (B) DG and elastic modulus, (C) DG and

Poisson’s ratio under different confining pressure conditions.

Fig 3. The regression results of DG and compressive strength

Fig 4. Rock properties and drilling performance logs from a well in the Southwest China

Fig A-1. The environment of a well in permeable rock at bottom hole

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

Table 2. The rock mechanical properties measured under uniaxial test conditions.

Rock code	Porosity (%)	Permeability (mD)	Compressive strength (MPa)	Coefficient of variation of compressive strength (%)	Elastic modulus(MPa)	Coefficient of variation of elastic modulus (%)	Poisson's ratio	Coefficient of variation of Poisson's ratio (%)
1	3.5	0.02048	106.71±8.7	8.15	23634±2120	8.97	0.223±0.022	9.87
2	4.6	0.1172	73.62±6.3	8.56	17340±1630	9.40	0.183±0.020	10.93
3	5.9	0.03824	113.43±7.7	6.79	23231±2634	11.34	0.210±0.020	9.52
4	5.6	0.04625	109.31±9.1	8.32	22036±1936	8.79	0.195±0.022	9.74
5	4.2	0.03185	49.34±3.4	6.89	17630±1250	7.09	0.16±0.022	9.20
6	4.8	0.02864	62.37±5.2	8.34	22053±1832	8.31	0.211±0.021	9.95
7	8.3	0.05327	150.12±10.6	7.06	26861±2453	9.13	0.263±0.02	9.13
8	6.4	0.04405	170.46±9.3	5.46	23201±1824	7.86	0.216±0.017	7.87
Overall average			--	7.44	--	8.86	--	9.53

Table 3. The rock mechanical properties measured at 30 MPa confining pressure.

Rock code	Compressive strength (MPa)	Coefficient of variation of compressive strength (%)	Elastic modulus (MPa)	Coefficient of variation of elastic modulus (%)	Poisson's ratio	Coefficient of variation of Poisson's ratio (%)
1	222.50±16.70	7.51	27042±3100	11.46	0.229±0.020	8.73
2	130.24±9.10	6.99	18958±2170	11.45	0.193±0.019	9.84
3	253.60±14.60	5.76	25235±1941	7.69	0.220±0.016	7.27
4	237.46±20.10	8.64	24923±2016	8.09	0.205±0.018	8.93
5	132.30±6.50	4.91	19272±2416	12.56	0.203±0.022	10.38
6	141.90±7.30	5.14	23752±2830	12.40	0.223±0.027	12.15
7	238.21±11.30	4.74	27822±2961	10.64	0.281±0.025	8.90
8	286.43±19.30	6.73	27502±2065	7.51	0.252±0.017	6.75
Overall average	--	6.30	--	10.23	--	9.12

Table 4. The rock mechanical properties measured at 60 MPa confining pressure.

Rock code	Compressive strength(MPa)	Coefficient of variation of compressive strength (%)	Elastic modulus(MPa)	Coefficient of variation of elastic modulus (%)	Poisson's ratio	Coefficient of variation of Poisson's ratio (%)
1	311.71±18.70	6.00	30054±3400	11.31	0.259±0.024	9.27
2	178.60±11.50	6.44	22241±1998	8.99	0.207±0.020	9.66
3	341.63±27.30	8.00	30472±2019	6.63	0.261±0.018	6.90
4	394.20±31.20	7.91	29381±1792	6.10	0.258±0.026	10.78
5	171.70±13.10	7.63	26009±2237	8.60	0.215±0.022	10.22
6	221.30±9.70	4.39	25376±2621	10.33	0.256±0.028	10.94
7	299.90±15.70	5.23	32101±2821	8.79	0.289±0.023	7.96
8	393.71±34.70	8.81	32290±2625	8.13	0.258±0.019	7.36
Overall average	--	6.80	--	7.61	--	9.14

Table 5. Summaries of drillability grade properties of rocks.

Rock type	Drilling time (sec)	Standard deviation	Coefficient of variation (%)	drillability grade
1	45.57	4.78	10.49	5.51
2	20.39	1.55	7.60	4.35
3	112.99	6.97	6.17	6.82
4	99.04	4.98	5.03	6.63
5	33.83	3.77	11.44	5.08
6	39.40	2.79	7.10	5.30
7	100.43	9.25	10.60	6.65
8	138.14	6.58	5.10	7.11
Overall average	--	--	7.94	--

Table 6. The regression results between DG and rock mechanical properties under different confining pressure conditions

Fitting condition	Variable	Standard Deviation	P-value	Significance level (F)	multiple correlation coefficient (R)	Regression equation
0MPa	σ	0.0045	0.0285	0.007	0.9687	$K_d=3.173+0.015\sigma-46.01\mu+5\times 10^{-3}\varepsilon$
	μ	12.2589	0.0199			
	ε	0.0001	0.0165			
30MPa	σ	0.0060	0.0460	0.033	0.9293	$K_d=2.8+0.015\sigma-0.794\mu-7\times 10^{-6}\varepsilon$
	μ	11.0301	0.9461			
	ε	0.00012	0.9567			
60MPa	σ	0.0034	0.0435	0.0066	0.9696	$K_d=1.373+0.0092\sigma+2.295\mu+5\times 10^{-5}\varepsilon$
	μ	7.1383	0.7639			
	ε	8.9×10^{-5}	0.5981			