Effect of heat exposure on anisotropic mechanical properties of host rock in the Tamusu pre-selected area for high-level radioactive waste disposal in China

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Abstract: As a typical sedimentary rock, clay rock with bedding structure shows clear anisotropy in its mineral composition and mechanical properties. When the clay rock is selected as the host rock for a high-level radioactive waste (HLW) geological repository, its temperature rises because of the continuous release of heat by the HLW. To examine the influence of temperature on the anisotropic mechanical properties of clay rock in the Tamusu pre-selected area for HLW repository in China, a series of direct shear tests in different directions were conducted on the Tamusu clay rock exposed to a range of temperatures. The microstructural characteristics were observed by scanning electron microscopy, and the morphology of the shear failure surface was analyzed with the help of 3D laser scanning. The results show that the shear strength parameters of specimens sheared perpendicular to the bedding plane were significantly higher than those of specimens sheared parallel to the bedding plane, and the former specimens exhibited a more rugged failure surface. Strength of both types of specimens increased with the increase in temperature from 30°C to 200°C because of water evaporation and mineral expansion. The mechanical anisotropy was also enhanced by heat exposure. These findings provide key information for the site characterization of the HLW repository, and a reference for the design and construction of underground engineering structures in layered clay rock.

1. Introduction
Deep geological repository is an internationally recognized solution for the safe disposal of high-level radioactive waste (HLW). Among the main types of repository host rocks, clay rock has attracted attention in many countries because of its wide prevalence, low permeability, good self-healing, and strong nuclide adsorption. France, Switzerland, and Belgium have selected clay rock as the host rock of repositories. However, the excavation damage zone and the tunnel stability will be affected by the strong mechanical anisotropy induced by the bedding structure during the construction of the repository[1]. In addition, the temperature of the repository host rock will increase, because of the decay of the radioactive waste. The microstructure and mechanical properties of clay rock are more sensitive to temperature variations of this intensity when compared to the granitic rock[2]. For example, the excessive pore pressure induced by heating affected the stability of the host rock of the Belgian
underground laboratory HADES, as did the variation of effective stress caused by thermal expansion\textsuperscript{[3]}. The temperature changes also affect the anisotropic response related to the deformation of bedding planes\textsuperscript{[4]}. The mechanical anisotropy and thermal effect of clay rock have widely been researched. For the Opalinus Clay, the preferred host rock of the Swiss HLW repository, Favero et al.\textsuperscript{[5]} investigated the anisotropic hydro-mechanical behavior through triaxial tests. Bertrand and Collin\textsuperscript{[6]} proposed an elasto-plastic constitutive modal considering the anisotropic behavior of this sedimentary rock. Chen et al.\textsuperscript{[7]} properly described the coupling between the inherent and induced anisotropies of sedimentary rocks using a fabric tensor and a discrete thermodynamic approach. Ajalloeian and Lashkaripour\textsuperscript{[8]} obtained the anisotropic strength ratio of mudrocks via uniaxial compression tests. Luo and Wang\textsuperscript{[9]} observed changes in rock structure and mechanical characteristics of coal seam mudstone samples from Inner Mongolia in a high-temperature environment, and found that high temperature causes thermal expansion of mudstone, which increases with temperature, as do the peak strength and elastic modulus. Zhang et al.\textsuperscript{[10]} also arrived at the same conclusion through high-temperature uniaxial compression tests, i.e., the increase of temperature limited to 400°C enhances the ability to resist deformation. It was also observed by SEM that as the temperature increased up to 200°C, the thermal expansion shrank the primary pores, or even closed them completely\textsuperscript{[11]}. With the help of SEM, Kim and Jeon\textsuperscript{[12]} identified the mechanism responsible for the change of friction angle of a rock discontinuity. Wang et al.\textsuperscript{[13]} studied the mechanical behavior of mudstone at the scale of their composite microstructure by conducting in-situ uniaxial compression tests in an environmental scanning electron microscopy (ESEM) chamber.

In China, geological, social, and economic considerations are key factors to prospect and compare the potential sites of HLW repositories. In this paper, we focused on the clay rock in the Tamusu area in Inner Mongolia Autonomous Region, one of the preferred areas for HLW disposal in China. Considering its anisotropic microstructural characteristics, such as the mineral composition and bedding structure, we mainly studied the effect of heat exposure on its shear properties.

2. Direct shear tests on anisotropic clay rock considering heat exposure effects

2.1. Basic information of clay rock from the Tamusu area

The clay rock in this study was taken from a borehole (103.2830 N, 40.3849 E) drilled in the north of the Yingejing depression in the Bayin Gobi Basin, with a buried depth of 514-531 m. According to the microscopic examination and X-ray diffraction analysis, the core samples were mainly composed of quartz, dolomite, and clay minerals (Table 1), most of which had particle size less than 0.063 mm. It had obvious thin parallel beddings, in which the dark part was dominated by clay minerals, such as illite and iron oxides, while the light part by quartz, mica, and feldspar ditritus. It is speculated that the clay rock was not affected by tectonic stress during the diagenetic period, for the parallel interbeds were intact.

| Table 1. Overall mineral composition of clay rock samples. |
|----------------------------------------------------------|
| Quartz (%)      | K-feldspar (%) | Plagioclase (%) | Mica (%) | Calcite (%) | Dolomite (%) | Pyrite (%) | Clay minerals and other complex bases (%) |
|-----------------|----------------|-----------------|----------|-------------|--------------|-----------|------------------------------------------|
| 9.8             | 2.4            | 0.5             | 5.2      | 2.8         | 36.1         | 3.3       | 39.9                                     |

2.2. Test design

The temperature rise of the HLW repository host rock induced by radioactive waste decay and exothermic heat can reach 90°C. Therefore, four temperature levels of 30°C, 90°C, 150°C, and 200°C, respectively, were selected to study the effect of heat exposure on the mechanical properties of thin-bedded clay rock. The drill core was formed into cubes with a side length of 5 cm for the direct shear test. When preparing a sample, the deviation of the unevenness of the two opposite faces shall be
within ±0.05 mm, each face shall be perpendicular to the axis of the specimen, the two adjacent sides shall be perpendicular to each other, and the deviation shall be less than ±0.25°.

Firstly, the specimens were heated to a predetermined temperature in a muffle furnace at a rate of 0.5°C/min, and then cooled to room temperature naturally after holding the temperature for 5 hours. According to the test plan (Table 2), after the heat exposure the specimens were divided into two groups, one group to be sheared parallel to the bedding plane (Parallel Specimens), and the other group to be sheared perpendicular to the bedding plane (Vertical Specimens). Depending on the shear direction, the specimens were placed accordingly in the fixture and then the direct shear test started. The normal force was applied at the rate of 0.5 kN/s, and the tangential force was applied at the rate of 0.4 mm/min after the normal deformation stabilized and until the specimen was damaged. The test results are shown in Table 2.

### Table 2. Summary of test results after exposure to different temperatures.

| Exposure temperature (°C) | Shear direction                  | Shear strength (MPa) | Normal stress: 10 MPa | Normal stress: 15 MPa | Normal stress: 20 MPa |
|---------------------------|----------------------------------|----------------------|-----------------------|-----------------------|-----------------------|
|                           | Parallel to bedding plane        | 9.08                 | 12.20                 | 15.31                 |
|                           | Perpendicular to bedding plane   | 15.93                | 18.54                 | 19.14                 |
| 90                        | Parallel to bedding plane        | 10.55                | 14.92                 | 17.63                 |
|                           | Perpendicular to bedding plane   | 15.53                | 17.15                 | 21.38                 |
| 150                       | Parallel to bedding plane        | 11.36                | 15.99                 | 18.40                 |
|                           | Perpendicular to bedding plane   | 17.70                | 21.14                 | 24.92                 |
| 200                       | Parallel to bedding plane        | 14.13                | 18.38                 | 22.10                 |
|                           | Perpendicular to bedding plane   | 24.37                | 24.21                 | 32.93                 |

3. Effect of heat exposure on shear properties of clay rock

3.1. Shear strength

Shear strength is an intuitive parameter to characterize the ability of rock to resist shear sliding. The shear strength of Parallel Specimens and Vertical Specimens under different normal stresses after heat exposure is plotted in Figure 1. It can be seen that both the bedding structure and heat exposure had obvious influence on the shear strength of the specimens. The shear strength of Vertical Specimens is significantly higher than that of Parallel Specimen under the same conditions. However, both of them increase with the increase of temperature from 30°C to 200°C.
In Figure 1, the strength ratio of Parallel Samples to Vertical Samples under different normal stresses is drawn with a polygon line. The overall trend is that the shear strength ratio decreases with the increase in temperature. In other words, the difference between the shear strength of Parallel Specimens and Vertical Specimens becomes larger, which also means that the mechanical anisotropy of the thin-bedded clay rock is further increased by heat exposure.

### 3.2. Internal friction angle and cohesion

According to the Mohr-Coulomb law, the relationship between shear strength and normal stress fits a straight line. The internal friction angle and cohesion of Parallel Specimens and Vertical Specimens after heat exposure are shown in Table 3. The regularity of these two parameters is consistent with the shear strength. For the same exposure temperature, the internal friction angle and cohesion of Vertical Specimens are generally higher than those of Parallel Specimens. With the increase in temperature, the internal friction angle and cohesion of Parallel Specimens increase gradually. For Vertical Specimens, the cohesion also increases gradually, while the internal friction angle first decreases and then increases, reaching a minimum value of 34.83° at 90°C, and a maximum value of 40.40° at 200°C.

**Table 3.** Strength parameters of different types of specimens after heat exposure.

| Exposure temperature (°C) | Specimen type     | Friction angle (°) | Cohesion (MPa) | R²      |
|---------------------------|-------------------|-------------------|----------------|---------|
| 30 | Parallel Specimens | 31.95             | 2.90            | 0.998   |
|  | Vertical Specimens   | 37.72             | 7.74            | 0.929   |
| 90 | Parallel Specimens | 34.83             | 3.87            | 0.959   |
|  | Vertical Specimens   | 30.39             | 9.24            | 0.883   |
| 150 | Parallel Specimens  | 35.14             | 4.69            | 0.935   |
|  | Vertical Specimens   | 35.57             | 10.54           | 0.998   |
3.3. Effect of heat exposure on microstructure of clay rock

To explain the effect of thin-bedding structure and heat exposure on the shear resistance of the Tamusu clay rock, core samples at 523.5 m depth of the same borehole were taken, and their microstructural characteristics were observed by SEM. Because of the change of sedimentary environment, the banded bedding plane shown in Figure 2 formed during the diagenetic period. There were obvious differences in the mineral composition and cementation degree between the two sides of the bedding plane. This kind of structural discontinuity has usually weak mechanical properties. Consequently, Parallel Specimens were more likely to shear along the bedding plane, while Vertical Specimens sheared only when the cementation in each layer was destroyed, exhibiting an overall failure at a higher shear strength.

|          | Parallel Specimens | Vertical Specimens |
|----------|--------------------|--------------------|
| 200 μm   | 38.59              | 40.40              |
| 100 μm   | 6.21               | 14.39              |
| 50 μm    | 0.997              | 0.491              |

Subsequently, the samples were exposed to heat in the same way as the shear specimens at temperatures of 150°C and 200°C, and typical micro-regions were selected for comparison, as shown in Figure 3. The results show that when the temperature was lower than 200°C, the change in microstructure was mainly reflected in the contact between mineral particles. As shown in the upper right corner of Figure 3 (a), the original microcracks were gradually closed due to thermal expansion of mica, or the layered structure inside mica was broken and rough fracture appeared due to the expansion of other adjacent minerals, as shown in the upper middle part of Figure 3 (b). As for the minerals themselves, quartz, dolomite, and feldspar were almost unaffected, while organic matter decomposed slightly under high temperature, which shows as widening of the existing fractures in Figure 3 (c).
Figure 3. SEM observations of thermally induced microstructure changes in Tamusu mudstone exposed to different temperatures (left column - 30℃, middle column - 150℃, right column - 200℃).

From the SEM images, we can infer that with the increase in temperature, the microcracks and micropores of natural rock samples, as well as water and gas stored on the surface of mineral particles gradually evaporated, reducing or eliminating the lubrication effect on the relative sliding of mineral particles, and improving cohesion. However, the thermal expansion promoted the closure of primary microcracks, increased the contact area between mineral particles, and improved the friction characteristics. This is consistent with the research results of Zhang et al.[10], however, the shear properties of Parallel Specimens were still largely controlled by the bedding plane, so the enhancement of Vertical Specimen strength by heat exposure was more obvious.

4. Comparison of failure modes of anisotropic clay rock

The shear direction has a significant effect on the failure mode of clay rock. Figure 4 shows the shear failure patterns of Vertical Specimens and Parallel Specimens under different normal stresses after heat exposure at 200℃. It can be seen that a relatively gentle and smooth main crack developed along the bedding plane in Parallel Specimens, while the main crack in Vertical Specimens exhibits a jagged shape, because of the limiting effect of the bedding plane on shear crack growth[14], with many wing cracks parallel to it.

Further, the morphology of the shear section of each specimen was analysed. Considering the three-dimensional characteristics of the structural plane, Belem et al.[15] proposed parameter $Z_2S$ to characterize the roughness, which represents the root mean square of the slopes of the elementary surfaces that make up the entire surface. The approximate calculation formula is as follows:

$$Z_2S = \left\{ \frac{1}{(N_x-1)(N_y-1)} \left[ \frac{1}{\Delta x^2} \sum_{i=1}^{N_x-1} \sum_{j=1}^{N_y-1} \frac{(z_{i+1,j+1}-z_{i,j+1})^2+(z_{i+1,j}-z_{i,j})^2}{2} \right] + \frac{1}{\Delta y^2} \sum_{j=1}^{N_y-1} \sum_{i=1}^{N_x-1} \frac{(z_{i+1,j+1}-z_{i,j+1})^2-(z_{i+1,j}-z_{i,j})^2}{2} \right\}^{1/2}$$

(1)

where $N_x$ and $N_y$ are the numbers of points along the x-axis and y-axis, respectively, $\Delta x$ and $\Delta y$ are the sampling steps along the x-axis and y-axis, respectively, and $z_{ij} = z(x_i, y_j)$. 
Figure 4. Shear failure patterns of Vertical Specimens and Parallel Specimens exposed to 200°C under different normal stresses: (a) 20 MPa, (b) 15 MPa, and (c) 10 MPa.

Figure 5. Contour map and parameter $Z_{2S}$ of shear surfaces of Vertical Specimens and Parallel Specimens exposed to 200°C and under different normal stresses.
Based on the point-cloud data of the shear sections obtained by 3D laser scanning, parameter $Z_{2S}$ of the shear surfaces of the six tested specimens were calculated, and are shown in Figure 5, together with contour maps. Corresponding to the higher shear strength, $Z_{2S}$ of Vertical Specimens shear surfaces are significantly higher than those of Parallel Specimens, and the differences in height of the shear surfaces is more than 14 mm. The contour lines are generally distributed in a strip shape, which is consistent with the bedding plane being sheared. There are also scarps on the edge of the specimens. However, the height differences of Parallel Specimens shear surface are less than 10 mm. The contour distributions are sparse, and the shear surfaces are gentle and smooth.

5. Conclusions

In addition to obtaining the shear strength parameters of the clay rock from the Tamusu area, one of the preferred area for a HLW disposal repository in China, this study focused on the effect of heat exposure on the anisotropic mechanical properties of the clay rock through direct shear tests, and revealed its micro-mechanisms by SEM. The main conclusions can be summarized as follows:

(1) Due to the relatively loose cemented structure of the bedding plane with weak shear resistance of the clay rock, the shear strength along the bedding plane is significantly lower than that perpendicular to the bedding plane, and the shear failure plane is gentler and smoother.

(2) In the temperature range from 30°C to 200°C, the effect of heat exposure on clay rock is mainly evaporation and expansion. Both water evaporation and mineral expansion enhance the friction between mineral particles, thus improving the shear strength parameters of the clay rock. These effects are more obvious in the same bedding than between two sides of bedding, so the increase in temperature further enhanced the anisotropy of the mechanical properties of the clay rock.

Acknowledgments

The work presented in this paper was supported by the National Natural Foundation of China under Grant No. 41702344, and the Scientific Research Project for Young Talents of China National Nuclear Corporation “Study on prediction technology of host rock crack propagation in multi-field coupled environment of high-level radioactive waste repository”.

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