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REVIEW

TEMPERATURE AND PRESSURE EFFECT ON PERMEABILITY OF CHINESE SANDSTONE: A REVIEW

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ARTICLE INFO	ABSTRACT				
Article history:	Permeability plays an important role in the field of geotechnical engineering. Under high				
Received 22 May 2018 Accepted 21 September 2018 Available online 27 September 2018	temperature and high pressure condition, the physical-chemical and structure properties (such decomposition, oxidation, dehydration, evaporation, phase transition etc.) of rock have obvious changing, which are significant affected the rock permeability. In order to analyze the influen of temperature and confining pressure on the permeability of rock (sandstones, siltstones a				
Keywords:	conglomerates) data for permeability was obtained from the literature. The results indicate that temperature and confining pressure have great influence on the permeability of rock especially				
High temperature Confining pressure Permeability Threshold temperature	for sandstone. There is a threshold temperature and when the heating temperature is lower that the threshold temperature, the permeability of sandstone gradually increases with an increase is temperature. When the heating temperature is higher than 300 °C (especially 400 °C), the permeability rapidly increases. The permeability of sandstone decreases gradually with the confining pressure increases. This study of the relationship between rock permeability and temperature and confining pressure lays a foundation for investigations of multi-disciplinar issues regarding high temperatures and high pressures and it can be used for the study of petroleum storage and safe nuclear waste disposal.				

1. INTRODUCTION

Permeability is an important physical parameter the geological sciences and geotechnical in engineering and has been investigated with regard to, coal gasification (Hetherington and Thambimuthu, 2003), disposal of high-level radioactive wastes (Takeda et al., 2009), underground oil and gas reservoirs (Shahverdi and Sohrabi, 2017), shale oil production (Egboga et al., 2016), extraction of geothermal energy (Somerton and Boozer, 1960; Zarichyak et al., 2013), protection of stone cultural relics (Hajpál, 2002; Hajpál and Török, 2004), underground oil or gasification (Wu et al., 2003; Kök, 2009; Zhao et al., 2009; Ranjith et al., 2012;), deep petroleum boring (Gao, 2005; Dutton et al., 2012), coal pyrolysis (Zhao et al., 2009; Liang et al., 2005), water inrushes in underground projects (Ding et al., 2016) and extraction of geothermal energy (Yang et al., 2017). In these experiments, the rock is always affected by certain temperatures and confining pressures.

Under high temperature, a series of physical and chemical changes occur in the rock and they have an important influence on rock permeability. Following a high temperature treatment, the changes in the pores and the cracks in the rock are related to the thermal expansion and structural changes in the rock (Xu et al., 2008 and Qian et al., 2015). The changes in the

pores and cracks of the rock are related to the deformation of the rock under different confining pressure. All these changes will affect the rock permeability. The permeability of the rock has an important impact on many engineering activities. For example, in the underground storage of nuclear waste, the decay of radioisotopes generates a large amount of heat, which causes the temperature of the rock mass around the nuclear waste to rise and the rock to be thermally damaged. Cracks and pores inside the rock increase, the permeability increases and radioactive materials penetrate into the groundwater, causing great harm to people's production and life. As for underground oil or gasification storage, high temperature will change the internal structure of the rock: improve the flow passage of the fluid and change the permeability of the rock, which is not good for oil storage.

In this study, we assembled a large amount of experimental data and developed charts based on these data. By analyzing the changes in the data, we can observe the changes in the permeability of sandstone and conglomerates under different temperatures and confining pressures. Although the specimen size is not uniform in the experiment (Table 1), it has no significant effect on the measurement of permeability. The remainder of this paper is organized as follows: in Section 2, we present

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Table 1 Characteristics of the reviewed sandy rock.

Туре	Rock type	Ref.	Site	Main mineral	Sample size	Sample Size (mm)	Test equipment	Test process
Permeability	Sandstone-1	You and Kang. (2009)	Sichuan, China	-	1	25.0×32.5	SCMS-B permeability test machine	keep 1h
Permeability	Sandstone-2	You and Kang. (2009)	Sichuan, China	-	1	24.8×52.7	SCMS-B permeability test machine	keep 1h
Permeability	Sandstone-3	You and Kang. (2009)	Sichuan, China	-	1	25.1×46.5	SCMS-B permeability test machine	keep 1h
Permeability	Sandstone-4	You and Kang. (2009)	Sichuan, China	-	1	25.1×48.6	SCMS-B permeability test machine	keep 1h
Permeability	Sandstone-5	You and Kang. (2009)	Sichuan, China	-	1	24.7×53.1	SCMS-B permeability test machine	keep 1h
Permeability	Siltstone	Liu et al. (2001)	Dongying, Shandong, China	-	4	25×50	Core permeability measuring device	keep 2h, 0.1MPa
Permeability	conglomerate	Liu et al. (2001)	Dongying, Shandong, China	-	4	25×50	Core permeability measuring device	keep 2h, 0.1MPa
Permeability	Siltstone	Gao (2004)	Liaoning, China	-	5	5×5×10	Core permeability measuring device	25°C, 3.0MPa
Permeability	conglomerate	Gao (2004)	Liaoning China	-	5	5×5×10	Core permeability measuring device	keen 2h 0 1MPa
Permeability	Sandstone	Zhang. (2015)	China	Feldspar Quartz Kaoninite Chlorite Illite	4	25×50	TAW-1000 type deepwater gap pressure servo experimental system	10°C/min, keep 4h, 5MPa, 10MPa, 20MPa, N ₂
Permeability	Sandstone	Liang et al. (2005)	Fuxin, Liaoning, China	-	4	25×50	Gas permeameter	0.1MPa, keep 3h
Permeability	Sandstone	Ding et al. (2016)	Shuozhou, Shanxi, China	Feldspar Siderite Kaolinite Illite Chlorite Calcite Siderite	21	50×100	MTS815.02 and a self-made water flow device	20°C/min, keep 2h, 8MPa
Permeability	Sandstone	Yang et al. (2017)	Rizhao, Shangdong, Chian	-	36	50×100	Servo-controlled triaxial equipment	5°C/min , keep 2h, 5MPa, 10MPa, 20MPa, 30MPa
Permeability	Fractured sandstone(MP)	Guo et al. (2017)	Chendu, China(2017)	-	5	25.2×40.4	Soap film flow meter	keep 2h, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50MPa, 20°C~100°C, N ₂
Permeability	Fractured shale(MP)	Guo et al. (2017)	Chendu, China(2017)	-	5	25.3×41.3	Soap film flow meter	keep 2h, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50MPa, 20°C~100°C N ₂
Permeability	Unfractured sandstone(LP)	Guo et al. (2017)	Chendu, China(2017)	-	5	25.0×50.3	Soap film flow meter	keep 2h, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50MPa, 20°C~100°C N ₂
Permeability	Unfractured sandstone(ultra-LP)	Guo et al. (2017)	Chendu, China(2017)	-	5	25.3×50.8	Soap film flow meter	keep 2h, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50MPa, 20°C~100°C N ₂
Permeability	Sandstone(ultra-LP)	Guo et al. (2017)	Chendu, China(2017)	-	5	25×50	Gas permeability meter	keep 3h, 100~800°C
Permeability	Siltstone(ultra-LP)	Guo et al. (2017)	Chendu, China(2017)	-	5	25×50	Gas permeability meter	keep 3h, 100~800°C
Permeability	Sandstone	Yu et al. (2015)	Jiangxi, China	Feldspar Quartz Kaolinite Chlorite Illite	16	25×50	TAW-1000 electro-hydraulic	10°C/min, keep 4h, 0MPa, 5MPa, 10MPa, 20MPa
Porosity	Sandstone	Sun et al (2016)	Linyi, Shangdong, China	Quartz Feldspar Dolomite ankerite	40	50×100	microporosity structure analyzer apparatus (type 9310)	30°C/min, keep 30 min









(c)

Fig. 1 Influence of high temperature on the permeability of (a) siltstones, (b) sandstones and (c) conglomerates.

experimental data from different researchers. Section 3 describes our reanalysis of the existing experimental data. For further validation, the changes in permeability were analyzed by heating and pressurization. The discussions are presented in Section 4 and Section 5 presents the conclusions.

2. COLLECTION OF EXPERIMENTAL RESULTS FROM PREVIOUS STUDIES

In past experiments, the physical and chemical properties of rocks under different conditions were studied by heating and pressing the rocks to determine the permeability, porosity, thermal conductivity of rocks, etc. Each study presents its own unique and novel conclusions. However, because each study has limited experimental data obtained from a small number of rock specimens, some researchers may focus extensively on the subtle differences of a specific rock type while ignoring important common characteristics. For this reason, we integrate data from different sources and derive a number of previously overlooked conclusions using a new perspective.

3. ANALYSIS AND DISCUSSION

3.1. INFLUENCE OF TEMPERATURE

Figure 1 shows that the permeability of sandstones, siltstones and conglomerates increases with an increase in the temperature; the change in the permeability indicates that a threshold temperature exists (the temperature at which the rate of increase in permeability increases considerably). When the heating temperature is lower than the threshold temperature, the rate of change in permeability is small and the slope of the curve is gentle; when the temperature is higher than the threshold temperature, the rate of change in permeability increases sharply and the curve becomes steeper. Different types of rocks have different threshold temperatures and the same rock is also different from different regions. Figure 1 shows that the permeability of sandstone, siltstones and conglomerates increases slowly when the heating temperature is lower than 400 °C; when the heating temperature is higher than 400 °C, the permeability increases sharply. The threshold temperature of sandstones, siltstones and conglomerates is between 400 °C and 600 °C.

3.2. INFLUENCE OF CONFINING PRESSURE

Figure 2 shows that the changes of sandstone permeability with confining pressure at different heating temperatures. Figure 2(a) shows the data of initial permeability of sandstone after heat treatment. Figure 2(b) and (c) shows the variation of the elastic modulus (*E*) of sandstone and the volume expansion ratio of three typical sandstones (Bandera, Berea and Boise). Under the same treatment temperature, the initial permeability generally decreases as the confining pressure increases. When the treatment temperature is higher than 400 °C, as shown by



Fig. 2 Influence of temperature and confining pressure on the permeability of sandstone.







Fig. 3 Changes in permeability of sandstone with changes in axial strain.

Figure 2(b) and Figure 2(c), the porosity (pores and cracks) of sandstone has a nonlinear increase, which results in the quick increasing of permeability, while the elastic modulus of the sandstone reduces significantly. Therefore, with the increasing of confining pressure, the compressibility of sandstone increases and the permeability decreases, especially when confining pressure is less than 10 MPa.

Figure 2(b) and (c) show that the elastic modulus of sandstone increases slowly with temperature at first and then decreases rapidly. When the heat treatment temperature is about 600 °C, the volume of the sandstone is rapidly expanded and the modulus of elasticity is small. This means that the damage inside the rock caused by heating is irreversible (Shafiei and Dusseault, 2013). Figure 2(d) shows the correlation between confining pressure and permeability of sandstone at 600 °C. It can be seen that as the confining pressure increases, the permeability of sandstone decreases significantly. When the confining pressure increases to a certain level, the permeability begins to decrease slowly.

Figure 2(e) and (f) show that the permeability of sandstone decreases with an increase in the confining pressure when the heating temperature is lower than 100 °C. For medium-permeability (MP) fractured sandstone and ultra-low-permeability (ultra-LP) unfractured sandstone, the permeability decreases sharply with the increasing confining pressure when the confining pressure is less than 25 MPa; when the confining pressure is greater than 25 MPa, the permeability decreases more slowly. The above results show that when the confining pressure is low, the permeability of sandstone decreases exponentially with the increase of confining pressure. When the confining pressure increases to a certain level, it begins to slow down and there is a mutation process.

Figure 3 shows the changes in the permeability of sandstone under different temperatures and different confining pressures during conventional triaxial compression. Figure 3(a) shows that, for different heating temperature of sandstone specimens, when the confining pressure is constant, the permeability of sandstone decreases slowly with the increase of axial strain in triaxial compression and axial strain increases to a certain extent, the permeability increases rapidly. When the heating temperature is greater than 400 °C, the permeability changed suddenly. Figure 3(b) shows that as the thermal treatment temperature increases from 25 °C to 800 °C, the initial permeability decreases in the range of 25 °C to 400 °C and subsequently increases by approximately one order of magnitude. For the sandstone specimens with the same heating temperature, at the initial stage of triaxial compression, the permeability of sandstone decreases with the increase of strain. When the strain reaches a certain stage, the permeability of sandstone increases rapidly. Under the same heat treatment temperature, the permeability of sandstone decreases with the increase of confining pressure (Fig. 3(c)).

Fig. 4 Rate of change for sandstone permeability and quartz volume due to temperature changes.

DISCUSSIONS 4

100

The rock's internal structure and the stress distribution reach a relatively stable state of equilibrium after diagenesis. When external factors such as temperature and confining pressure change, the balance changes together with physical parameters change, thus affects the rock's permeability.

When the heating temperature is lower than the 1 threshold temperature, the main change in the rock specimen is the change in the amount of adsorbed water and interlayer water. The water mainly exists in very small gaps in the rock and gradually evaporates as the temperature increases; therefore, this effect has little influence on the rock permeability. When the heating temperature is higher than the threshold temperature, the water in the rock channel evaporates improving the rock permeability. Moreover, between 300 to 400 °C, the water reaches its critical temperature (i.e. 374 °C) (Zhang et al., 2007), at which the water may turn into supercritical fluid, causing changes in the rock internal stress and increase the rock thermal damage. The high temperature also changes the thermal stress in the rock and changes the rock structure, which produces many small cracks inside the rock and enhances the flow capacity of the fluid, thus increasing the rock permeability. Some minerals such as quartz facilitate decomposition and volatilization (such as dehydroxylation of clay minerals) in the process of losing structural water, which may cause an increase in the pores and fractures. When the heating temperature is greater than 600 °C (Fig. 4), the oxidation-decomposition reaction is strong and the α -quartz transforms into β -quartz and quartz volume dramatic expansion caused structural damage within sandstone, which increases the porosity and permeability.

Variation in the porosity of sandstone after Fig. 5 different treated temperature.

300

400

500

600

- 2. During the initial stage of compression, internal fractures are closed and the porosity decreases under deviatoric stress, leading to decreased permeability. As the fractures close, the rock enters the elastic deformation stage. At this stage, the internal structure of the rock is relatively stable and new fractures are not formed; therefore, the permeability change rarely. As the strain increases, new fissures occur in the rock and the internal fissures are reopened and expand, thereby increasing the permeability. When the strain reaches a certain stage, the fissures in the rock expand and connect in a random fashion, which results in a rapid increase the effective porosity and the permeability.
- Because of differences in the rock composition, 3. the internal structure and the degree of cementation between mineral particles, different rocks have different threshold temperatures. The porosity of the rock is closely related to defects. As the number of defects increases, the quartz volume expands rapidly resulting in a sudden change in the permeability of sandstone (Popp and Kern, 1993; Bai et al., 2002). When the heating temperature is lower than 400 °C, the porosity changes very little, but when the temperature is higher than 400 °C, it begins to increase significantly, resulting in an increase in permeability (Fig. 5). The effects of thermal effect on the permeability are: (a) increased interconnectivity between pre-existing and newly formed cracks or pore, (b) new-microcracks provide additional flow paths and (c) widening of crack aperture reduces impedance to fluid flow resulting from boundary friction. The first two effects are expected to be more important at the lower thermal-cycle temperatures, whereas crack widening is expected to dominate at the higher temperatures (Bauer and Johnson, 1979).



Rate of change in permeability (%)

60

40

20

-20

Through the study, we find that temperature and confining pressure have great influence on the permeability of rock. The main conclusions are as follows:

- Rock permeability increases rapidly at temperatures higher than 300 °C (especially 400 °C). The threshold temperature of sandstones, conglomerates and siltstones is between 400 °C and 600 °C. The rock permeability decreases exponentially with an increase in the confining pressure at heating temperatures of less than 100 °C.
- 2. The permeability of sandstone decreases significantly with the confining pressure increases. When the confining pressure increases to a certain level, the permeability begins to decrease slowly. The permeability of sandstone is larger under the condition of high temperature and low confining pressure.
- 3. Under high temperatures, sandstone expands when heated and this expansion behavior is mainly caused by the phase transition of quartz. The structural damage resulting from the heating is an important cause for the increase of the permeability of the heated specimens.

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