Research Article

The Research on Strength and Deformation Behaviors of Buffer/Backfill Material under High-Temperature and High-Pressure Conditions

Hao Chen,1,2,3 Hai-Bo Lv,3 Zheng-han Chen,4 and Yu-han Li1,2

1Geotechnical Engineering Department, Nanjing Hydraulic Research Institute, Nanjing, Jiangsu Province 210024, China
2College of Civil and Transportation Engineering, Hohai University, Nanjing 210028, China
3College of Civil Engineering, Guangxi University, Nanning 530004, China
4Department of Architecture & Civil Engineering, LEU, Chongqing 401311, China

Correspondence should be addressed to Hai-Bo Lv; lhb@glut.edu.cn

Received 26 May 2018; Revised 8 October 2018; Accepted 4 November 2018; Published 23 January 2019

By using the high-temperature and high-pressure triaxial apparatus, 81 undrained triaxial shearing tests of GMZ bentonite were carried out, and the effects of temperature, confining pressure, water content, and dry density on the deformation and strength characteristics of GMZ bentonite were systematically analyzed. Five results are presented in this paper: (1) confining pressure and dry density have a great influence on the failure forms of GMZ bentonite; under the nonconfined pressure condition, the failure forms of the specimen are brittle failure, and it is the same with high dry density, but the specimens with low dry density and high confining pressure exhibit plastic failure; (2) the strength of GMZ bentonite decreases with increasing water content; the position of the deviator stress-axial strain curve under low dry density rises with the increase of temperature, whereas the location of the curve under high dry density decreases with the rise of temperature; (3) initial Young’s modulus rises with increasing temperature under low dry density, but it is on the contrary under high dry density; with rising water content, initial Young’s modulus generally decreases; (4) Poisson’s ratio rises with rising temperature. The effect of dry density and water content on Poisson’s ratio is insignificant; and (5) the formulae of cohesion and internal friction angle of GMZ bentonite with the changing dry density, water content, and temperature are proposed, respectively. The research results of this paper provide a scientific basis for analyzing the thermo-hydro-mechanical coupling characteristics of buffer materials.

1. Introduction

With the continuous development of China’s nuclear industry, the stock of spent fuel in the nuclear power station is becoming larger and larger, which has become the main source of high-level radioactive waste in China [1]. Deep geological disposal of radioactive waste in spent fuel is considered worldwide as the best way to protect human beings and the environment. The bentonite is considered as the ideal buffer/backfill material to fill the gap between bedrock and packaging container which contains the radioactive waste. Over the past few decades, a number of research studies have been done on the behaviors of bentonite at room temperature. The swelling behaviors and unconfined compression performance of GMZ bentonite have been studied by Liu et al. [2, 3]. Wang et al. [4] conducted a series of gas permeability tests on compacted bentonite-sand mixture samples with different dry densities, water contents, and sand-mixing rates and obtained the law of gas permeability under different conditions. Shen et al. [5, 6] studied the uniaxial and triaxial compression and permeability behaviors of high-compacted bentonite under different water contents. Ye et al. [7] and Chen et al. [8] studied the one-dimensional swelling behaviors of high-compacted GMZ bentonite and the effect of salt solution on it. The heat conduction, hydraulic conductivity, mechanical properties, and swelling behaviors with different dry densities of GMZ bentonite were studied by Wen et al.
Advances in Civil Engineering

2 Advances in Civil Engineering

Qin et al. [11] studied the three-dimensional swelling pressure of Gaomiaozui sodium bentonite GMZ001 under different initial dry densities and suction. Sun et al. [12] studied the three-dimensional swelling pressure of the bentonite-sand mixture under different dry densities and sand contents. Anisotropy of swelling pressure is observed in the mixture. Meanwhile, an empirical model of three-dimensional swelling pressure of the bentonite-sand mixture was obtained through fitting. Hoffmann et al. [13, 14] presented the characteristic of hydromechanical behaviour of compacted pellet’s mixtures of bentonite used in the engineered barrier (EB) experiment.

Due to the high-level radioactive waste continuing to generate heat and the deep buried depth, the temperature which bentonite suffers will be as high as 100°C [15]; when the bentonite is immersed in groundwater, it will generate an expansion pressure up to 2 MPa [16]. In this complex environment, the behaviors of bentonite are different from those at room temperature. Therefore, it is necessary to study the thermodynamic properties of bentonite under high-temperature and high-pressure conditions, and some researchers have begun to do it. The research on the water retention characteristic of compacted GMZ bentonite at cyclic changing temperatures has been done by Lu et al. [17]. The thermal expansion coefficient of compacted buffer/backfill materials was determined by Cui et al. [18], and the effects of temperature and suction on the compression deformation parameters have been discussed; the thermal pressurization occurring around the galleries and the mechanical and thermal hardening are however observed. Delage et al. [19], Delage [20], and Ye et al. [21, 22] studied the effects of the temperature and pH value on the swelling pressure and saturated hydraulic conductivity of compacted GMZ bentonite. Romero et al. [23] investigated the volume change behaviour of the soils during suction reduction paths at different temperatures and during heating-cooling cycles at constant water content or suction. But there is still a lack of systematic research on the strength and deformation behaviors of GMZ bentonite under high-temperature and high-pressure conditions. In this paper taking GMZ001 bentonite as the study object, by using a high-temperature and high-pressure geotechnical triaxial apparatus developed by the Institute of Logistics Engineering, the corresponding law has been revealed through the undrained triaxial test with temperature controlled on the deformation and strength behaviors of the bentonite.

2. Experimental Investigation

2.1. Test Apparatus and Calibrations. The test instrument is a high-temperature and high-pressure triaxial test apparatus, developed independently by the Institute of Logistics Engineering. This is the first self-developed high-temperature and high-pressure geotechnical triaxial test apparatus in China. It is composed of the platform, pressure chamber, constant temperature box, stepping motor, pressure-volume controller, suction control device, and data collector. The apparatus is shown in Figure 1. The pressure chamber and bench are made of special alloy and have been placed in a specially designed constant temperature box; the diameter of the pedestal at the bottom is 39.1 mm, and the cross-sectional area of it is 12 cm²; the constant temperature box can be heated from the left side; on the bottom, it has the stainless steel plate; it provides the convenience for laying the triaxial test apparatus, and the temperature can be up to 350°C. The GDS pressure-volume controller is directly connected to the pressure chamber by injecting water into it to apply constant confining pressure, the maximum confining pressure can be applied up to 3 MPa, and the volume change of the sample can be calculated by measuring the volume change of the water in the pressure chamber through the GDS pressure-volume controller. The measuring accuracy of volume strain is 1 mm³. It has a high measurement accuracy (interface 16 in Figure 1(a) is connected to interface 22 in Figure 1(b)). Axial pressure is applied by the stepping motor and axial loading piston, and it can also be applied by the GDS volume-pressure controller. The measuring accuracy of the pressure is 1 kPa.

Since the temperature and confining pressure will cause an initial volume change to the apparatus and the sample itself, before the test begins, the apparatus has been calibrated under different temperatures and confining pressures. When the volumetric strain reading no longer changed in 10 min, it was considered to be in a steady state. The volumetric strain in this time was called the final volumetric strain, and the specific calibration results are shown in Table 1.

2.2. Specimen Preparation. The soil sample used in the test is sodium bentonite (GMZ001) in GaoMiaoZi Village, Xinghe County, Inner Mongolia. The sample is light gray and white in colour. The basic physical properties of the sample are shown in Table 2. The composition and content of the exchangeable cation are shown in Table 3. The mineral composition is shown in Table 4. The data in Tables 2 and 3 are quoted from the study in [11], and the data in Table 4 are quoted from the study in [16].

At the beginning of the test, the bentonite was configured with the target water content by the water spray method; this specific method is carried out as follows: a certain amount of bentonite is weighed and its moisture content is measured; the quality of water needed for the target water content is calculated; after weighing it with the electronic balance, the water is filled into the sprayer; a layer of bentonite is sprinkled over the soil dish, and then water is sprayed above the bentonite evenly; the operations are repeated like this until the soil dish is filled up, and no water is sprayed on the last layer of soil. Using the plastic film to seal up the soil dish, the soil is mixed after 3 days, the mixture is sealed for 3 days, and then it can be used after mixing. The water content of bentonite at this time can be measured as the initial water content of the sample.

The amount of bentonite required for each sample is weighed during sample preparation, and the special mould is used to compact the soil with 5 layers, in order to make a good combination; the soil shall be chiseled between layers. The diameter of the sample is 39.1 mm, and the height is 80 mm.
According to Liu et al. [16], the dry density of compacted bentonite in the large-scale test of China’s high-level radioactive waste disposal is 1.6 g/cm³. In order to provide more data for future design of the buffer material, the initial dry density of the samples has been controlled to 1.4 g/cm³, 1.6 g/cm³, and 1.8 g/cm³, respectively. The initial water content is 5%, 15%, and 25%. The confining pressure is 0 kPa, 1000 kPa, and 2000 kPa. The temperature is 20°C, 50°C, and 80°C; by 4 factors intersecting each other, a total of 3 × 3 × 3 × 3 = 81 tests were carried out, and they all are unconsolidated and undrained triaxial shear tests.

2.3. Experimental Procedures. The permeability coefficient of unsaturated soil is far less than that of saturated soil, in order to make the pore pressure and suction in the soil more balanced; the usual shear rate is much lower than that of the saturated soil [24]. In consideration of the fact that there is no test procedure for unsaturated soil at present, in order to determine the appropriate shear rate, several tests of different shear rates must be done before the formal test to make a comparison and selection [24]. For this purpose, three experiments with different shear rates, namely, 0.011 mm/min, 0.015 mm/min, and 0.033 mm/min, were carried out, and the corresponding strain rates were 0.014%/min, 0.019%/min, and 0.041%/min. The result is shown in Figure 2. It can be seen from the diagram that although the shear rate is different, the stress-strain relationship curve and the peak value of the failure are basically the same for the same specimen, so it can be considered that the shear rate has little effect on the test results. According to this, the strain rate 0.041%/min is chosen to test. This shear rate is used in all tests in this paper. For the test of controlling temperature at 50°C and 80°C, the whole device should be preheated before the start of the test to ensure that the sample and its whole surroundings reach the specified temperature to start the test. According to actual measurements, heating up to 50°C requires 30 min or heating up to 80°C requires 1 h.

3. Experimental Results

3.1. Deviator Stress-Axial Strain. Figure 3 is a photograph of the soil sample’s typical failure. It can be seen that there are two failure forms of soil samples: one is the brittle failure, in which the soil has a distinct fracture surface, and the other is the plastic failure. The middle part of the soil sample bulged, and there is no fracture surface. Figures 4–6 show the deviator stress-axial strain curves of all specimens under different conditions. From the figures, the following can be seen:

(1) The confining pressure has a great influence on the shape of the curve. When there is no confining pressure, the deviator stress-axial strain curves of specimens all have a peak value, and the specimens show brittle failure.

(2) The dry density has a significant effect on the shape of the curve. When the dry density is lower (1.4 g/cm³ and 1.6 g/cm³) and the confining pressure is higher (1000 kPa and 2000 kPa), the specimen mainly shows plastic failure; when the dry density is higher (1.8 g/cm³), all the specimens show brittle failure regardless of the confining pressure, the temperature, and the water content.

(3) Temperature and water content have little effect on the failure form of specimens.

As shown in Figures 4–6, the dry density, moisture content, and temperature have a great influence on the deviator stress-axial strain relationship of the specimen: (1) when dry density is low (1.4 g/cm³ and 1.6 g/cm³), the position of the deviator stress-axial strain curve is corresponding to the temperature; that is, the higher the temperature, the higher the deviator stress-axial strain curve’s position. However, when dry density is high (1.8 g/cm³),
Table 4: Mineral compositions of GMZ001 bentonite (%).

<table>
<thead>
<tr>
<th>Sample name</th>
<th>Quartz</th>
<th>Feldspar</th>
<th>Cristobalite</th>
<th>Montmorillonite</th>
<th>Kaolinite</th>
<th>Calcite</th>
</tr>
</thead>
<tbody>
<tr>
<td>GMZ001</td>
<td>8.7</td>
<td>7.6</td>
<td>9.0</td>
<td>73.2</td>
<td>0.75</td>
<td>0.75</td>
</tr>
</tbody>
</table>

Figure 2: Stress-strain relationship curves of GMZ001 in different shear rate tests.

Figure 3: Typical failure forms of test samples of GMZ001. (a) Brittle failure. (b) Plastic failure.

Figure 4: Continued.
Figure 4: The relationship curves of $\sigma_1 - \sigma_3$ vs $\varepsilon_3$ and $\varepsilon_1$ vs $\varepsilon_3$ of the samples under the dry density of 1.4 g/cm$^3$ with different water contents, confining pressures, and temperatures. (a) $\rho_d = 1.4$ g/cm$^3$, $w = 5\%$, $\sigma_3 = 0$ kPa. (b) $\rho_d = 1.4$ g/cm$^3$, $w = 5\%$, $\sigma_3 = 1000$ kPa. (c) $\rho_d = 1.4$ g/cm$^3$, $w = 5\%$, $\sigma_3 = 2000$ kPa. (d) $\rho_d = 1.4$ g/cm$^3$, $w = 15\%$, $\sigma_3 = 0$ kPa. (e) $\rho_d = 1.4$ g/cm$^3$, $w = 15\%$, $\sigma_3 = 1000$ kPa. (f) $\rho_d = 1.4$ g/cm$^3$, $w = 15\%$, $\sigma_3 = 2000$ kPa. (g) $\rho_d = 1.4$ g/cm$^3$, $w = 25\%$, $\sigma_3 = 0$ kPa. (h) $\rho_d = 1.4$ g/cm$^3$, $w = 25\%$, $\sigma_3 = 1000$ kPa. (i) $\rho_d = 1.4$ g/cm$^3$, $w = 25\%$, $\sigma_3 = 2000$ kPa.

Figure 5: Continued.
Figure 5: The relationship curves of \((\sigma_1 - \sigma_3)/\varepsilon_v\) and \(\varepsilon_v\) of the samples under the dry density of 1.6 g/cm\(^3\) with different water contents, confining pressures, and temperatures. (a) \(\rho_d = 1.6\) g/cm\(^3\), \(w = 5\%\), \(\sigma_3 = 0\) kPa. (b) \(\rho_d = 1.6\) g/cm\(^3\), \(w = 5\%\), \(\sigma_3 = 1000\) kPa. (c) \(\rho_d = 1.6\) g/cm\(^3\), \(w = 5\%\), \(\sigma_3 = 2000\) kPa. (d) \(\rho_d = 1.6\) g/cm\(^3\), \(w = 15\%\), \(\sigma_3 = 0\) kPa. (e) \(\rho_d = 1.6\) g/cm\(^3\), \(w = 15\%\), \(\sigma_3 = 1000\) kPa. (f) \(\rho_d = 1.6\) g/cm\(^3\), \(w = 15\%\), \(\sigma_3 = 2000\) kPa. (g) \(\rho_d = 1.6\) g/cm\(^3\), \(w = 25\%\), \(\sigma_3 = 0\) kPa. (h) \(\rho_d = 1.6\) g/cm\(^3\), \(w = 25\%\), \(\sigma_3 = 1000\) kPa. (i) \(\rho_d = 1.6\) g/cm\(^3\), \(w = 25\%\), \(\sigma_3 = 2000\) kPa.

Figure 6: Continued.
it is the opposite of the above; that is, the higher the temperature, the lower the deviator stress-axial strain curve’s position. (2) When the dry density, the confining pressure, and the temperature are the same, by comparing the deviator stress-axial strain curve under different water contents, it can be found that the greater the water content, the lower the curve position and the smaller the strength.

With the increase of water content, the shear strength of the sample decreases. The variation laws of the deviatoric stress-axial strain curve caused by dry density are quite different at different temperatures; the reasons are quite complex, and they are discussed as follows: many scholars have noticed that the structure of water molecules near montmorillonite is disturbed in the study of bentonite. The water molecules in this state are different from free water, and they are adsorbed water in the adsorbed state of montmorillonite. The density of adsorbed water is as high as 1.4 g/cm³ or even 1.5 g/cm³ through molecular dynamics simulations and other macroscopic experiments. With the increasing dry density of soil samples, the density of adsorbed water also increased, and there is an exponential relationship between them [25]. On the contrary, Romero et al. and Carlsson [23, 26] noticed that increasing temperatures appear to generate structural disturbance of the interlayer water lattice in smectite clays, inducing aggregate contraction on heating due to a denser grouping of stacks of flakes and favouring the transition from adsorbed water to free water. Dumont et al. [27] found that heating would lead to the decrease of the attraction forces due to water menisci, resulting in the decrease of capillary stress and matrix suction. In addition, it was found that elevated temperatures will cause volumetric strains in soils, which depends on soil’s suction and OCR [19]. When the temperature rises to 80°C, high OCR and high suction will lead to an expansion strain and then decrease the dry density of the soil and low OCR will lead to a shrinkage strain and increase the dry density of the soil.

In summary, two opposite mechanisms can be considered when the temperature rises: (1) the hardening of the soil skeleton caused by the shrinkage of the aggregates during heating and the volume shrinkage caused by the aggregate contraction due to a denser grouping of stacks of flakes will increase the strength of the soil and (2) the decrease of matrix suction caused by the transition of adsorbed water to free water and the volume expansion caused by high OCR will lead to the decrease of soil strength. The two mechanisms controlled the variation of soil strength jointly.

When the dry density of bentonite is low, the amount of adsorbed water in soil is low and there are few free water molecules that can be released at high temperatures, so the decrease of attraction forces due to water menisci is not obvious and the matrix suction is not significantly reduced; on the contrary, the OCR of bentonite is close to 1. The volume shrinkage and hardening of the soil skeleton are the dominant factors. The above factors result in a slight increase of soil strength with rising temperature.

When the dry density of bentonite is high, the amount of adsorbed water in soil is high and there are a lot of free water molecules that can be released at high temperatures, so the decrease of attraction forces due to water menisci is obvious and the matrix suction is significantly reduced; at this time, the OCR of bentonite is much more larger than 1; rising temperature will lead to an expansion strain and then decrease the dry density of the soil. The above factors result in the decrease of soil strength with rising temperature.

3.2 Volumetric Strain. It can be seen from Figures 4 to 6 that dry density, temperature, confining pressure, and water content all have significant influence on the volumetric strain curve: (1) when the confining pressure is 0, the volumetric strain of all specimens generally shows shear contraction at normal temperature, but most of them show shear dilatancy at 50°C and 80°C. (2) Under high confining pressure (1000 kPa and 2000 kPa), the volumetric strain of the specimens is mainly shear contraction, which reflects the inhibition effect of confining pressure on dilatancy. (3) Under the same confining pressure, with the increase of temperature, the shear contraction of specimens decreased and some samples even showed dilatancy; the reason is related to the expansion of bentonite minerals at high

\[
(\sigma_1 - \sigma_3) \text{ (103 kPa)}
\]

\[
\varepsilon_a \text{ (%)}
\]

\[
\varepsilon_v \text{ (%)}
\]

**Figure 6:** The relationship curves of \((\sigma_1 - \sigma_3)\)~\(\varepsilon_a\) and \(\varepsilon_v\) of the samples under the dry density of 1.8 g/cm³ with different water contents, confining pressures, and temperatures. (a) \(\rho_d = 1.8 \text{ g/cm}^3, w = 5\%, \sigma_3 = 0 \text{ kPa}\). (b) \(\rho_d = 1.8 \text{ g/cm}^3, w = 5\%, \sigma_3 = 1000 \text{ kPa}\). (c) \(\rho_d = 1.8 \text{ g/cm}^3, w = 5\%, \sigma_3 = 2000 \text{ kPa}\). (d) \(\rho_d = 1.8 \text{ g/cm}^3, w = 15\%, \sigma_1 = 0 \text{ kPa}\). (e) \(\rho_d = 1.8 \text{ g/cm}^3, w = 15\%, \sigma_3 = 1000 \text{ kPa}\). (f) \(\rho_d = 1.8 \text{ g/cm}^3, w = 15\%, \sigma_3 = 2000 \text{ kPa}\). (g) \(\rho_d = 1.8 \text{ g/cm}^3, w = 25\%, \sigma_3 = 0 \text{ kPa}\). (h) \(\rho_d = 1.8 \text{ g/cm}^3, w = 25\%, \sigma_3 = 1000 \text{ kPa}\). (i) \(\rho_d = 1.8 \text{ g/cm}^3, w = 25\%, \sigma_3 = 2000 \text{ kPa}\).
temperatures and the release of free water. (4) For the soil samples with the same dry density, the higher the water content, the more likely the dilatancy at high temperatures. (5) When the dry density is low (such as 1.4 g/cm³), the sample has mainly shear contraction, while the sample with high dry density (such as 1.8 g/cm³) has mainly shear dilatancy.

3.3. Strength Parameter of Bentonite. According to different failure modes, different failure criteria were adopted, respectively. For brittle failure, take the stress corresponding to the peak point of the deviatoric stress-axial strain curve as the failure stress. For plastic failure, take the stress corresponding to the axial strain equal to 15% on the deviatoric stress-axial strain curve as the failure stress. The failure stress of all specimens is not listed separately due to the limits of space, and the details can be found in [28].

The destruction points of each specimen are drawn in the ($q_t$−$p_t$) plane, as shown in Figure 7. As can be seen from Figure 7, a group of destruction points at the same temperature generally falls on the same straight line and can be expressed by the following formula:

$$q_t = \xi' + p_t \tan \omega,$$

(1)

where $\xi'$ is the intercept of the straight line, which represents the destruction deviator stress of bentonite in the condition of no confining pressure (kPa), and $\tan \omega$ is the slope of the straight line, which represents the change rate of destruction stress with the confining pressure and is a dimensionless quantity. Using the least square method to fit the strength envelope, the values of $\xi'$ and $\tan \omega$ can be obtained.

The cohesion $c$ and internal friction angle $\phi$ of the soil can be calculated by the following formulae, respectively:

$$c = \frac{3 - \sin \phi \xi'}{6 \cos \phi},$$

(2)

$$\sin \phi = \frac{3 \tan \omega}{6 + 18 \omega} \tan \omega$$

(3)

As can be seen from Figure 7, the shear strength envelope and cohesion of specimens increased with the increase of temperature under the dry density of 1.4 g/cm³ and 1.6 g/cm³, but the shear strength envelope and cohesion of specimens decreased with the increasing temperature under the dry density of 1.8 g/cm³. Because the amount of adsorbed water that can be converted to free water is less at low dry density, it is not enough to offset the increase in shear strength of specimens caused by rising temperature. But when the density of adsorbed water is higher and the content of free water is also higher under high dry density, more free water can be converted at high temperatures. The decrease of matrix suction begins to dominate, which can offset or even exceed the increasing shear strength caused by rising temperature. Therefore, the cohesion of samples is decreasing with the increasing temperature under high dry density. All the strength envelopes are parallel to each other, indicating that temperature has little effect on the internal friction angle. When dry density and temperature are the same, the strength envelope of the sample decreases sharply with the increase of water content. Under the condition of constant water content and temperature, the higher the dry density, the stronger the shear strength of the specimen, and it is also consistent with the conclusion drawn from Section 3.1.

3.3.1. Cohesion of Bentonite. In order to find out the variation rule of cohesion and internal friction angle under different dry densities, water contents, and temperatures, the test data have been fitted, respectively. Taking the dry density of 1.4 g/cm³ as an example, first of all, the cohesion of specimens with different water contents and temperatures has been plotted in Figure 8, and the relationship between water content and cohesion has been fitted at the same temperature, as shown in Figure 8(a). Then, the relationship between cohesion $c$ and water content $w$ can be obtained as follows:

$$c = A + Bw + Cw^2.$$  

(4)

The parameters $A$, $B$, and $C$ at different temperatures are listed in Table 5. It can be seen from the table that, since the value of $B$ and $C$ is generally independent of temperature, they can be regarded as constants and their average values ($B = 11.58$ and $C = -0.47$) have been taken. The parameter $A$ varies greatly with temperature, and it can be fitted under different temperatures. The result is shown in Figure 8(b). It can be seen from the graph that the parameter $A$ varies linearly with temperature, and its rule can be described by the following formula:

$$A = 260.20 + 1.777T,$$  

(5)

where letter $T$ is the temperature and the unit is °C. Finally, taking $B = 11.58$ and $C = -0.47$ and substituting them into formula (4) with $A$, the following formula for cohesion changing with temperature and water content under the dry density of 1.4 g/cm³ is obtained:

$$c = 260.20 + 1.777T + 11.58w - 0.47w^2.$$  

(6)

The changing range of water content is 5%–25%, and the temperature range is 20°C–80°C. Similarly, the function for cohesion changing with temperature and water content under the conditions of dry density of 1.6 g/cm³ and 1.8 g/cm³ is also obtained as follows:

$$c = 319.65 + 1.927T + 29.76w - 1.06w^2,$$  

(7)

$$c = 1022.22 - 7.937T + 126.17w - 4.71w^2.$$  

(8)

By observing the expression of cohesion under different dry densities, it can be written in the same way as follows:

$$c = K_1 + K_2T + K_3w - K_4w^2.$$  

(9)

$K_1$, $K_2$, $K_3$, and $K_4$ were fitted again under different dry densities. They could be described by formulae (9), (10), (11), and (12), respectively:

$$K_1 = \exp(3.82 \rho_d),$$  

(9)

$$K_2 = -279.28 + 375.75 \rho_d - 125 \rho_d^2,$$  

(10)

$$K_3 = -4.96 \times 10^{-4} [1 - \exp(6.91 \rho_d)],$$  

(11)
K_4 = -1.50 \times 10^{-5} \left[ 1 - \exp(7.03 \rho_d) \right] \tag{12}

The cohesion of bentonite under different dry densities, water contents, and temperatures can be obtained by substituting $K_1$, $K_2$, $K_3$, and $K_4$ into formula (9), respectively. It can be seen from the above formula that the influence of temperature on the cohesion of bentonite is obvious. Based on the analysis of the shear strength envelope in Figure 7, the values of cohesion changing with temperature variation can be obtained, as shown in Table 6.

3.3.2. Internal Friction Angle of Bentonite. Take the case of dry density of 1.4 g/cm$^3$ as an example. The internal friction angle of specimens with different water contents and temperatures is plotted in Figure 9, and the relationship between internal friction angle and water content can be obtained as follows:
The parameters $D$ and $E$ at different temperatures are shown in Table 7. It can be seen from the table that, since the value of $D$ and $E$ is generally independent of temperature, they can be regarded as constants, their average values ($D \approx 11.58$ and $E \approx -0.47$) have been substituted into formula (13), and then the formula of internal friction angle changing with temperature and water content is obtained:

$$\varphi = D + Ew.$$  \hspace{1cm} (13)

where $w$ represents the water content and its unit is % and the range of variation is 5%–25%.

Equivalently, the formulae of internal friction angle changing with temperature and water content are obtained as follows:

$$\varphi = 38.92 - 0.96w,$$  \hspace{1cm} (14)

$$\varphi = 42.93 - 1.15w,$$  \hspace{1cm} (15)

By observing the formula of internal friction angle, it can also be written as follows:

$$\varphi = 38.92 - 0.96w,$$  \hspace{1cm} (14)

Table 5: The parameters’ value under different dry densities and temperatures.

<table>
<thead>
<tr>
<th>$\rho_d$ (g/cm³)</th>
<th>$T$ (°C)</th>
<th>Parameter A</th>
<th>Parameter B</th>
<th>Parameter C</th>
<th>Parameter $K_1$</th>
<th>Parameter $K_2$</th>
<th>Parameter $K_3$</th>
<th>Parameter $K_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.4</td>
<td>20°C</td>
<td>296.59</td>
<td>11.49</td>
<td>-0.44</td>
<td>260.20</td>
<td>1.77</td>
<td>11.58</td>
<td>0.47</td>
</tr>
<tr>
<td></td>
<td>50°C</td>
<td>347.02</td>
<td>11.79</td>
<td>-0.47</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>80°C</td>
<td>402.99</td>
<td>11.46</td>
<td>-0.50</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.6</td>
<td>20°C</td>
<td>357.14</td>
<td>29.97</td>
<td>-1.06</td>
<td>319.65</td>
<td>1.92</td>
<td>29.76</td>
<td>1.06</td>
</tr>
<tr>
<td></td>
<td>50°C</td>
<td>418.07</td>
<td>29.18</td>
<td>-1.03</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>80°C</td>
<td>472.73</td>
<td>30.14</td>
<td>-1.09</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.8</td>
<td>20°C</td>
<td>870.21</td>
<td>125.40</td>
<td>-4.92</td>
<td>1022.22</td>
<td>-7.93</td>
<td>126.17</td>
<td>4.71</td>
</tr>
<tr>
<td></td>
<td>50°C</td>
<td>612.24</td>
<td>127.30</td>
<td>-4.76</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>80°C</td>
<td>394.21</td>
<td>125.82</td>
<td>-4.44</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 6: The cohesion change of GMZ001 bentonite with temperature variation.

<table>
<thead>
<tr>
<th>Cohesion changing ratio</th>
<th>20°C–50°C</th>
<th>20°C–80°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho_d = 1.4$ g/cm³; $w = 5%$</td>
<td>15.20% (342–394)</td>
<td>30.70% (342–447)</td>
</tr>
<tr>
<td>$\rho_d = 1.4$ g/cm³; $w = 15%$</td>
<td>12.73% (369–416)</td>
<td>25.20% (369–462)</td>
</tr>
<tr>
<td>$\rho_d = 1.4$ g/cm³; $w = 25%$</td>
<td>12.09% (306–343)</td>
<td>22.87% (306–376)</td>
</tr>
<tr>
<td>$\rho_d = 1.6$ g/cm³; $w = 5%$</td>
<td>12.08% (480–538)</td>
<td>23.95% (480–595)</td>
</tr>
<tr>
<td>$\rho_d = 1.6$ g/cm³; $w = 15%$</td>
<td>9.88% (567–623)</td>
<td>19.4% (567–677)</td>
</tr>
<tr>
<td>$\rho_d = 1.6$ g/cm³; $w = 25%$</td>
<td>13.54% (443–503)</td>
<td>21.44% (443–538)</td>
</tr>
<tr>
<td>$\rho_d = 1.8$ g/cm³; $w = 5%$</td>
<td>-17.83% (1374–1129)</td>
<td>-33.62% (1374–912)</td>
</tr>
<tr>
<td>$\rho_d = 1.8$ g/cm³; $w = 15%$</td>
<td>-11.74% (1643–1450)</td>
<td>-22.09% (1643–1280)</td>
</tr>
<tr>
<td>$\rho_d = 1.8$ g/cm³; $w = 25%$</td>
<td>-11.75% (927–818)</td>
<td>-18.01% (927–760)</td>
</tr>
</tbody>
</table>
\[ \varphi = \lambda_1 - \lambda_2 w, \]  

(16)

where \( \lambda_1 \) and \( \lambda_2 \) were fitted again under different dry densities as follows:

\[ \lambda_1 = 22.55 + 12.08 \rho_d, \]

\[ \lambda_2 = -0.66 + 1.15 \rho_d. \]

The internal friction angle under different dry densities, water contents, and temperatures can be obtained by substituting \( \lambda_1 \) and \( \lambda_2 \) into formula (16).

### 3.4. Young’s Modulus of Bentonite

The \( (\sigma_1 - \sigma_3) - \varepsilon_a \) relationship of the triaxial test can be approximately described by the following hyperbolic equation:

\[ \sigma_1 - \sigma_3 = \frac{\varepsilon_a}{a + b \varepsilon_a}, \]

(18)

It can be known after the transformation of coordinates that

\[ \frac{\varepsilon_a}{\sigma_1 - \sigma_3} = a + b \varepsilon_a, \]

(19)

where \( a \) is the reciprocal of initial Young’s modulus and \( b \) is the reciprocal of \( (\sigma_1 - \sigma_3)_{ult} \); \( (\sigma_1 - \sigma_3)_{ult} \) is the asymptotic value of principal stress difference. Plotting the \( \varepsilon_a/(\sigma_1 - \sigma_3) - \varepsilon_1 \) relation curves under different confining pressures, the values of \( a \) and \( b \) can be obtained by least square fitting and then the initial Young’s modulus can be obtained. Figure 10 is the relationship between initial Young’s modulus and temperature. Generally speaking, the initial Young’s modulus under the dry density of 1.4 g/cm\(^3\) and 1.6 g/cm\(^3\) increased with increasing temperature. But the initial Young’s modulus under the dry density of 1.8 g/cm\(^3\) decreases with increasing temperature. When dry density is the same, with the increasing water content, the initial Young’s modulus \( E_i \) of the sample is also decreasing.

### 3.5. Poisson’s Ratio of Bentonite

The specimens in the triaxial shear process are cylindrical, and their stress and deformation are axisymmetric, so the lateral strain can be determined as follows:

\[ \varepsilon_t = \frac{\varepsilon_y - \varepsilon_a}{2}, \]

(20)

where \( \varepsilon_a \) is the lateral strain, \( \varepsilon_y \) is the volumetric strain, and \( \varepsilon_a \) is the axial strain. The ratio of lateral strain to axial strain \( \mu_t \) is Poisson’s ratio, and the results are shown in Figure 11. It can be seen from the diagram that Poisson’s ratio of samples presents an increasing trend with the increase of
temperature. When the dry density is low (1.4 g/cm³ and 1.6 g/cm³), Poisson’s ratio decreased with the increasing confining pressure. But the phenomenon is not obvious under high dry density (1.8 g/cm³). It can be seen that dry density and moisture content have little effect on Poisson’s ratio.

4. Conclusions

Based on the high-temperature and high-pressure triaxial apparatus, a series of triaxial shear tests were carried out to study the thermodynamic properties of GMZ bentonite. The effects of temperature, water content, dry density, and confining pressure on the strength and deformation characteristics were analyzed systematically. The main conclusions are as follows:

1. The confining pressure and dry density have great influence on the failure modes of the GMZ bentonite, and the specimens without confining pressure all exhibit brittle failure. When the dry density is low and the confining pressure is high, the specimens exhibit mainly plastic failure, while the specimens exhibit brittle failure under high dry density.
The strength of GMZ bentonite decreases with the increasing water content. The influence of temperature and dry density on its strength is complex; the position of deviator stress-axial strain curves is rising with the increase of temperature under low dry density, but it is on the contrary under high dry density. The reason is that the adsorbed water in bentonite gradually transforms into free water at high temperatures, resulting in the decrease of matrix suction. When the strength reduction caused by the decrease of matrix suction is enough to offset the increase of shear strength brought by temperature, the shear strength of specimens decreases with the increasing temperature.

The formulae of cohesion and internal friction angle of GMZ bentonite changing with dry density, water content, and temperature were established, respectively.

In general, the initial Young’s modulus increases with the increasing temperature when dry density is low, while under high dry density, it is the opposite. With the increasing water content, the initial Young’s modulus decreases.
(5) With the increase of temperature, Poisson’s ratio tends to increase slightly. The reason is that the adsorbed water with high density at high temperatures is converted into the free water with low density, and it caused the reduction of the shear shrinkage of the sample; some samples even show dilatancy, so Poisson’s ratio is also increasing. When dry density is low, Poisson’s ratio decreases with the increasing confining pressure, but this phenomenon is not obvious under high dry density. In general, dry density and water content have little effect on Poisson’s ratio.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Additional Points

Highlights. (i) Temperature-induced strength change of GMZ001 bentonite depends on dry density. (ii) Temperature has significant influence on volumetric strain. (iii) Confining pressure and dry density have significant influence on the failure form.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

The authors are grateful to the National Key Research and Development Program of China (No. 2017YFC0405100), the National Natural Science Foundation of China (Nos. 11672330, 11272353, 11072265, and 51879166), and the Technology Demonstration Project of Ministry of Water Resources (SF-201704).

References


