Drillability characteristics of sandstone with different pores under simulated bottom hole conditions

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Abstract. Rock drillability has an important application value in oil and gas well engineering. Accurate evaluation of rock drillability characteristics is the theoretical basis of improving the rate of penetration (ROP) in the drilling process of the deep well. Up to date, few scholars have studied the degree of rock break difficulty according to the rock's pore structure characteristics. In order to study the influence of pore structure characteristics on sandstone drillability under the condition of the bottom hole and realize the accurate prediction of sandstone drillability. Sandstones with different pore structures were collected as the research object. The pore structure characteristics of the collected sandstone were studied by casting thin section identification. The porosity, permeability, acoustic wave, and Richter hardness of sandstone with different pore structures were tested, and the sandstone drillability experiment was carried out under simulated bottom hole conditions. The relationship between the characteristics of pore structure and drillability was analyzed by statistical method. The experiment results show that sandstone's pore structure characteristics have an important effect on the drillability of sandstone. The porosity, permeability, and acoustic wave of sandstone have a very high correlation with the Richter hardness. The drillability of sandstone decreases exponentially with the increase of porosity and permeability. With the increase of borehole pressure, sandstone's drillability with different pore structures generally increases exponentially. When the porosity is less than 0.19, the drillability of rock decreases gradually with the increase of porosity. When the porosity is more than 0.19, the drillability of rock decreases significantly under different borehole pressures. The characteristics of pore structure are an important factor affecting the drillability of rock, which should be paid more attention to by related scholars. The study is of great significance for revealing the mechanism of rock breaking, objectively evaluating the characteristics of drillability, and establishing the prediction model of drillability.

1. Introduction
With the rapid development of our country's economy, the demand for oil and gas has risen sharply, and the gap between supply and demand has continued to expand. How to increase drilling speed has always been a difficult problem in the oil and gas field. Rock drillability has important application value in drilling engineering, such as guiding bit selection, optimizing bit parameters, predicting drilling speed, and formulating production quotas [1, 2].

The drillability of rock is related to many factors, among which the physical and mechanical properties of the rock are the main factors affecting the drillability, and the physical and mechanical properties of the rock depend on the pore structure of the rock [3]. The rock's microstructure is the main controlling factor of the macrophysical characteristics [4]. Many scholars have tried to quantitatively describe the
impact of meso-structure features on the macro-physical properties of rocks and try to quantitatively describe the meso-structure of rocks. There are dozens of quantitative indicators of meso-structure established at present[5]. Many studies have shown that these meso-structure quantitative indicators have a good correlation with the mechanical properties of rock[6]. For example, Howarth and Rowlands studied the influence of the meso-structure coefficient on the drillability of rock, and the results showed that the meso-structure coefficient has a good correlation with the ROP[7].

In the future, deep oil and gas resources will become an important position for exploring and developing oil and gas resources in my country, playing an increasingly important role[8]. At this time, the impact of high-pressure environments on drillability cannot be ignored. Relevant scholars have studied the influence of wellbore pressure on drillability under a simulated bottom hole environment, but the types of rocks used in the study are still few. The research results show significant differences in the impact of wellbore pressure on the drillability of different rocks[9-11]. Relevant scholars have conducted research on the acoustic wave prediction of rock pore characteristics, and we have further revealed the mechanism of rock pore characteristics affecting acoustic waves [12]. In addition, some scholars found a good correlation between rock hardness and uniaxial compressive strength [13], but did not study the relationship between rock porosity and hardness. At present, no scholars have systematically studied the relationship between porosity and drillability, and the influence of wellbore pressure on drillability needs further study. In this study, on the one hand, we study the influence of sandstone with different pore characteristics on hardness, sonic wave and drillability, and on the other hand, the effect of wellbore pressure on drillability.

2. Experimental materials and methods

2.1 Material characteristics

We tested the physical properties of five sandstones with different pore structures. The porosity and permeability of the sandstone used in the test are shown in Table 1. By analyzing the data in Table 1, it can be concluded that the porosity and permeability have a good logarithmic relationship, and the fitting coefficient reaches 0.92. The fitting result is shown in equation (1).

\[ \phi = 15.449 + 2.992 \log_{10} K \]  

(1)

Where \( \phi \) is porosity, and \( K \) is permeability.

| Numbering | Origin | Porosity (%) | Permeability (mD) |
|-----------|--------|--------------|-------------------|
| S-O       | E103.4 N28.6 | 8.57 | 0.0182 |
| S-A       | E108.3 N34.2 | 12.74 | 0.0343 |
| S-B       | E104.6 N28.6 | 18.54 | 4.81 |
| S-C       | E114.4 N37.2 | 19.08 | 80.9 |
| S-D       | E113.5 N36.7 | 24.59 | 516 |

We tested the sound waves and hardness of five sandstones (five rock samples of each type). The test results show that the sound waves and hardness of the five types of sandstones are quite different. In comparison, the sound waves and hardness (see Table 2) of each type of sandstone are relatively close. The experimental results show that the five sandstones selected in this study can represent the characteristics of different pore structures and avoid the influence of the heterogeneity between each sandstone on the experimental results. In addition, there is also a complicated relationship between the acoustic velocity and hardness of sandstone and the pore characteristics. This complicated relationship depends on the difference of the mineral composition of the rocks in different formations. Only by deepening the understanding of the influence of rock mineral composition on sound waves, so as to correctly deduce the relationship between pore structure and sound waves.
Table 2 Sandstone acoustic velocity and hardness

| Numbering | S-wave velocity (m/s) | P-wave velocity (m/s) | Hardness test-1 (HL_D) | Hardness test-2 (HL_D) | Hardness test-3 (HL_D) | Hardness test-4 (HL_D) | Hardness test-5 (HL_D) |
|-----------|----------------------|-----------------------|------------------------|------------------------|------------------------|------------------------|------------------------|
| S-O       | 2596                 | 2723                  | 708                    | 729                    | 713                    | 727                    | 730                    |
| S-A       | 3236                 | 3379                  | 649                    | 652                    | 659                    | 664                    | 683                    |
| S-B       | 2272                 | 2355                  | 545                    | 544                    | 508                    | 508                    | 534                    |
| S-C       | 3841                 | 4147                  | 488                    | 487                    | 506                    | 446                    | 531                    |
| S-D       | 2999                 | 3145                  | 437                    | 391                    | 429                    | 417                    | 452                    |

Through the thin section identification of 5 types of sandstone (see Figure 1), the pore distribution, grain roundness, and degree of cementation of the sandstone can be observed. The surface porosity of sandstone is obtained by analyzing the cast thin section images of five types of sandstone. From sandstone O to sandstone D, the surface porosity is 0.0221, 0.0287, 0.0922, 0.1769, 0.2450. Sandstone S-O particles are mainly silt grade, with a small amount of fine sand, with medium roundness, mainly line contact, and pore cementation. Sandstone S-A has a few cracks, medium roundness of grains, mainly point-line contact, and pore cementation. Sandstone S-B grains are mainly fine-medium grains, and the grains are mainly point-line contact and pore cementation. Occasionally, argillaceous cemented ring edges are seen on the edges of the grains. Sandstone S-C has many internal scratches, poor particle sorting, poor particle roundness, mainly point contact, and pore cementation. Sandstone S-D has many internal scratches, extremely poor particle sorting, poor particle roundness, mainly point contact, poor pore cementation.

2.2 Experimental method

The rock drillability test is based on the determination and classification of rock drillability in oil and gas drilling engineering [14]. The equipment uses the drillability tester developed by the national oil and gas field development and geological engineering laboratory of southwest petroleum university (see Figure 2). The device can apply confining pressure, liquid column pressure, and pore pressure in the range of 0 MPa to 100 MPa. The overlying layer can be controlled not only by displacement but also by force. The maximum drill bit rotation speed can reach 200 rpm. During the test, the weight on bit (WOB) can be kept stable to ensure the accuracy of the test results. Figure 3 shows the shape of broken pits after the drillability micro-drilling experiment of all sandstones.
3. Results
The experiment tested the physical property data (see Table 2) and drillability data (see Table 3) of sandstone with different pore characteristics. The results focus on analyzing the relationship between pore characteristics and hardness, the law of pore characteristics affecting drillability, and the influence of confining pressure on sandstone drillability.

Table 3 Drillability index of sandstone with different wellbore pressure

| Numbering | Wellbore Pressure (MPa) |
|-----------|------------------------|
|           | 0          | 10         | 20         | 30         |
| S-O       | 3.09       | 4.72       | 5.26       | 5.49       |
| S-A       | 1.95       | 4.83       | 4.96       | 5.21       |
| S-B       | 1.61       | 4.41       | 4.73       | 5.14       |
| S-C       | 1.61       | 2.91       | 3.99       | 4.11       |
| S-D       | 1.51       | 3.13       | 4.02       | 4.50       |

3.1 Pore characteristics influence on sandstone physical properties
It can be seen from Figure 4 (a) that when the porosity of sandstone increases linearly, the hardness of sandstone shows a linearly decreasing trend. Similarly, when the permeability line of sandstone increases in logarithm, the hardness of sandstone also shows a linearly decreasing trend (see Figure 4 (b)). The porosity and permeability of sandstone have good correlations with hardness, and the correlation coefficients are all above 0.9. It is found through research that this result is mainly due to the increase in rock porosity and permeability, which makes contact between rock particles change from line contact to point connection and weaker rock cementation. Therefore, the hardness of the rock decreases with the increase of porosity and permeability. Table 4 shows the percentages of the mineral component content of the five types of sandstone. The five types of sandstones have relatively large differences in the proportion of mineral components, and S-C and S-D contain no clay minerals. The relationship between acoustic wave and pore characteristics of sandstone can only be accurately obtained by removing the influence of mineral component on acoustic wave.
3.2 Pore characteristic influence on sandstone drillability

Figure 5 shows the changing trend of the drillability index with porosity and permeability under different wellbore pressures. When the wellbore pressure is 0 MPa, the increase in sandstone porosity will cause the drillability index to decrease exponentially. The degree of tight sandstone will seriously affect the drillability index. When the wellbore pressure is not less than 10 MPa, the drillability index of sandstone decreases slowly with the increase of porosity, then rapidly decreases near 0.19 porosity, and finally has a slight upward trend. The significant drop in drillability index is due to the fact that the wellbore pressure breaks through the capillary pressure on the rock surface, which leads to significant changes in the pore space inside the rock, and finally rises slowly because the increase in wellbore pressure makes the rock more compact. During the drillability test of sandstones with different pore characteristics under triaxial conditions, hydraulic oil will invade the inside of the rock. After the wellbore pressure breaks through the capillary force generated by the internal pores of the rock, it will severely destroy the original pore structure of the rock. The experiments in this article found that when the porosity is around 0.19, the sandstone drillability index will change significantly. Aimed at the result that the rock drillability index differs greatly when the porosity is around 0.19. This shows that the impact of rock pore structure on drillability can no longer be ignored. It has been found through experiments that sandstone porosity and permeability have a good correlation. Therefore, the impact of sandstone permeability on drillability under different wellbore pressures is similar to the effect of porosity on drillability. When the wellbore pressure is 0 MPa, the drillability index changes with porosity and permeability as shown in equation (2) and equation (3).

\[
K_d = 1.52 + 21.59e^{-0.1476}\phi \quad (2)
\]

\[
K_d = 1.75 - 0.34\log_{10} K + 0.11(\log_{10} K)^2 \quad (3)
\]

Where \(K_d\) is drillability index, \(\phi\) is porosity, and \(K\) is permeability.
In this paper, through experiments, the relationship between different wellbore pressures and five types of sandstone drillability index is studied (see Figure 6). The experiment found that the five types of sandstone all increased exponentially with the increase of wellbore pressure. The equation (4) for the change of drillability index with wellbore pressure is obtained by fitting. Table 5 shows the parameters and fitting effect after fitting. During the experiment, the wellbore pressure will increase the strength of the rock so that it is more difficult to be broken. On the other hand, the specific wellbore pressure will break through the capillary force inside the specific pore sandstone, which will make it easier to be broken. The impact of wellbore pressure on sandstone drillability has two opposite trends. Although the wellbore pressure has a more significant effect on increasing the rock drillability index, more attention should be paid to the impact of wellbore pressure on breaking through the capillary force of sandstone for drilling engineering.

$$K_d = a + b_1 \left( 1 - e^{-\beta c} \right)$$  \hspace{1cm} (4)
Where $K_d$ is drillability index, $P$ is wellbore pressure, and $a, b, c$ are fitting parameters.

| Numbering | a    | b    | c    | $R^2$ |
|-----------|------|------|------|-------|
| S-O       | 2.96 | 2.53 | 10.29| 0.97  |
| S-A       | 1.95 | 3.26 | 3.21 | 0.98  |
| S-B       | 1.60 | 3.53 | 4.60 | 0.97  |
| S-C       | 1.53 | 2.59 | 8.62 | 0.95  |
| S-D       | 0.93 | 3.57 | 16.45| 0.75  |

4. Discussion

4.1 The influence of sandstone physical properties on drillability

Some scholars have found that carbonates are mainly filled in the pores of sandstone, causing the porosity and permeability of the sandstone to change accordingly, which in turn affects the hardness of the rock[15]. In this paper, it is found that sandstone hardness, porosity, and permeability have a good correlation, and the specific fitting effect is given. The better linear relationship between porosity and hardness is mainly due to the strong homogeneity of sandstone, but it may not be suitable for rocks with strong heterogeneity. In 1980, Raymer et al. proposed that the average time formula can be used to calculate porosity for sandstones that do not contain mud, but the formula is purely empirical, and there is no clear physical model[16]. In 1986, Nicoletie et al. proposed a calculation formula with a certain physical meaning[17]. The model pointed out that the acoustic wave velocity is not only related to the porosity and skeleton hardness but also related to the pore structure. Zhang et al. obtained a significant nonlinear relationship between acoustic velocity and porosity through many data analyses [12]. The acoustic wave and porosity of the sandstone in this article are not very relevant, mainly because the five sandstones are collected in five different areas, and the mineral components of the five sandstones are quite different. Only by fully understanding the influence of mineral composition on sound waves can we accurately predict rock physical parameters and drillability through sound waves.

4.2 The influence of pore structure on sandstone drillability

Research by Yang Mou et al. found that the permeability of the rock has a greater influence on the calculated drillability index, but the specific degree of influence and the mechanism of the effect has not been pointed out[18]. Research by Mao Shuai et al. found that the difference between rock microstructure characteristics and mineral composition led to significant differences in characteristics such as hardness, abrasiveness, and drillability[19]. Mao Shuai et al. [10] found that when the wellbore pressure is 0 MPa, the rock microstructure will affect the drillability of the rock. When the wellbore pressure is not less than 5 MPa, the wellbore pressure will change the impact of rock microstructure on the drillability, and point out that the pore structure is the cause of rock drillability. The pore structure is an important reason for the significant difference in the drillability under the wellbore pressure. Our research concludes that the porosity and permeability have a significant impact on the drillability of sandstone in a non-bottom hole environment. It is also concluded that the sandstone porosity in the simulated bottom hole environment has the characteristic points that significantly reduce the drillability, and the extent to which rock porosity and permeability specifically affect drillability have been measured through experiments.

4.3 Differences in the rock drillability under different wellbore pressure condition

In this paper, the drillability indexes of five sandstones with different pore structures under simulated bottom hole environment (0 MPa-30 MPa) are tested, and the drillability index increases exponentially with the increase of wellbore pressure. Chen et al.[11] tested the drillability of shale with different dip angles in a simulated bottom hole environment (0 MPa-25 MPa). It is concluded that the drillability
indexes of shale with different dip angles show an exponential upward trend with the increase of wellbore pressure, and an empirical formula for predicting the drillability index is given. Mao Shuai et al. tested the drillability indexes of basalt, shale, and sandstone under simulated bottom hole environment (0 MPa-50 MPa). The test results found that the drillability indexes of basalt and shale increased exponentially with the increase of wellbore pressure. However, the drillability index of sandstone presents three stages of change with the increase of wellbore pressure, and three effects of wellbore pressure on the rock (Surface compaction effect, regional compaction effect, and skeleton compaction effect) are proposed[10]. The trend that the rock drillability index increases exponentially with wellbore pressure can be extended to most rocks. For sandstone, different pore characteristics have significant differences in the impact of wellbore pressure on drillability.

5. Conclusions
In order to study the influence of sandstone with different pore characteristics on the acoustic wave, hardness, and drillability, related experiments were carried out. The following conclusions are obtained:
(1) The porosity and permeability of sandstone have a good correlation with hardness, respectively. The porosity and hardness have a good linear correlation, and the fitting coefficient is about 0.92. Permeability and hardness have a good logarithmic correlation, and the fitting coefficient is about 0.91. The tightness of sandstone affects the sound wave and hardness of the rock. The proportion of rock mineral component greatly influences its sound wave, but has little effect on hardness.
(2) In a non-bottom hole environment, the rock drillability will show a downward trend with the increase of porosity and permeability. In the simulated bottom hole environment, when the wellbore pressure is not less than 10 MPa, the porosity near 0.19 will significantly affect the drillability of the rock. When the drillability indexes of sandstones with similar porosity differ greatly, it indicates that the pore structure of the rock has a significant influence on drillability.
(3) First, the increase in wellbore pressure will significantly enhance rock drillability. Secondly, with the increase of wellbore pressure, the drillability index of sandstone in this paper will increase exponentially. Finally, the degree and mechanism of the impact of wellbore pressure on sandstones with different pore structures are different.

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