Effect of thermal cycling and hydro-thermal cycling on physical and mechanical properties of sandstone

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Abstract
Thermal storage of sandstone is widely distributed in sedimentary basins in China with a very high degree of exploitation and utilization, while the low recharge rate is the bottleneck of its sustainable development. A new method is proposed to discover the physical and mechanical behaviors of sandstone after thermal cycling and hydro-thermal cycling treatments in this study. The stress-strain curves, strength, failure behavior, acoustic emission (AE), P-wave velocity, density features, X-ray, and microscope images of specimens are analyzed in detail to investigate and describe the differences of the sandstone after the two different experimental treatments. The results indicate that multiple thermal cycling and hydro-thermal cycling have an obvious effect on the compaction stage of sandstone at the temperature of 100°C. Meanwhile, strengths and Young's modulus of specimens after hydro-thermal cycling treatment decrease with cycling times and the reduce degree is greater than that of the thermal cycling treatment on sandstone. The brittleness of the sandstone decreases as the hydro-thermal cycling number increases from 0 to 15, and the influence of hydro-thermal cycling is greater than that of thermal cycling on sandstone. In addition, based on the limited cycling experimental results, the action of the thermal cycling leaded the thermal stress of the crystal to nonuniform, which leaded to micronarrow and sharp cracks in specimens. Furthermore, the action of the hydro-thermal cycling generated thermal stress and ablation coupling effect, which leaded wider and rounder cracks than that of the specimen under thermal cycling condition. Finally, it indicates that hydro-thermal cycling has a greater effect than that of the thermal cycling treatment on the physical and mechanical properties of sandstone on the macro- and microlevels.

KEYWORDS
hydro-thermal cycling, mechanical behavior, sandstone, thermal cycling, thermal stress

1 | INTRODUCTION

For the urgency of the world’s energy problems, the development of new energy sources is as important as the effective management of existing resources. In recent years, the development of geothermal energy and energy storage systems makes it uses renewable energy sources for heating and geothermal electric power generation, which improves and
resolves the problems caused by intermittent and variable characteristics of renewable energy sources (such as solar energy, hydropower, wind power, biomass energy, and wave energy). However, according to the principles of “heat extraction without water” and “irrigation with fixed production,” the development of geothermal resources has been restricted by the difficulty of tailwater recharge for a long time; especially, the geothermal tailwater recharge for sandstone thermal storage is a world problem. Therefore, in order to improve the overall efficiency and flexibility of the energy system, it is necessary to understand the physical behavior of rocks subjected to thermal and hydro-thermal variation which is the most basic research content.

The shallow geothermal energy storage utilizes nature groundwater as a thermal energy source, which is technically feasible even under poor geological conditions, and it can be customized for various purposes. In Denmark, geothermal energy for district heating has been extracted from deep sandstone aquifers at temperatures as high as 75°C. Therefore, the possibility of storing excess heat seasonally in these geothermal aquifers was considered. The heat loss of these aquifers may be minimized due to the relatively high in situ temperatures and low aquifer flow rates. In addition, heat storage can increase the thermal potential of aquifers and extend the service life of geothermal aquifers.

In order to improve the heat production, reservoir stimulation must be used to create a large number of inter-connected fractures because of its ultralow permeability (0.001-0.1 md). To stimulate the reservoir, researchers have proposed several methods, including traditional rock fracturing, hydraulic fracturing, thermal fracturing, shear stimulation, and multilateral wells. And then, the mechanical characteristics of HDR under thermo-hydro-mechanical (THM) effect were also researched. While the thermal cycling influences on sandstone are the key problems during geothermal reservoir stimulation, especially the coupled hydro-thermal effect on physical and mechanical properties of sandstone thermal storage is a worldwide problem.

The fundamental understanding of the behavior of rocks under thermos-mechanical coupling (TM) is very important, which has been widely investigated in recent years. Furthermore, there are many necessary measurements of basic physical and mechanical parameters to be tested. It includes rock deformation modulus, Poisson’s ratio, tensile strength, compressive strength, cohesion, internal friction angle, viscosity, thermal expansion coefficient, and other changes with temperature. As is well known, temperature plays an important role in many engineering practices. The influence of temperature on the physical and mechanical properties of sandstone has become an important field of rock mechanics research. Furthermore, it was observed that the compressive strength and tensile strength of rock increased with the gradual increase in temperature up to 300°C and decreased sharply after reaching 300°C. More and more researchers have studied the influence of temperature on the physical and mechanical properties of salt rock. It was found that both uniaxial compressive strength and axial strain increase with the increasing temperature; however, the tangent modulus decreases with the increasing temperature. By extension, researchers studied the influence of high temperature on the peak strength, elastic modulus, and damage characteristics and compared the stress-strain curves of different sandstones between normal temperature and the high temperature of 950°C. Based on these researches, the high-temperature effects on the mechanical behaviors and physical characteristics of rocks are fully conducted. Although almost all the deep rocks exist in a hydro-thermal environment, the mechanical behavior of brittle rocks after the hydro-thermal cycling treatment is few studied.

In this study, the primary purpose is to investigate the effects of thermal cycling and hydro-thermal cycling, which is to simulate the reservoir stimulation environment of TES, on the physical and mechanical properties of sandstone. We conducted a series of laboratory experiments to investigate the breakdown pressure of high-temperature sandstone specimens with different thermal and hydro-thermal cycling treatments. The compressive stress, strain, and acoustic emission rate of the treated specimens were monitored during the uniaxial compression experiments. The fracturing pressure-time curves, breakdown pressures, and fracture patterns of the specimens after different treatments were compared. Finally, the physical characteristics including P-wave velocity and density of specimens were discussed in detail. The results obtained provide reference in the experimental basis, theoretical guidance, and engineering safety for the reservoir stimulation of TES.

2 | EXPERIMENTAL DETAILS

2.1 | Specimen preparation

In our investigation, the sandstone specimens were collected from interior formations in Chongqing, China. The range of mineral particle size of the specimen is from 0.35 to 0.74 mm with an average size of 0.58 mm, which is the coarsest sandstone. Standard cylindrical sandstone specimens with the dimensions of 50 mm in diameter and 100 mm in length were prepared to evaluate the compressive strength. The prepared sandstone specimens have basic physical properties of the average density of 2.45 g/cm³, the quasi-static compressive strength of 97.6 MPa, and elasticity modulus of 135 GPa. There were 60 original specimens in total, which were divided into two groups with thirty specimens in each group. One group was marked as thermal cycling group (H group), and the other group was marked as hydro-thermal cycling...
2.2 | Experimental program

In order to represent the real environmental conditions of deep rocks, two heating schemes were executed that the thermal cyclic treatment (H) and hydro-thermal cyclic treatment (WH) experiments. The specimens of the thermal cycling group were numbered and heated to the designed temperature of 100°C using an auxiliary heating device. The specimens are kept constant for 10 hours per cycle once the temperature up to the target value (100°C) in order to ensure the uniform heating of the specimens. Then, the heated specimens are left in the furnace to cool down naturally to room temperature for 2 hours. For different specimens, the heating and cooling processes are repeated for 5, 10, and 15 cycles, respectively. The heating rate of the device is controlled in 6°C/min. The experimental result of specimen is marked as the 5H1, 10H1, and 15H1, which means that the number of thermal cycling is 5, 10, and 15, respectively. Meanwhile, there are two identical specimens under the same conditions. The other specimens are marked as 5H2, 10H2, and 15H2, respectively. The definition rules of specimen names in the hydro-thermal cycling groups are the same as thermal cycling group.

For the hydro-thermal cycling group, the specimens were heated to the designed temperature of 100°C (heated at normal atmospheric pressure) by using a water bath shaker for 5, 10, and 15 cycles, separately. The temperature of the water bath shaker was kept in 97-100°C. Corresponding to the thermal cycling group, the specimens were maintained for 10 hours per cycle in the target temperature state for the hydro-thermal cycling group. The result was marked as the 5WH1, 10WH1, and 15WH1 in the hydro-thermal cycling group, which represents that the number of the hydro-thermal cycling was 5, 10, and 15, respectively. After the heating process, both the thermal and hydro-thermal treated specimens were cured at normal temperature condition (25°C) for two hours during each cycle. Then, the specimens were prepared for the next treatment. The geothermal environment diagram is shown in Figure 1(A). The treatment schedule applied for the sandstone specimens was depicted in Figure 1(B).

3 | TESTS RESULTS AND ANALYSIS

3.1 | Stress-strain curve

As shown in Figure 3, the complete stress-strain curves of sandstone specimens under different treating cycles show a similar tendency, which are characteristics of four stages that
the compaction, elasticity, yielding, and failure procedures. As the stress-strain curves of specimens after thermal cycling and hydro-thermal cycling treatments, the compaction stage prolongs and the rate of slope decreases with the cycles rising. However, the yielding stage of treated specimens has no obvious difference compared with the original ones. For the stress-strain curves under two types of treatment conditions, the stress quickly declines after it reached the peak stress. By a comparison of the complete stress-strain curves of the original sandstone specimens and that of treated ones, the brittleness seems no significant difference under the two treated experimental conditions, while the peak stresses of specimens after hydro-thermal cycling treatment were lower than that of specimens after thermal cycling treatment.

As shown in Figure 4, the peak strength deformation modulus and strains at peak strength of specimens are plotted. The peak strength strain of sandstone after experimental treatment is decreasing first and then increasing, while peak strength strain of WH group decreases and increases faster than that of H group specimens. The reason is that hydro-thermal ablation effect results in the brittleness of the sandstone to decrease. The thermal cycling effect only results in microlevel local damage of sandstone. The peak strength deformation modulus of the two groups is decreasing with increasing cycling times. However, the decline of peak strength
deformation modulus of WH group specimens is lower than that of H group specimens. It shows that the effect of hydrothermal cycling treatment on mineral composition content and mesostructure of sandstone is stronger than that of the thermal cycling treatment.

As seen from Figure 5, for sandstone specimens after experimental treatments, the curves move toward left because the peak stresses of specimens in WH groups are lower than that of specimens in H groups with the unobvious changing elasticity modulus when the cycling times are bigger than 10. When the cycling cycles are reaching 15, the compaction stage of specimens in WH groups is longer than that of specimens in H groups. As shown in Figure 5, the influence of hydro-thermal cycling on specimens' strength and Young's modulus becomes greater than that of thermal cycling with cycles increase.

As seen from Figure 6, the complete stress-strain curves of specimens in the H group and WH group are plotted, separately. In the H group, the peak stresses of specimens have no obvious differences, while it decreases with the cyclic number increase of specimens in the WH group. Although the compaction stage of specimen 15H is longer than that of the other two specimens, there is no clear variation for Young's modulus in H groups. However, compared with the stress-strain curves of sandstone after hydro-thermal cycling
treatment, the duration of the compaction stage and Young’s modulus of sandstone specimens 15WH shows an obvious reduction. That is to say, the hydro-thermal cycling treatment has a greater influence than that of thermal cycling treatment on Young’s modulus of sandstone.

From the above, we can know that multiple 100°C thermal cycles and hydro-thermal cycles have an obvious effect on the compaction stage of sandstone, while, for the strength and Young’s modulus, hydro-thermal cycling has a greater effect than that of thermal cycling treatment with the same treating cycles.

3.2 Strength and failure behavior of treated specimen

Table 1 represents the peak stress ($\sigma_p$), Young’s modulus ($E$), and peak strain ($\varepsilon_p$) of the treatment sandstone specimen, which is obtained from the stress-strain curves of Figure 3. Over the results of the entire treatment cycles, the original $\sigma_p$ decreases from 97.64 to 71.98 MPa and the original Young’s modulus decreases from 148.90 to 110.10 GPa of the specimen with the 15 treatment cycles. The Figure 7 shows the typical fracture pattern of specimens under different treated condition. From Table 1 and Figure 7, we can see that with an increase in cycle times, the failure mode of sandstone changed from mixed tension and shear fracture (single shear fracture) to shear fracture with double slippage planes and complicated fracture. Researchers believe that the change of the internal structure of sandstone and experimental treatment can result in different failure modes. All the experimental treatments cause the internal structure to change remarkably, such as fissure expansion, dehydration, and the enlargement of voids. Therefore, with the increase in thermal cycling and hydro-thermal cycling times, the apparent internal structural changes result in different failure paths. Consequently, different types of failure were observed in treated specimens. In addition, for sandstone under thermal and hydro-thermal cycling treatments, the thermal and hydro-thermal influence on specimens can be simply considered as the confining pressure in local and lead to local damages.

3.3 Acoustic emission (AE) results

As is well known, the AE technique is predominantly related to the release of elastic energy within rock materials. AE hits and energy are often monitored to detect the initiation and evolution of microcracking and to analyze the spatial and temporal progression of internal cracks.

Figure 8 shows the normalized AE energy number versus time of specimens during the loading process. All the normalized AE energy of the specimens starts to increase approximately at 1000 seconds in the H group, while, in the WH group, the normalized AE energy monitoring data of specimen 15WH1 starts at time of around 800 seconds, about 950 seconds of specimen 10WH1 and 970 seconds of specimens 5WH1, separately. After thermal cycling treatment for five cycles, 10 cycles, and 15 cycles, there is a rapid increase in the AE event at the time of 1000 seconds. When the load increases to peak stress, there is a sharp increase in the number of total cracks and AE energy. The total crack number and AE energy almost simultaneously reach the peak value. A substantial degree of crack coalescence of the specimen has occurred, and it quickly fails. This phenomenon indicates that the sandstone presents brittleness under low thermal cycles. When the thermal cycles increase to 15, the increase in AE energy becomes slow in the final stage of loading. That is to
say, thermal cycling has an effect on the brittleness of sandstone. For the specimens after hydro-thermal cycling treatment, the AE energy has obvious distinctions under different hydro-thermal cycling cycles. The AE energy of specimen 15WH1 starts to increase at approximately 800 seconds with a slow process compared with the other two specimens in the WH group. Then, when the time reaches the 1050 seconds, the AE energy increases rapidly, and the specimen fails. For the specimens of 5WH1 and 10WH1, the increased speed of AE energy of specimen 10WH1 is slower than that of specimen 5WH1, while the normalized AE energy of specimen 10WH1 starts earlier than that of specimen 5WH1. This phenomenon illustrates that the brittleness of the sandstone decreases as the hydro-thermal treatment cycles increases from 5 to 15. As a result, the influence of hydro-thermal cycling on the sandstone is greater than that of thermal cycling.

### 3.4 | P-wave velocity data and density features

The results of the average P-wave velocity of the two groups of specimens were analyzed. As shown in Figure 9, the values of the average P-wave velocity of the sandstone after experimental treatments are correlated with the treatment cycles. The average P-wave velocity of sandstone increases first and then decreases with the rising of cycles in the WH group. However, the average P-wave velocity of the specimen is characterized by an increasing tendency and it is going to increase slowly when the treatment cycles more than 10 in the H group. Furthermore, the P-wave velocity of sandstone in the WH group is obviously lower than that of specimens in the H group. The reason is that the actual propagation velocity of P-wave depends on the density and intrinsic elasticity of the rock. When the cycling times is increasing of WH group, density and elasticity of specimens decrease, while the elasticity decreases slower than the density of specimens. Furthermore, the density is in the denominator of the P-wave velocity formulas. So, P-wave velocity increases first and then decreases with increasing cycling times of the WH group.

A very strong correlation between average P-wave velocity and physicomechanical properties of the sandstone is also found based on the experimental results. Table 2 and Figure 9 show the density versus average P-wave velocity of
the treated specimens. It can be observed that there is an approximately linear relation between the densities average and P-wave velocity of the sandstone specimens. The semiempirical formula is presented in Figure 10; the gradient of the fitting line of the H group is 0.00168, which is lower than that is 0.02576 of the WH group. This result confirms that the hydro-thermal cycling treatments can more obviously affect the physical property of the sandstone specimens than the thermal cycling treatments do.

The density of sandstone also varies with the cycles of thermal cycling and hydro-thermal cycling treatments. The density decreased greatly, the max value decreases from 2.45 to 2.445 g/cm³, and the minimal value decreases from 2.40 to 2.375 g/cm³ when the treatment cycles index up to 15, as shown in Figure 11. And the decrease in density also leads to the stress falling according to Figure 3. In authors’ opinion, all the above changes can be seen as the result of the microscopic damage. In addition, the XRD and microscope analysis will be discussed in the next subsection.

4 | DISCUSSION

All the experimental treatments cause the internal structure to change remarkably, such as fissure expansion, dehydratation, and the enlargement of voids. With the increase in thermal cycling and hydro-thermal cycling times, the apparent internal structural changes result in different failure paths. For sandstone under thermal and hydro-thermal cycling treatments, the thermal and hydro-thermal influence on specimens can be simply considered as the confining pressure in local and lead to local damages. The physical and mechanical properties of rocks under different hydro-thermal conditions are different. In order to discover the fracture mechanism of sandstone after thermal
cycling and hydro-thermal cycling treatments on the microlevels, the X-ray diffraction experiments are conducted and the results are presented in Figure 12. It can be seen from Figure 12 that the primary minerals of sandstone are KAlSi$_3$O$_8$, NaAlSi$_3$O$_8$, KAlSi$_3$O$_{10}$(OH)$_2$, CaAl$_2$Si$_2$O$_6$, SiO$_2$, and CaCO$_3$. For the original specimen, the content of CaAl$_2$Si$_2$O$_6$ and NaAlSi$_3$O$_8$ is higher than those of other mineral components. Under the action of the thermal cycle, mineral composition began to decompose and mineral content decreased. In the hydro-thermal cycling group, with the same temperature, it has a hydro-thermal ablation effect on mineral components, which results in a greater reduction of mineral components of CaAl$_2$Si$_2$O$_6$ and NaAlSi$_3$O$_8$. So, the effect of hydro-thermal cycling treatment on mineral composition content is stronger than that of the thermal cycling treatment.

The uneven thermal expansion state of various minerals under the action of temperature appears due to the different thermal expansion coefficient of various mineral components in the rocks. The thermal stress is generated between mineral crystal particles, and then, cracks are initiated if the thermal stress is larger than the yield limit of mineral when the sandstone specimens are subjected to thermal cycling or hydro-thermal cycling treatments. Finally, the cracks caused by thermal or hydro-thermal stress would lead to the intergranular fracture in the mineral particles as long as the thermal cycling and hydro-thermal treatment cycles are large enough.

The electronic magnifier technique was applied to verify the mesoscopic difference of the specimens, which is caused by thermal cycling and hydro-thermal cycling treatments. The typical morphology of the microscopic cracks of the specimens with 15 treated cycles is shown in Figure 13. It can be seen that the crack caused by thermal cycling treatment in the specimen 15H1 is formed narrow and sharp features, while the crack induced by the hydro-thermal treatment in the specimen 15WH1 is wider and...
FIGURE 12  X-ray diffraction of specimen with different treatment conditions: (A) original specimen, (B), (C), and (D) represent 5, 10, and 15 treatment cycles, respectively.
rounder than that of the specimen 15H1. In the authors’ opinion, the differences in mechanical properties of the sandstone specimen are mainly caused by these microscopic cracks with different characteristics.

5 | CONCLUSION

Many tests show that the physical performances of rocks after the serials high-temperature treatments are different. In this work, the mechanical properties of the sandstone specimen under the thermal cycling treatment in laboratory tests were investigated and analyzed; especially, the hydro-thermal cycling treatment effect was taken into account to fully understand the performance of deep rocks.

Multiple thermal cycling treatment and hydro-thermal cycling treatment experiments at the temperature of 100°C show that the treatments had an obvious effect on the compaction stage of sandstone specimens, while the hydro-thermal cycling treatment has a greater effect on the strength and Young’s modulus of sandstone specimens than that of thermal cycling treatment. In addition, for sandstone under thermal and hydro-thermal cycling treatments, the thermal and hydro-thermal effectiveness can be simply considered as a confining pressure in local and lead to the local damages of specimen. The AE result deduces that the brittleness of the sandstone decreases as the hydro-thermal cycle index increases from 0 to 15, and the influence of hydro-thermal cycling treatment is greater than that of thermal cycling treatment on sandstone. The density of sandstone specimens presents a decreasing tendency with increasing cyclic treatment. Finally, the crack of the specimen (15H1) is featured by the narrow and sharp forms, which is caused by the 15 times thermal cycling treatments. However, the crack induced by the 15 times hydro-thermal cycling treatments in the specimen (15WH1) is wide and round. In the authors’ opinion, compared with the thermal cycling treatment conditions, the differences in the sandstone specimen after the hydro-thermal cycling treatment can be attributed to the ablation effect verified by the microscope. This difference may be the main reason for the different mechanical properties of the specimen under different treatment conditions. Of course, more work is needed to be done for exploring the complicated mechanism and physical and mechanical properties of rocks under hydro-thermal conditions.

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CONFLICT OF INTEREST

The authors declared that they have no conflicts of interest in this work. We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

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