Effect of the drilling fluid on hardness characteristics of tight sandstone

Feng Xu, Zongling Yan, Lei Wang, Yintong Guo and Chunhe Yang

To understand the effect of the drilling fluid on hardness characteristics of tight sandstone, indentation hardness tests were conducted on tight sandstone which were soaked in a water- or oil-based drilling fluid at different temperatures and time. The results of the study indicate that: (1) the hardness of tight sandstone decreased rapidly after being soaked in the water-based or oil-based drilling fluid and it decreased by 22.9% and 10.1% respectively after two hours; (2) with the increase in soaking time, the hardness remained almost constant when soaked in the oil-based drilling fluid. However, the reduction in hardness reached 33.1% after soaking in the water-based drilling fluid for 15 days; (3) there was little change in the hardness with the increase in temperature in the oil-based drilling fluid, but in the water-based drilling fluid, the hardness decreased at a temperature above 50℃; (4) high temperature would cause mineral expansion and hydration, resulting in hardness reduction with increase in soaking time in the water-based drilling fluid which would lead to the softening of the tight sandstone's surface structure.

Tight gas reservoir is a type of reservoir that cannot produce economic flow rates or yield economic volumes of natural gas unless the well into it is stimulated by a large hydraulic fracturing or production is facilitated by use of horizontal well bore or multilateral wellbores[1,2]. Nowadays these technologies have highly contributed to the increase in unconventional gas production from reservoirs in China, and the annual production from tight gas reservoirs by the end of 2015 accounted for 29.92% of the total natural gas produced in the country. Therefore, tight gas production is listed as a priority in the exploration and exploitation of unconventional gas in China[3,4]. Drilling is an important part of exploration and exploitation and the effects of wellbore stability on highly efficient and safe production are crucial for the tight gas related operations[5].

The properties of rock mechanics are important for both drilling efficiency and wellbore stability. Earlier publications focused mainly on understanding the effect of water, oil and chemical solution on the mechanical properties of rocks[6–10], but there are very few studies on hardness characteristics of tight reservoir sandstone. Wen *et al.*[11] studied the brittle shale failure caused by the drilling fluid activity and results showed that the water activity difference directly affected the formation mechanism of brittle shale fractures. The Schmidt hardness of red sandstones in dry state and at different soaking times was measured by Fan *et al.*[12] and the results obtained revealed that the Schmidt hardness decreases with increase in soaking time and water content. Moreover, even in the case of saturated samples, the Schmidt hardness continued to decrease. Contrary to the oil-based drilling fluid, the water-based drilling fluid has a significant influence on the strength of shale rock and causes wellbore instability[13]. Luo[14] observed that with a longer soaking time, the hardness of shale decreases and the indentation depth increases. Based on the above results, the main motivation of this study was to investigate the effects of the drilling fluid on hardness characteristics of tight sandstone.

Specimen preparation and test equipment

The tight sandstone samples were taken from the Xujiahe Formation in the city of Chongqing located in the southwest of China. The average density of sandstone is 2.60 g/cm^3 and it is composed mainly of quartz (39%), feldspar (21%) and clay (34%). The samples were cored, cut and polished in the Institute of Rock and Soil Mechanics, Chinese Academy of Sciences[15]. The specimens thus prepared for the test, had a diameter of 25 mm and a length of 25 mm.

Considering the soaking time and the temperature of different drilling fluids, three groups of tight sandstone, from a total of 120 specimens, were tested and each test was conducted five times. The mean value of the five results was retained so as to eradicate any discrepancies. The detailed test schemes of the three groups of tight sandstone are listed in Tables 1 and 2 and Figure 1.

A thermostatic oil bath with a digital display was used to heat the drilling fluid containing tight sandstone specimens coming from the Jiangsu province in China as shown in Figure 2. Under a specific temperature, five specimens were heated in the thermostatic oil bath

Table 1. Soaking test under different temperature in 8 hours

Numbers	25°C	50°C	70°C	90°C	110°C
Oil-based drilling fluid	5	5	5	5	5
Water-based drilling fluid	5	5	5	5	*

Table 2. Soaking test under different time at 25°C

Numbers	2 h	4 h	8 h	24 h	48 h	7 d	15 d
Oil-based drilling fluid	5	5	5	5	5	5	5
Water-based drilling fluid	5	5	5	5	5	5	5

filled with the drilling fluid. After reaching the target temperature value, the specimens were maintained in the bath for a predetermined soaking time.

All indentation hardness tests were conducted using the HYY-B10 computer-controlled hardness testing system as shown in Figure 3. During the tests, we measured the axial load with a loading capacity of 10 kN and the axial deformation with a displacement capacity of 5 mm. The loading rate was set as 0.2 mm/min under a displacement control and both the axial force and displacements were recorded in real time.

Results

The effect of water-based drilling fluid

The relationship between the hardness of tight sandstone and the soaking time in the water-based drilling fluid is shown in Figure 4. At the beginning of the soaking process (0–2 h), the hardness of tight sandstone decreased sharply by 22.9%. When the soaking time started to increase after 2 h until 15 days later, the hardness decreased slowly by 13.1%. Figure 5 shows the variation curve of hardness versus soaking time in the water-based drilling fluid and there is a good logarithmic correlation between the peak hardness and the soaking time. It can be seen that the effect of water-based drilling fluid on the hardness is mainly concentrated in the early stage of the soaking process. From 0 to 48 h, the peak hardness of 523.0 MPa at the beginning decreases sharply to 375.5 MPa for tight sandstone, which corresponds to a reduction of 28.2%. However, when the soaking time increased from 48 h to 15 days, the hardness of 375.5 MPa decreases slowly to 350.2 MPa which represents a decrease of hardness by 6.7%. The tight sandstone composed mainly of quartz, mica, clay and cement physically or chemically reacts with water when soaked in the water-based drilling fluid, which affects its microstructure and mechanical properties. Previous studies showed that quartz and mica are stable minerals which do not react with water under normal conditions; but water can cause the swelling of clay minerals leading to the reduction of cementing strength of tight sandstone. This would be followed by a sharp decrease in the hardness of tight sandstone[16]. This reflects the complex nonlinear relationship between water absorption and time. Water absorption due to soaking quickly increases at first and then has a slow augmentation[17]. At the beginning of the soaking process in the water-based drilling fluid, water seeped into the inner pore structure of the tight sandstone, which led to the structural deformation and damage because of the swelling force created by the reaction of clay with water.

The relationship between the tight sandstone hardness and the soaking temperature in the water-based drilling fluid is presented in Figure 6. When the temperature is below 50°C, the change in hardness is not obvious, but hardness starts to decrease above 50°C. This can be attributed to the fact that the inner-pore structure deforms and fails due to expansion resulting from swelling of clay and the differential thermal expansion coefficients of minerals. As the hydration

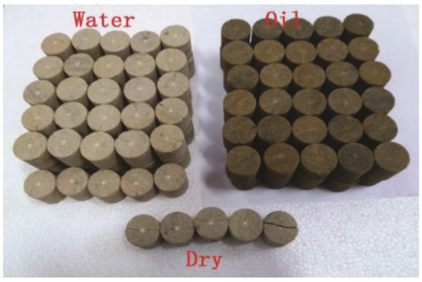

Figure 1. Tight sandstone sample after failure.

Figure 2. The thermostatic oil bath with digital display.

Figure 3. Rock indentation sclerometer under microprocessor control.

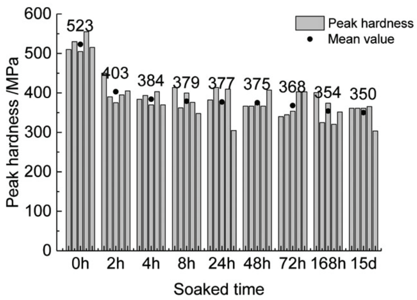

Figure 4. Relationship between the hardness of tight sandstone versus the soaking time in the water-based drilling fluid

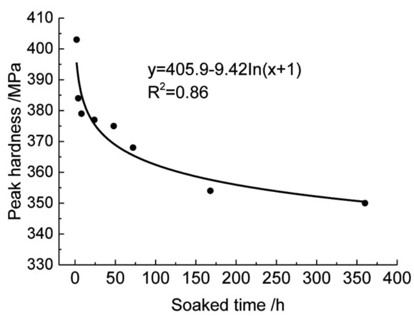

Figure 5. Curve of hardness of tight sandstone versus soaking time in water-based drilling fluid.

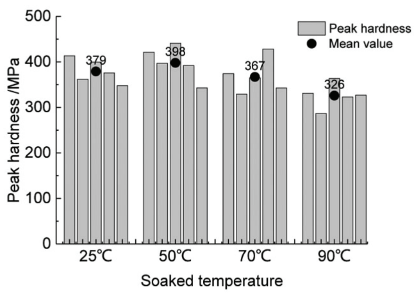

Figure 6. Relationship between the hardness of tight sandstone versus the soaking temperature in the water-based drilling fluid.

reaction of the clay material goes deeper and the temperature goes up as well, the specimen's hardness will decrease[18].

The effect of oil-based drilling fluid

The relationship between the hardness of tight sandstone and the immersion time in the oil-based drilling fluid is shown in Figure 7. At the beginning of the immersion (0–2 h), the hardness of tight sandstone decreased by 10.1%, but afterwards, there was no obvious change in hardness with the increase in immersion time. The minerals contained in the tight sandstone do not react with the oil-based drilling fluid and a little organic matter dissolves in the oil-based drilling fluid, thus leading to a slight reduction in hardness. The hardness of sandstone does not change as soaking duration in the oil-based drilling fluid increases, because the minerals are relatively stable in that state. The relationship between the tight sandstone hardness and the immersion temperature in the oil-based drilling fluid is shown in Figure 8. The different heat stresses derived from different thermal expansion coefficients of minerals could not damage the internal structure of sandstone because the heat stress was lower than the damage stress.

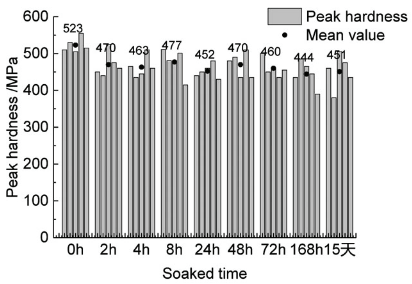

Figure 7. Relationship of hardness of tight sandstone versus soaking time in oil-based drilling fluid.

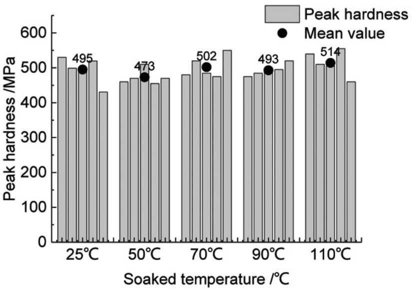

Figure 8. Relationship between the hardness of tight sandstone versus the soaking temperature in the oil-based drilling fluid.

The effect of soaking time and temperature

Figure 9 shows the relationships between the hardness and time for different soaking times in the water and oil-based drilling fluids. The curves in Figure 9 can be divided into four stages. The first stage is the compaction stage between 0 and 40 sec, where the curve slope increases with time due to the fact that the tight sandstone surface structure becomes loose after the soaking process. The second stage known as the elastic stage occurs at about 40 sec when the hardness value is 80% of the peak hardness and during that stage, the slope remains stable. Third, the slope starts to decrease from the position of 80% of the peak hardness to the peak hardness point and this is defined as the softening stage. Lastly, after the peak hardness point, the slope turns negative. The slopes of the curves in Figure 9 *a* decrease with increasing soaking time in the water-based drilling fluid which can be explained by the fact that the depth and extent of softened zones increase along with the increase in soaking time. The clay at the surface of the specimens swells and dissolves in water at first and then the clay within the interior of the specimens reacts with water gradually. The curves in Figure 9 *b* from the oil-based drilling fluid have no obvious changes because minerals do not physically or chemically

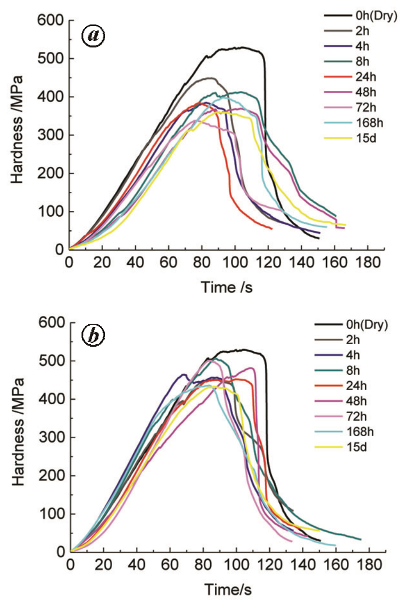

Figure 9. Curve of the hardness of tight sandstone versus the time after different soaking times. ***a***, Water-based drilling fluid; ***b***, oil-based drilling fluid.

react with oil except that some organic matter dissolves in the oil-based drilling fluid.

The relationship between the peak hardness and the soaking time in the water and oil-based drilling fluid is presented in Figure 10. It can be seen from the overall trend that the peak hardness is maximum in dry tight sandstone. Under different treatment conditions it is apparent that it is easier to weaken sandstone by water-based drilling fluid rather than by oil-based one. After two hours of soaking, the extent of the decrease in the value of peak hardness for sandstone soaked in water- and oil-based drilling fluid was 22.9% and 10.1% respectively. The hardness of sandstone soaked in water-based drilling fluid decreased significantly with increase in soaking time. In contrast, the decrease in sandstone hardness soaked in the oil-based drilling fluid was relatively small. After fifteen days of immersion, the reduction in peak hardness for water- and oil-based drilling fluid was 33.1% and 14.2% respectively.

Temperature had an important effect on the hardness of sandstone soaked in the water-based drilling fluid; but it was negligible in sandstone soaked in the oil-based drilling fluid. This study found that there is no obvious effect of the temperature on the initial stage of curves for tight sandstone soaked in the water-based drilling fluid, but the temperature has a great impact on the peak hardness, as shown in Figure 11. The authors consider that thermal expansion at high temperature has a positive impact on hydration, bringing about changes of pore structure and decreasing the strength of cementing material.

Discussion

The peak hardness of sandstone soaked in water- and oil-based drilling fluid is

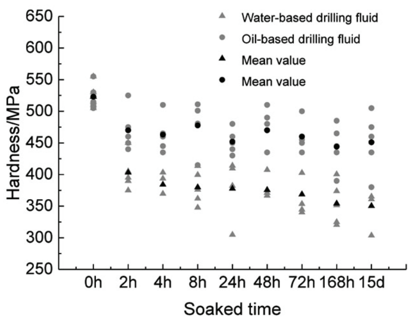

Figure 10. Relationship of hardness of tight sandstone versus soaking time.

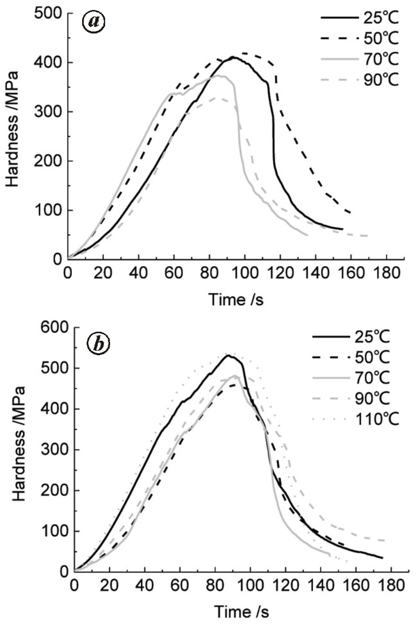

Figure 11. Curve of hardness of tight sandstone versus time after different temperature. ***a***, Water-based drilling fluid; ***b***, Oil-based drilling fluid.

lower than that of dry sandstone but the peak hardness is nearly invariable with regard to the soaking time and the temperature in the case of the oil-based drilling fluid. The authors observed that few organic matter dissolve in oil within two hours and the total quantity of dissolved organic matter does not change with the temperature and the soaking time. The peak hardness of sandstone soaked in the water-based drilling fluid decreased with increase in soaking time and temperature. The slope of the curves decreased with the increase on soaking time, but it was not affected by the temperature.

According to the above experimental results, the soaking time and the temperature have a relatively small impact on the peak hardness when using oil-based drilling fluid, but have a relatively large impact on the peak hardness in the case of water-based drilling fluid. For water-based drilling fluid, an increase in exploitation depth, and length for the drilling of oil and gas wells will lead to an augmentation of the formation temperature and the soaking time. This has a positive effect on drilling efficiency, but a negative effect on wellbore stability under high reservoir temperature. The wellbore will soften if it is soaked in the drilling fluid for a long time, which would thus affect the wellbore shape and stability. For the oil-based drilling fluid, poor drilling efficiency and groundwater pollution are the principal disadvantages, but the problems related to wellbore stability would not occur. On the oil field, petroleum engineers should select a drilling fluid which helps avoid wellbore instability while considering the drilling efficiency and environmental issues.

Conclusion

The water- and oil-based drilling fluids have a different influence on the peak hardness of sandstone. In general, the peak hardness is more affected by the water-based drilling fluid than by the oil-based drilling fluid.

(1) At the beginning of the soaking process (0–2 h), the reduction of the tight sandstone hardness was 22.9% in the case of water-based drilling fluid and 10.1% in the case of oil-based drilling fluid. With the increase in soaking time, the peak hardness reduction was equal to 33.1% when soaked in water-based drilling fluid for 15 days but the peak hardness remained stable after soaking for two hours in the oil-based drilling fluid.

(2) The temperature has almost no influence on the peak hardness of sandstone soaked in the oil-based drilling fluid. But in the case of tight sandstone soaked in the water-based drilling fluid, when the temperature was above 50°C, the peak hardness decreased with increase in the soaking temperature.

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Feng Xu and Zongling Yan are in the National and Local Joint Engineering Laboratory for Road Engineering and Technology in Mountainous Areas, Chongqing, People's Republic of China; China Merchants Chongqing Communications Research & Design Institute Co., Ltd, Chongqing, People's Republic of China; Lei Wang, Yintong Guo and Chunhe Yang are in the State Key Laboratory of Geomechanics and Geotechnical Engineering, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan, People's Republic of China.*
**e-mail: ucasxf@163.com*