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## Thermal-mechanical behavior of compacted GMZ Bentonite

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► **To cite this version:**

Yu-Jun Cui, Anh Minh A.M. Tang, Li-Xin Qian, Wei-Min Ye, Bao Chen. Thermal-mechanical behavior of compacted GMZ Bentonite. *Soils and Foundations*, 2011, 51 (6), pp.1065-1074. hal-00655766

**HAL Id: hal-00655766**

**<https://enpc.hal.science/hal-00655766>**

Submitted on 2 Jan 2012

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1 disposal systems, large investigations are generally needed for a selected bentonite. The  
2 experiments in these investigations must cover various scales, from small-scale elementary  
3 laboratory tests through to mid-scale to large-scale tests in underground research facilities.  
4 Various reference bentonites have been studied in various countries for this purpose:  
5 Kunigel-V1 is used as the reference material for all the clay-based components in the  
6 repository concepts in Japan (Sugita et al., 2007); MX80 was used in the Swedish prototype  
7 repository project (Johannesson et al., 2007); the FoCa clay from the Paris Basin and the  
8 Serrata clay from Spain (which is equally known as the FEBEX bentonite (Lloret and Villar,  
9 2007) were considered in the RESEAL project performed in Belgium (Van Geet et al., 2007).

10 The preliminary long-term plan for the implementation of China's high-level radioactive  
11 waste repository (Wang et al., 2006) suggests that a high-level radioactive waste repository  
12 will be built in the middle of the 21<sup>st</sup> Century. In the Chinese concept of geological disposal,  
13 bentonite has been selected as the buffer/backfill material. The Gaomiaozi (GMZ)  
14 Na-bentonite taken from a large-scale deposit located in the North Chinese Inner Mongolia  
15 Autonomous Region (300 km northwest of Beijing) has been chosen for this purpose. After  
16 Wen (2006), preliminary research conducted on the swelling, mechanical, hydraulic, and  
17 thermal properties have shown that the GMZ bentonite is a good buffer/backfill material.  
18 Indeed, as reported by Wen (2006), it has relatively high thermal conductivity ( $K =$   
19  $1.51 \text{ W/mK}$  at a dry density of  $1.6 \text{ Mg/m}^3$  and a water content of 26.7%), quite low water  
20 permeability (at saturated state,  $k = 1.94 \times 10^{-13} \text{ m/s}$  at a dry density of  $1.6 \text{ Mg/m}^3$  and a  
21 temperature of  $25 \text{ }^\circ\text{C}$ ), a relatively high unconfined compression strength ( $1.74 \text{ MPa}$  at a dry  
22 density of  $1.6 \text{ Mg/m}^3$  and a water content of 23.6%), and quite a high swelling pressure  
23 ( $3.17 \text{ MPa}$  at a dry density of  $1.6 \text{ Mg/m}^3$ ). Chen et al. (2006) completed the experimental  
24 investigation by determining the water retention curves of the GMZ bentonite and showed its  
25 high retention capacity which is necessary for ensuring the containment function of the EBS.

26 Though sufficient preliminary experimental data have been obtained, allowing the  
27 candidature of the GMZ bentonite to be retained, there is still a great need of experimental  
28 data needed in terms of THM coupling behavior in order to confirm this candidature. In this  
29 regard, there have been some results allowing a relevant analysis. In one study, Ye et al. (2009)  
30 determined the unsaturated hydraulic conductivity of the GMZ bentonite under constant  
31 volume conditions and they observed a strong coupling between water flux and mechanical  
32 confining: the hydraulic conductivity determined was found first to decrease and then increase  
33 with decreasing suction. The decrease can be attributed to the large pore clogging due to soft  
34 gel creation by the exfoliation process. This coupling phenomenon was also observed on a  
35 mixture of the Kunigel-V1/Hostun sand (Cui et al. 2008). In the present work, a  
36 complementary study was performed to further investigate the coupled thermo-mechanical  
37 behavior of the GMZ bentonite. The suction-temperature controlled isotropic cell developed  
38 by Tang et al. (2007) was used for this purpose. The results obtained cover the swelling upon  
39 wetting, the volumetric changes upon heating, and the compressibility at controlled suction  
40 and temperature. Furthermore, the properties found for GMZ bentonite in this investigation  
41 were compared with those of other reference bentonites available in the literature.

42

## 1 **Materials and methods**

### 2 *Materials*

3 Table 1 presents the mineralogical properties of the GMZ bentonite, as well as other reference  
4 bentonites: the Kunigel-V1, FoCa, MX80 and FEBEX. These bentonites contain mainly  
5 montmorillonite, which is an essential mineral to ensure sealing properties. Beside the  
6 montmorillonite, there is quartz, which is also an important mineral for its particular influence  
7 on thermal conductivity (Tang et al., 2008b). Note that a high thermal conductivity of the  
8 engineered barrier allows the heat to dissipate quickly from the canisters, consequently  
9 reducing the maximum temperature in the EBS. This is one of the reasons why sand/bentonite  
10 mixtures are equally studied as buffer material in the repository concepts of Canada (Martino  
11 et al., 2007) and Japan (Sugita et al., 2007).

12 The physical properties of GMZ bentonite are presented in Table 2. Compared to other  
13 bentonites, GMZ bentonite has high montmorillonite content, which gives it a high Cations  
14 Exchange Capacity (CEC = 77.30 meq/100g), a large plasticity index ( $I_p = 275$ ), and a large  
15 specific surface area ( $S = 570 \text{ m}^2/\text{g}$ ). Note also that the main base cations are Na and Ca.

### 16 *Methods*

17 As mentioned previously, the present work aims at investigating the thermo-mechanical  
18 behavior of the GMZ bentonite. For the samples preparation, soil powder with an initial water  
19 content of 12.2% was firstly compacted in an isotropic cell under a static pressure of 30 MPa.  
20 The dry density after compaction was about  $1.70 \text{ Mg/m}^3$ . The compacted sample was then cut  
21 and machined to obtain smaller samples of size 80 mm diameter and 10 mm high. All the  
22 samples were then put in a sealed box with a relative humidity controlled by a saturated  
23 solution of  $\text{K}_2\text{CO}_3$  for about one week (see technical details in Delage et al., 1998). That  
24 permitted an initial suction of 110 MPa to be imposed on the samples. The soil volume  
25 changes during this suction initialization have been found to be negligible. That is in  
26 agreement with the water retention curve obtained by Chen et al. (2006), showing a suction of  
27 about 110 MPa at a water content of about 12% for a sample compacted to a dry density of  
28  $1.70 \text{ Mg/m}^3$ .

29 The isotropic cell developed by Tang et al. (2007), which enables the study of mechanical  
30 properties of compacted expansive soils using simultaneous control of suction and  
31 temperature, was used in the present work. The basic scheme of the cell is presented in Fig. 1.  
32 The soil specimen (80 mm in diameter and 10 mm high) was sandwiched between two dry  
33 porous stones, both of which were embedded in metallic plates. Small holes (2 mm diameter)  
34 were drilled in the lower plate, allowing the moisture exchange between the soil specimen and  
35 chamber below the lower plate. A glass cup containing an over-saturated saline solution was  
36 placed in the chamber to control the soil suction. A neoprene membrane (1.2 mm thick)  
37 covered the soil specimen and the two metallic plates, avoiding any exchange between the  
38 confining water in the cell and the soil pore water. A thermocouple installed inside the cell  
39 was used to monitor the cell temperature, which was considered equal to the temperature of  
40 the soil specimen during the test. The cell was immersed in a temperature-controlled bath  
41 within a temperature fluctuation of  $\pm 0.1 \text{ }^\circ\text{C}$ . A volume/pressure controller was used to apply  
42 the confining pressure in the cell. This volume/pressure controller was also used to monitor  
43

1 the volume change of the soil specimen through the volume change of the confining water in  
 2 the cell. During the test, volume and pressure readings of the volume/pressure controller as  
 3 well as the cell temperature were recorded by a computer.

4 Following the tests carried out by Tang et al. (2008a) on compacted MX80 bentonite,  
 5 thermal loadings were applied over a short duration of less than 24 h, and the soil suction was  
 6 assumed to remain unchanged within this short time. The soil suction was then equal to the  
 7 total suction imposed by the saturated salt solution. Tang and Cui (2005) measured the  
 8 suctions generated by saturated salt solutions at different temperatures, and these results were  
 9 applied in this investigation to determine the imposed suction at a given temperature. The  
 10 saturated salt solution, which filled the glass cup of the cell, was chosen according to the  
 11 desired values of suction and temperature during the test. Three suctions were considered: 9  
 12 MPa (KNO<sub>3</sub> at 25 °C and K<sub>2</sub>SO<sub>4</sub> at 60 °C); 39 MPa (NaCl at 25 °C and 60 °C); and 110MPa  
 13 (K<sub>2</sub>CO<sub>3</sub> at 25 °C, MgNO<sub>3</sub> at 60 °C).

14 For tests at suctions lower than the initial suction of 110 MPa, the total suction was  
 15 initially imposed outside the cell by putting the samples in a sealed box containing saturated  
 16 KNO<sub>3</sub> solution (9 MPa suction) or NaCl solution (39 MPa suction). The soil sample volume  
 17 change due to this suction decrease was monitored using a precision caliper. The mass of the  
 18 soil sample was determined every 3 days until it reached a stable value. The sample was  
 19 installed inside the isotropic cell only after this suction equilibrium process. Prior to the test,  
 20 the dimensions of the sample were adjusted to fit the required size (80 mm in diameter and 10  
 21 mm high).

22 A total of six tests were performed (T1 to T6) and their stress paths are presented in Table  
 23 3 and Fig. 2, in a space of total suction ( $s$ ), pressure ( $p$ ) and temperature ( $T$ ). During a  
 24 mechanical compression test the cell pressure was increased in steps from 0.1 to 0.2, 0.5, 1, 2,  
 25 5, 10, 20 and 50 MPa. The volume change of water in the volume/pressure controller was  
 26 recorded for each step. Calibration tests at various temperatures and pressures were performed  
 27 with a metallic specimen that had the same dimensions as the soil specimen. An example of  
 28 the determination of soil volume change for a loading step from 1 to 2 MPa (test T1) is shown  
 29 in Fig. 3. The deformation of the metallic specimen was assumed to be negligible within this  
 30 range of pressure (lower than 50 MPa) and the water volume change recorded during the  
 31 calibration corresponds mainly to the deformation of the cell and the tubing. The volume  
 32 change of the soil sample was then deduced from the difference between the calibration curve  
 33 and the curve from test, as depicted in Fig. 3. This volume change was used to calculate the  
 34 volumetric strain of the soil sample upon mechanical loading.

35 Fig. 4 shows the determination of the soil volume change during heating from 25 °C to  
 36 60 °C under a constant pressure of 0.1 MPa (test T4). Upon heating, the water in the cell  
 37 expanded and moved into the volume/pressure controller. According to Romero et al. (2005),  
 38 the thermal expansion coefficient of compacted expansive soil is approximately  $10^{-4} \text{ }^\circ\text{C}^{-1}$ ,  
 39 much higher than the metal specimen ( $10^{-6} \text{ }^\circ\text{C}^{-1}$ ) used for the calibration. Thus, it can be  
 40 reasonably assumed that the thermal expansion of the metal was negligible in comparison  
 41 with that of the soil. The soil volume change during heating can be then determined from the  
 42 difference between two curves obtained during the calibration and the test (Fig. 4a). In the  
 43 case of test T4 while heating from 25 to 60 °C, the soil volume increased by 310 mm<sup>3</sup> (Fig.  
 44 4b), which corresponds to a volumetric strain  $\varepsilon_v$  of -0.622%.

1

## 2 **Experimental results**

### 3 *Soil volume change during the initial humidification*

4 Fig. 5 shows a typical result of volumetric strain of the soil specimens due to wetting from the  
5 initial suction (110 MPa) to 39 and 9 MPa, as well as axial and radial strains. It can be seen  
6 that the radial strain is almost equal to the axial strain, showing isotropic behavior in the soil  
7 specimen. This observation is consistent with the procedure of compaction under isotropic  
8 pressure adopted for the specimen preparation. A similar observation was also made by Tang  
9 et al. (2008a). Furthermore, it can be noticed that the total volume of the soil specimen is  
10 increased by 32.9% when the suction is decreased to 9 MPa from 110 MPa.

11

### 12 *Volume change under thermal loading*

13 As shown in Fig. 2, the initial state was defined by zero pressure, 25 °C temperature and  
14 110 MPa suction. For test T4, the soil specimen in its initial state was confined to a pressure  $p$   
15 = 0.1 MPa, and heated to a temperature  $T = 60$  °C under  $p = 0.1$  MPa. For test T5, a decrease  
16 of suction from 110 to 39 MPa at  $T = 25$  °C was first undertaken during the initial wetting  
17 before the application of the confining pressure  $p = 0.1$  MPa; heating to  $T = 60$  °C then  
18 followed. For test T6, the soil specimen was wetted to a suction of 9 MPa and then loaded to  $p$   
19 = 0.1 MPa and heated to  $T = 60$  °C.

20 Fig. 6 shows the results for the thermal volume change under  $p = 0.1$  MPa. The results  
21 from tests T4 (110 MPa) and T5 (39 MPa) show that heating induces expansion and the  
22 coefficients of thermal expansion is  $\alpha = 2 \times 10^{-4}$  °C<sup>-1</sup>. On the contrary, the result from test T6 (9  
23 MPa) shows a volume decrease upon heating.

24

### 25 *Volume change under mechanical loading*

26 As shown in Fig. 2, the mechanical loadings in tests T1-T5 were performed at constant  
27 suction and temperature. Two temperatures (25 and 60 °C) and three suctions (110, 39 and  
28 9 MPa) were applied. The results (the void ratio  $e$  against the logarithm of pressure  $\log p$ ) for  
29 all these tests are presented in Fig. 7. The compressibility parameters, such as the yield  
30 pressure  $p_0$ , defined as the pressure at the intersection between the two quasi-linear segments,  
31 the elastic compressibility parameter,  $\kappa$ , which is related to the slope of small changes in the  
32 void ratio, and the plastic compressibility parameter,  $\lambda(s)$ , which is related to the slope of  
33 large changes in void ratio, can be determined from these curves. It is to be noted that the  
34 notations defined by Alonso et al. (1990) are adopted here for the compressibility parameters.

35 From Fig. 7a it can be observed that temperature increase from 25 °C to 60 °C raises the  
36 void ratio from 0.508 to 0.518 at a pressure of 0.1 MPa and constant suction of 110 MPa.  
37 Furthermore, there is no increase in the void ratio due to the temperature change after a  
38 pressure of 11 MPa. This indicates thermal expansion due to heating at low pressure which is  
39 consistent with the results shown in Fig. 6. The effect of heating on volume change is much  
40 smaller than the volume change under subsequent mechanical loading. This phenomenon can  
41 be observed again at constant suction of 39 MPa, as depicted in Fig. 7b. Heating from 25 °C  
42 to 60 °C slightly increased the void ratio  $e$  from 0.754 to 0.768. Again, the volume change due

1 to heating is small compared to that due to subsequent mechanical loading. When comparing  
 2 the compression curves of T2 (25 °C) and T5 (60 °C), it is observed that the difference is not  
 3 significant. Moreover, the shape of the compression curve is similar to that obtained for T1  
 4 and T4. At 9 MPa suction, only one loading test was performed (T3); a technical problem  
 5 occurred during test T6. The compression curve for test T3 is presented in Fig. 7c.

6 Though the temperature effects on  $\lambda(s)$  and  $\kappa$  are found to be negligible, this is not the  
 7 case for the suction effect. Indeed, Fig. 8 shows that  $\lambda(s)$  and  $\kappa$  increase significantly when the  
 8 suction is decreased. When the suction is decreased from 110 to 9 MPa,  $\kappa$  increases from  
 9 0.023 to 0.036 and  $\lambda(s)$  increases from 0.120 to 0.165. Fig. 9 shows the yield pressures  $p_0$   
 10 determined from Fig. 7 at various suctions and temperatures. It can be seen that  $p_0$  decreases  
 11 from 21 MPa at the initial suction  $s = 110$  MPa to 10 MPa at  $s = 39$  MPa and 2 MPa at  $s = 9$   
 12 MPa for the tests at 25 °C. As far as the temperature effect is concerned, at  $s = 110$  MPa,  
 13 heating from  $T = 25$  °C to 60 °C decreases  $p_0$  from 21 to 16 MPa. At  $s = 39$  MPa heating  
 14 decreases  $p_0$  from 10 to 7.3 MPa.

## 16 **Discussions**

17 In this section the thermo-mechanical behavior of the GMZ bentonite identified will be  
 18 discussed by comparing it with that of other reference bentonites (listed in Table 1) which  
 19 have been studied worldwide.

### 21 *Mineralogical properties*

22 Table 1 shows that the montmorillonite content of the GMZ bentonite is lower than that of the  
 23 MX80 bentonite and the FEBEX bentonite but it is higher than that of the Kunigel-V1  
 24 bentonite. The FoCa bentonite contains 80% of interstratified smectite/kaolinite. The quartz  
 25 content of the Kunigel-V1 and the GMZ bentonites is relatively high: 29-38% and 11.7%  
 26 respectively (smaller than 6% for the others). Good correlations can be established between  
 27 the montmorillonite content and the CEC values (Fig. 10a). Indeed, the higher the  
 28 montmorillonite content, the larger the CEC; the FEBEX bentonite with the highest  
 29 montmorillonite content has the largest values of CEC. The FoCa clay with an 80%  
 30 interstratified smectite/kaolinite content is not considered in these correlations. As far as the  
 31 other properties are concerned (Table 2), it seems that the specific surface area ( $S$ ), liquid  
 32 limit ( $w_L$ ) and the plasticity index ( $I_p$ ) are not directly related to the montmorillonite content  
 33 (Fig. 10b,c,d). For instance, the FEBEX bentonite with the highest montmorillonite content  
 34 has the smallest values of  $w_L$  and  $I_p$  while the MX80 bentonite (79% montmorillonite) has the  
 35 highest values of  $w_L$  and  $I_p$ . This shows that the montmorillonite content is not the only factor  
 36 which influences the basic geotechnical properties; other factors, such as the nature of the  
 37 base cations exchange (see Table 2), must play an important role also.

### 39 *Thermal conductivity*

40 Tang et al. (2008b) studied the thermal conductivity of the compacted MX80, FEBEX and  
 41 Kunigel bentonites. Tests on the compacted specimens having various dry densities (ranging  
 42 from 1.45 to 1.85 Mg/m<sup>3</sup>) and water contents show that the thermal conductivity of bentonites

1 is strongly dependent on these two parameters: at the same water content, the higher the density  
 2 the higher the thermal conductivity, and at the same dry density, the higher the water content,  
 3 the higher the thermal conductivity. After testing various models for predicting the thermal  
 4 conductivity, Tang et al. (2008b) found that a unique relationship can be established between  
 5 the thermal conductivity  $K$  and the air-pore volume fraction  $V_a/V$  for all these soils, as follows:

$$6 \quad K = \alpha(V_a/V) + K_{sat} \quad (1)$$

7 where  $\alpha$  is the slope of  $K - V_a/V$  plot;  $K_{sat}$  is the thermal conductivity at saturated state which  
 8 corresponds to the intersection of  $K - V_a/V$  plot with the  $K$  axis.

9 Fig. 11 shows the  $K - V_a/V$  plot for the compacted GMZ bentonite that was drawn using  
 10 data reported by Wen (2006). It can be seen that there is also a good linear relationship for this  
 11 bentonite. From Fig. 11 the parameters of Eq. [1] deduced are as follows:

$$12 \quad \alpha = -2.81 \text{ W/mK and } K_{sat} = 1.57 \text{ W/mK}$$

13 These values are slightly larger than those for other bentonites: FEBEX ( $\alpha = -2.29 \text{ W/mK}$   
 14 and  $K_{sat} = 1.30 \text{ W/mK}$ ), MX80 ( $\alpha = -1.79 \text{ W/mK}$  and  $K_{sat} = 1.1 \text{ W/mK}$ ), Kunigel V1  
 15 ( $\alpha = -2.36 \text{ W/mK}$  and  $K_{sat} = 1.39 \text{ W/mK}$ ). Even though relatively larger values of the  
 16 thermal conductivity at saturated state ( $K_{sat}$ ) for the GMZ and Kunigel-V1 bentonites can be  
 17 related to their higher quartz contents (see Table 1), it appears that the difference is too small to  
 18 allow establishing a relevant correlation. Further study is needed to clarify this phenomenon by  
 19 working on the different bentonites but using the same test protocol and measurement  
 20 technique.

### 21 *Swelling behavior*

22 Fig. 5 shows that for the GMZ bentonite compacted at  $1.70 \text{ Mg/m}^3$  of dry density (initial  
 23 suction of 110 MPa), wetting to suction at 9 MPa induced a swelling volumetric strain of  
 24 32.9%. The volumetric swelling strain of GMZ is plotted together with that of other soils in  
 25 Fig. 12. A higher value of 50% was obtained by Tang et al. (2008a) when wetting from a  
 26 suction of 110 MPa to 9 MPa the MX80 bentonite compacted at  $1.78 \text{ Mg/m}^3$  of dry density.  
 27 Delage et al. (1998) showed that wetting the compacted FoCa clay ( $1.85 \text{ Mg/m}^3$  of dry density,  
 28 initial suction of 110 MPa) to a suction of 9 MPa induced a volumetric strain of 17%. After  
 29 ENRESA (2000), wetting the FEBEX bentonite (initially compacted at  $1.67 \text{ Mg/m}^3$  of dry  
 30 density) from a suction of 110 MPa to a suction of 9 MPa induced a volumetric strain of 19%.  
 31 Kanno and Wakamatsu (1993) studied the volume change behavior of the compacted Kunigel  
 32 V1 (initially compacted at  $1.82 \text{ Mg/m}^3$  of dry density) and obtained a volumetric strain of  
 33 13% when wetting from 110 to 9 MPa suction. The comparison shows that the swelling  
 34 potential of the GMZ and the MX80 is higher than that of FoCa, Kunigel-V1 and FEBEX.  
 35 This is due to their montmorillonite contents (a higher montmorillonite content gives rise to a  
 36 higher swelling potential, see Marcial et al. 2002) and the nature of exchangeable basic  
 37 cations (Na-based bentonites show higher swelling potential than Ca-based bentonites, see  
 38 Marcial et al. 2002).

1 *Thermal-mechanical volume changes*

2 The coefficient of thermal expansion of the compacted GMZ bentonite deduced from Fig. 6 is  
 3  $2 \times 10^{-4} \text{ } ^\circ\text{C}^{-1}$  (mean value determined from the thermal expansion curve of tests T4 and T5).  
 4 Similar values were obtained for the compacted MX80 bentonite (Tang et al., 2008a) and the  
 5 compacted FEBEX bentonite (Romero et al., 2005). As far as the nature of the volume  
 6 changes upon heating is concerned, Tang et al. (2008a) observed that heating the compacted  
 7 MX80 bentonite under 0.1 MPa pressure gave rise to thermal expansion at high suctions (39  
 8 and 110 MPa) and to thermal contraction at a lower suction (9 MPa). The same phenomenon  
 9 was observed in the present work on the GMZ bentonite. This behavior was explained using  
 10 an elasto-plastic constitutive model proposed by Tang & Cui (2009). The thermal expansion  
 11 corresponds to an elastic behavior when the heating path remains in the elastic zone while the  
 12 thermal contraction corresponds to a plastic behavior when the heating path under constant  
 13 stress and suction touch the yield surface.

14 The compression curves obtained at controlled suction and temperature (Fig. 7) show an  
 15 elasto-plastic behavior with a clear change in slope. That allowed the determination of the  
 16 compressibility parameters:  $\kappa$ ,  $\lambda(s)$  and  $p_0$ . Similar observations were made by Tang et al.  
 17 (2008a) on the MX80 bentonite and by Lloret et al. (2004) on the FEBEX bentonite. The  
 18 plastic behavior in compacted soil is usually associated with the collapse of macro-pores that  
 19 can be evidenced by MIP (Mercury Intrusion Porosimetry) test as in the works of Lloret et al.  
 20 (2003), Tang & Cui (2009), and Tang et al. (2011). However, Cui et al. (2002) performed  
 21 suction-controlled isotropic compression tests on the highly compacted FoCa clay (compacted  
 22 initially at  $1.85 \text{ Mg/m}^3$  of dry density) and observed a reversible volume change behavior in a  
 23 range of pressures up to 60 MPa. The authors explained this by the absence of collapsible  
 24 macro-pores in this material. That means the volume change behavior of compacted clays can  
 25 be strongly dependent on the dry density; the higher the dry density (or the lower the volume  
 26 of macro-pores) the higher the yield stress. Note that the initial dry densities of bentonite in  
 27 other studies are lower than in Cui et al. (2000):  $1.70 \text{ Mg/m}^3$  for FEBEX bentonite in Lloret et  
 28 al. (2003);  $1.78 \text{ Mg/m}^3$  for MX80 bentonite in Tang & Cui (2009). In the study of Tang et al.  
 29 (2011), even at a high dry density of  $2.00 \text{ Mg/m}^3$ , the volume of macro-pores measured by  
 30 MIP tests is still high. It shows that isotropically compacting GMZ bentonite at 30 MPa  
 31 pressure (to a dry density of  $1.70 \text{ Mg/m}^3$ ) can not avoid macro-pores. Further study is  
 32 necessary to clarify this point.

33 The effects of suction and temperature on  $\kappa$  and  $\lambda(s)$  of GMZ bentonite are similar to that  
 34 of MX80:  $\kappa$  and  $\lambda(s)$  increase with the decrease of suction but are independent of the  
 35 temperature changes (between 25 and 60 °C). Lloret et al. (2004), however, observed that  
 36 both the increase of temperature and the decrease of suction induced an increase of  $\lambda(s)$  in  
 37 FEBEX bentonite. Comparing the values of  $\lambda(s)$ , GMZ bentonite shows the highest values:  $\lambda(s)$   
 38 = 0.12 – 0.16 at  $s = 9 - 110 \text{ MPa}$  for GMZ bentonite;  $\lambda(s) = 0.08 - 0.12$  at  $s = 9 - 110 \text{ MPa}$  for  
 39 MX80 bentonite;  $\lambda(s) = 0.065 - 0.080$  at  $s = 8 - 14 \text{ MPa}$  for FEBEX bentonite (from  
 40 suction-controlled oedometer tests by Lloret et al., 2003).

41 The effect of temperature on the yield stress  $p_0$  of GMZ bentonite and MX80 bentonite  
 42 (see Tang et al. 2008a) is similar; only a slight decrease of  $p_0$  was observed for high suction  
 43 values ( $s = 110$  and  $39 \text{ MPa}$ ). In contrast, for FEBEX bentonite, at  $s = 120 \text{ MPa}$ , Lloret et al.  
 44 (2004) showed that  $p_0$  decreased drastically from 20 MPa (at 20°C) to 3 MPa (at 50 °C).

1 In order to compare the effect of suction decrease on the yield stress, the results of three  
 2 bentonites (GMZ, MX80 and FEBEX) are plotted together in Fig. 13. At high suctions ( $s =$   
 3  $110 - 127$  MPa), the yield stresses of the three soils are close to 20 MPa. Upon wetting, the  
 4 yield stress decreases in similar pattern for GMZ bentonite and FEBEX bentonite but at a  
 5 lower rate than MX80 bentonite: at  $s = 9$  MPa,  $p_0$  of GMZ and FEBEX bentonites decreases  
 6 to 2 MPa while that of MX80 is much lower (0.38 MPa).

## 7 **Conclusions**

8  
 9 The thermo-mechanical behavior of GMZ bentonite, which has been selected as a possible  
 10 material for the engineered barriers in the high-level radioactive waste disposals in China, was  
 11 experimentally investigated. The results obtained were compared with other bentonites which  
 12 have been widely investigated as reference materials in the projects carried out in other  
 13 countries (MX80, FEBEX, FoCa, and Kunigel-V1). The following conclusions can be drawn  
 14 from the present study:

- 15 i) The montmorillonite content of GMZ bentonite is lower than that of MX80 bentonite  
 16 and FEBEX bentonite but it is higher than that of Kunigel-V1 bentonite. That explains  
 17 the large values of its cations exchange capacity (CEC) and specific surface area  $S$ . In  
 18 general, good correlations can be established between the montmorillonite content and  
 19 the CEC values or the specific surface area  $S$  (Table 2). Nevertheless, no direct  
 20 correlation can be made between the montmorillonite content and the basic geotechnical  
 21 properties; other factors, such as the nature of base exchangeable cations, also appear to  
 22 have a significant influence.
- 23 ii) The same observation has been made in terms of swelling potential. In general, the  
 24 higher the montmorillonite content, the higher the swelling potential. However, a  
 25 Ca-based bentonite generally shows lower swelling potential than a Na-based bentonite.  
 26 For GMZ bentonite it was observed that wetting (suction decreased from 110 to 9 MPa)  
 27 induced a swelling volumetric strain of 30%. That is lower than MX80 (50%) and  
 28 higher than that of other bentonites (less than 20%).
- 29 iii) The quartz content of GMZ bentonite is relatively high (11.7%) just behind Kunigel V1  
 30 bentonite (29-38%). This could explain their relatively large values of thermal  
 31 conductivity. Note that compared to the values for other bentonites, the difference is too  
 32 small to allow for a relevant correlation to be drawn between their thermal conductivity  
 33 and the quartz content.
- 34 iv) The coefficient of thermal expansion of the compacted GMZ bentonite is  $2.10^{-4} \text{ } ^\circ\text{C}^{-1}$ , that  
 35 is similar to the values obtained for the compacted MX80 bentonite (Tang et al., 2008a)  
 36 and the compacted FEBEX bentonite (Romero et al., 2005). As the compacted MX 80  
 37 bentonite, the GMZ bentonite also showed a thermal expansion upon heating at high  
 38 suctions (39 and 110 MPa) and a thermal contraction at lower suction (9 MPa).
- 39 v) The effect of suction and temperature on  $\kappa$  and  $\lambda(s)$  of GMZ bentonite is similar to  
 40 MX80:  $\kappa$  and  $\lambda(s)$  increase with decreasing suction but are independent of the  
 41 temperature changes. Compared to other bentonites, GMZ bentonite has the highest  
 42 values of  $\lambda(s)$ : 0.12 – 0.16 at  $s = 9 - 110$  MPa.

- 1 vi) The effect of temperature on the yield stress  $p_0$  of the GMZ bentonite has been found to  
 2 be insignificant. A similar observation was made for MX80 bentonite by Tang et al.  
 3 (2008a). In contrast, a significant suction effect was identified. As is also the case for  
 4 MX80 bentonite and FEBEX bentonite, the yield stress  $p_0$  of the GMZ bentonite  
 5 decreased significantly, at a rate similar to that of FEBEX bentonite but lower than that  
 6 of MX80 bentonite.  
 7

## 8 **Acknowledgements**

9 The authors are grateful to the National Natural Science Foundation of China (No 40728003  
 10 and No 41030748), Kwang-Hua Fund for College of Civil Engineering at Tongji University,  
 11 and Program for Changjiang Scholars and Innovative Research Team in University (PCSIRT,  
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24 **Table 1. Mineral composition of some bentonites**

Mineral	Kunigel V1 <sup>a</sup>	FoCa <sup>b</sup>	MX80 <sup>c</sup>	FEBEX <sup>d</sup>	GMZ <sup>e</sup>
Montmorillonite (%)	46-49	80% (interstratified smectite/kaolinite)	79	92±3	75.4
Plagioclase (%)	—	—	9.2	2±1	—
Pyrite (%)	0.5-0.7	—	0.-	0.02±0.01	—
Calcite (%)	2.1-2.6	1.4	0.8	Traces	0.5
Dolomite (%)	2.0-2.8	—	—	0.60±0.13	—
Gypsum (%)	—	0.4	—	0.14±0.01	—
Halite (%)	—	—	—	0.13±0.02	—
Analcite (%)	3.0-3.5	—	—	—	—
Mica (%)	—	—	<1	—	—
Feldspar (%)	2.7-5.5	—	2.0	Traces	4.3
Cristobalite (%)	—	—	—	2±1	7.3
Kaolinite (%)	—	4	—	—	0.8
Quartz (%)	29-38	6	2.8	2±1	11.7
Field organic	0.31-0.34	—	0.1	0.35±0.05	—

25 <sup>a</sup> JNC (2000); <sup>b</sup> Guillot et al. (2002); <sup>c</sup> Montes-H. et al.(2003); <sup>d</sup> ENRESA (2000); <sup>e</sup> Wen  
 26 (2006).

1 **Table 2. Physical properties of some bentonites**

Parameter	Kunigel V1 <sup>a</sup>	FoCa <sup>b</sup>	MX80 <sup>c</sup>	FEBEX <sup>d</sup>	GMZ <sup>e</sup>
particle < 2 $\mu$ m (%)	64.5	—	60	68	60
CEC(meq/100g)	73.2	54	82.3	102 <sup>j</sup>	77.30
Base cations exchange	Na-Ca	Ca	Na	Ca-Mg	Na-Ca
w <sub>L</sub> (%)	474	112	519	102	313
w <sub>P</sub> (%)	27	50	35	53	38
I <sub>P</sub>	447	62	484	49	275
$\rho_s$ (Mg/m <sup>3</sup> )	2.79	2.67	2.76	2.70	2.66
S (m <sup>2</sup> /g)	687	300	522	725	570

2 <sup>a</sup> Komine (2004); <sup>b</sup> Marcial et al. (2002); <sup>c</sup> Tang and Cui (2005); <sup>d</sup> ENRESA (2000); <sup>e</sup> Wen  
3 (2006).

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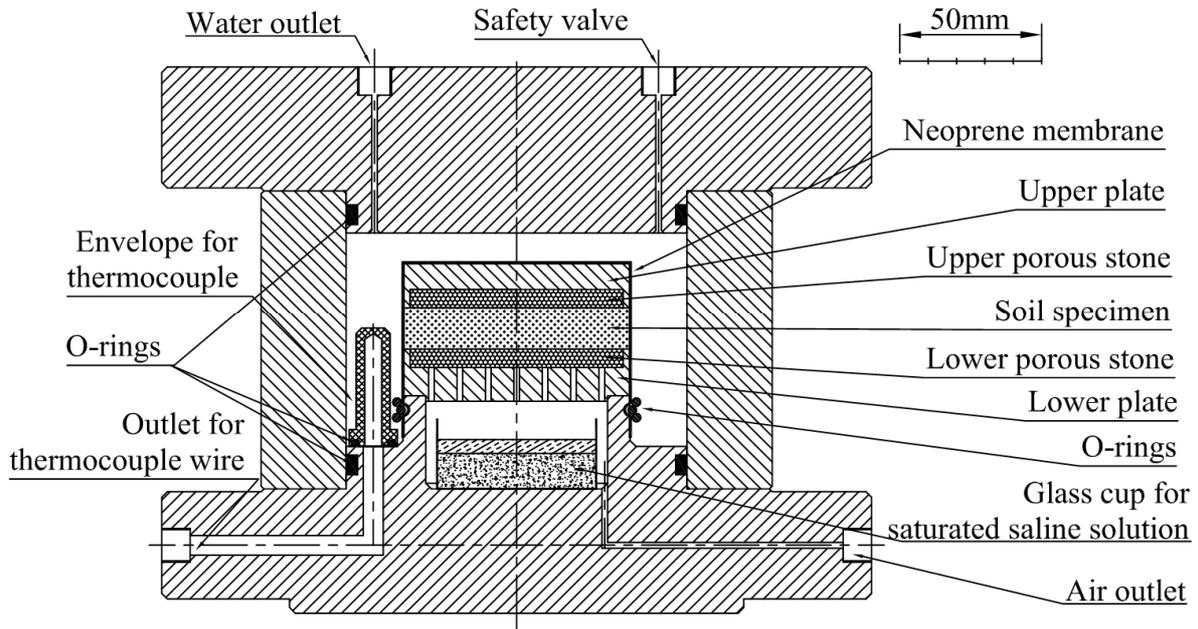
1 **Table 3. Stress paths of thermo-mechanical tests**

2

		T1	T2	T3	T4	T5	T6
Initial condition	$p$ : MPa	0	0	0	0	0	0
	$s$ : MPa	110	110	110	110	110	110
	$T$ : °C	25	25	25	25	25	25
Path I	$p$ : MPa	0.1	0	0	0	0	0
	$s$ : MPa	110	39	9	110	39	9
	$T$ : °C	25	25	25	25	25	25
Path II	$p$ : MPa	50	0.1	0.1	0.1	0.1	0.1
	$s$ : MPa	110	39	9	110	39	9
	$T$ : °C	25	25	25	25	25	25
Path III	$p$ : MPa		50	50	0.1	0.1	0.1
	$s$ : MPa		39	9	110	39	9
	$T$ : °C		25	25	60	60	60
Path IV	$p$ : MPa				50	30	30
	$s$ : MPa				110	39	9
	$T$ : °C				60	60	60

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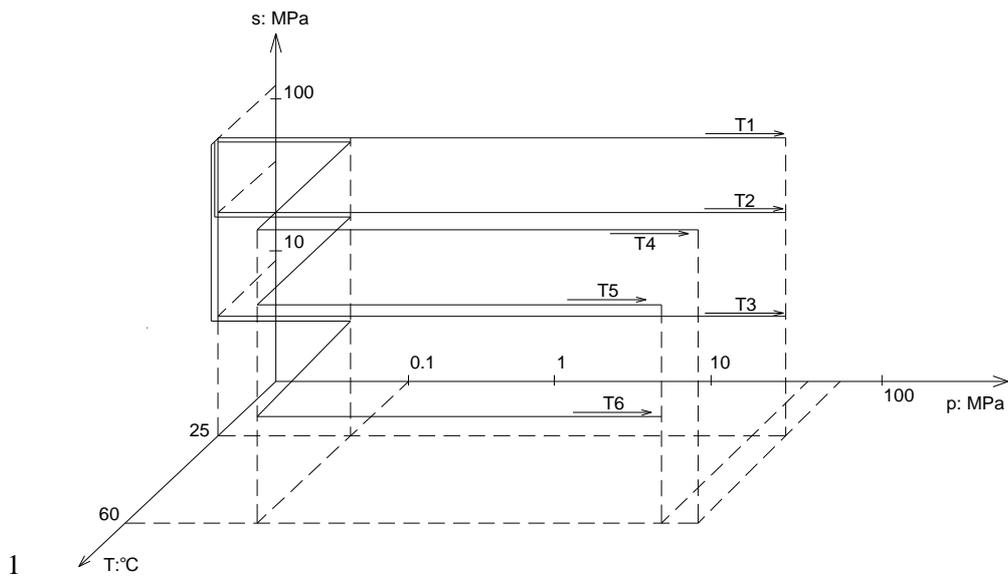
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6 **Fig. 1. Basic scheme of the suction-temperature controlled isotropic cell (after Tang et al., 2007)**

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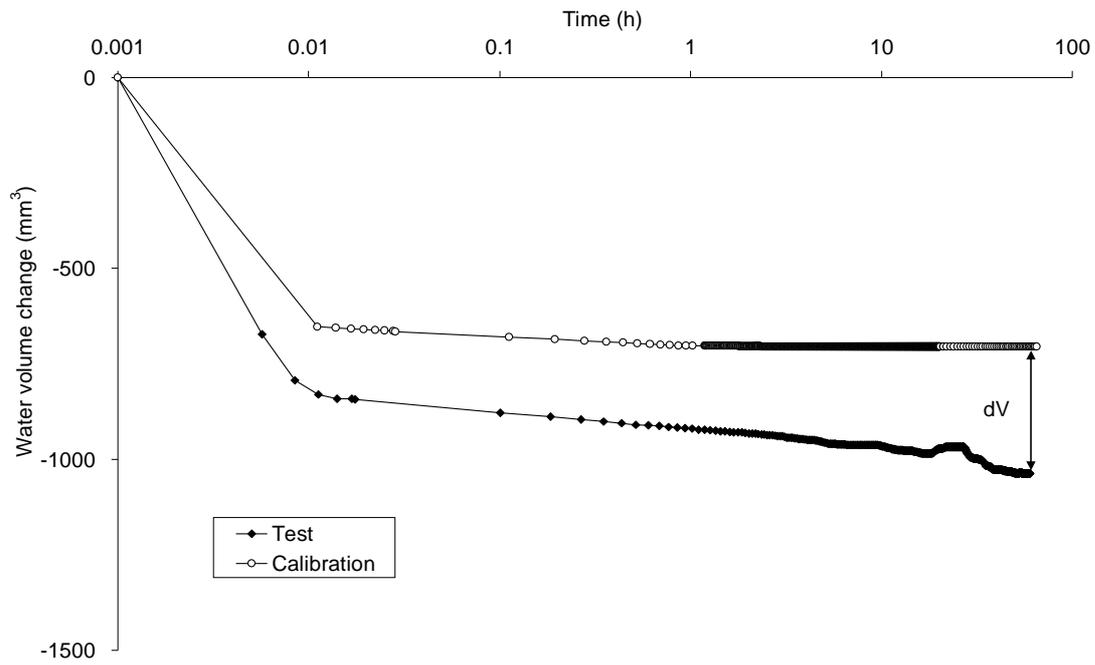
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# Behaviour of GMZ bentonite



**Fig. 2. Stress paths of tests T1-T6**

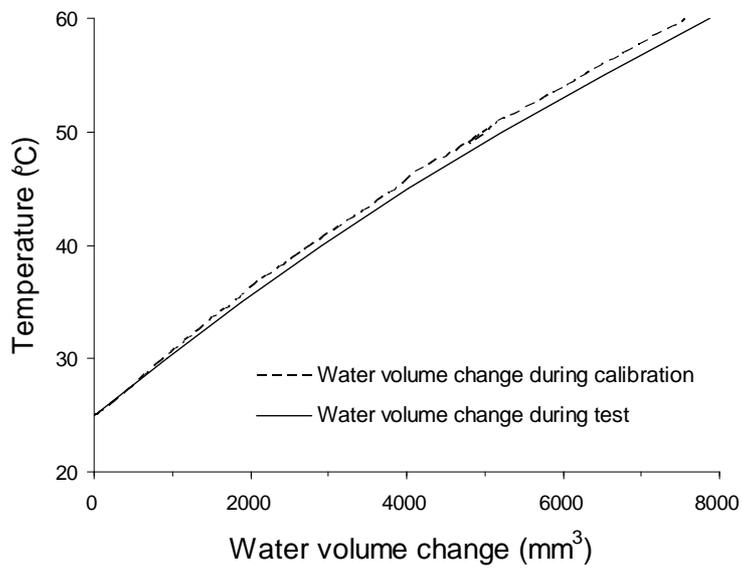
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3 **Fig. 3. Determination of soil volume change during loading step from 1 to 2 MPa**

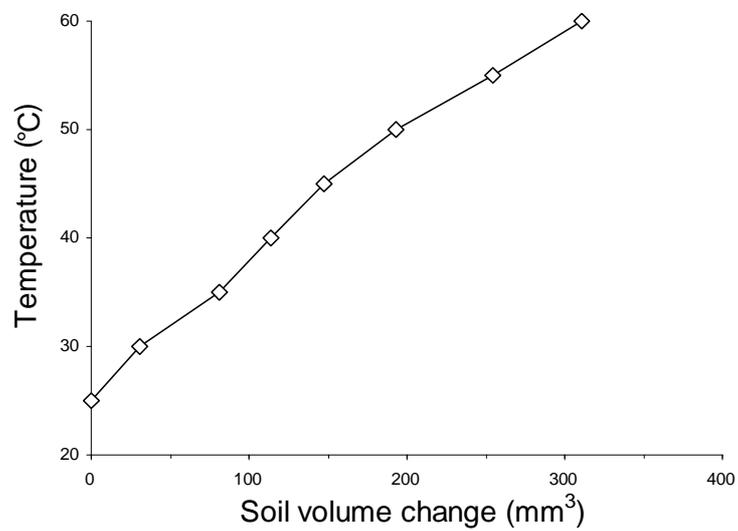
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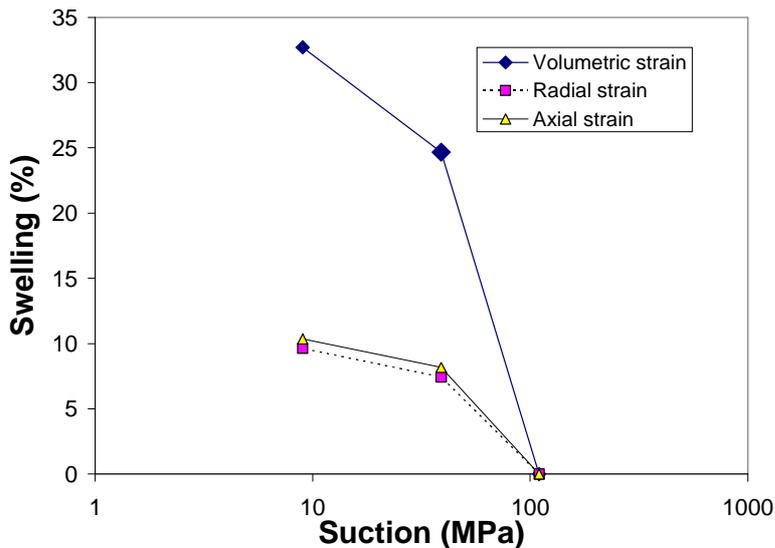
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(b)

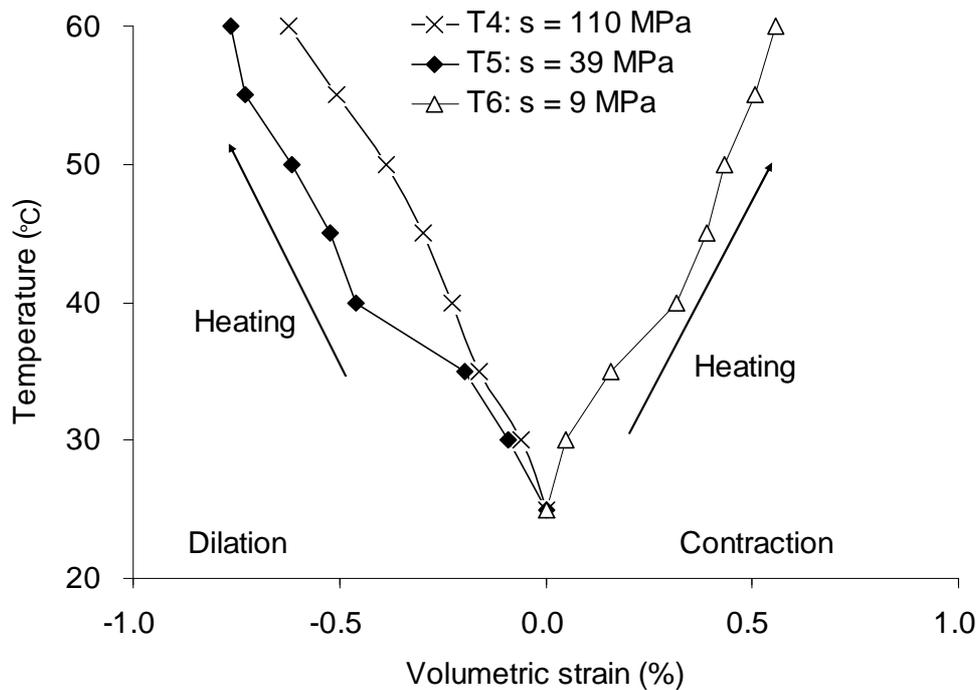
Fig. 4. Determination of soil volume change during heating under confining pressure of 0.1 MPa

Behaviour of GMZ bentonite



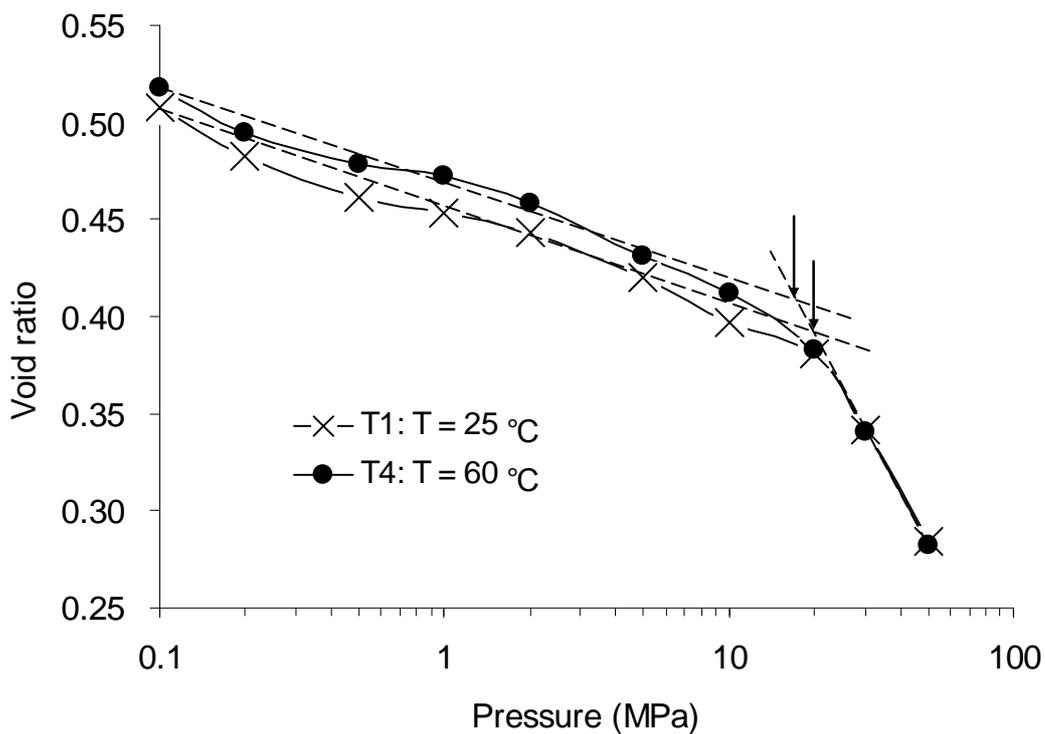
1  
2 Fig. 5. Axial, radial and volumetric strain during wetting

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6 Fig. 6. Volumetric strain during thermal loading under constant pressure at 0.1 MPa: tests T4-T6

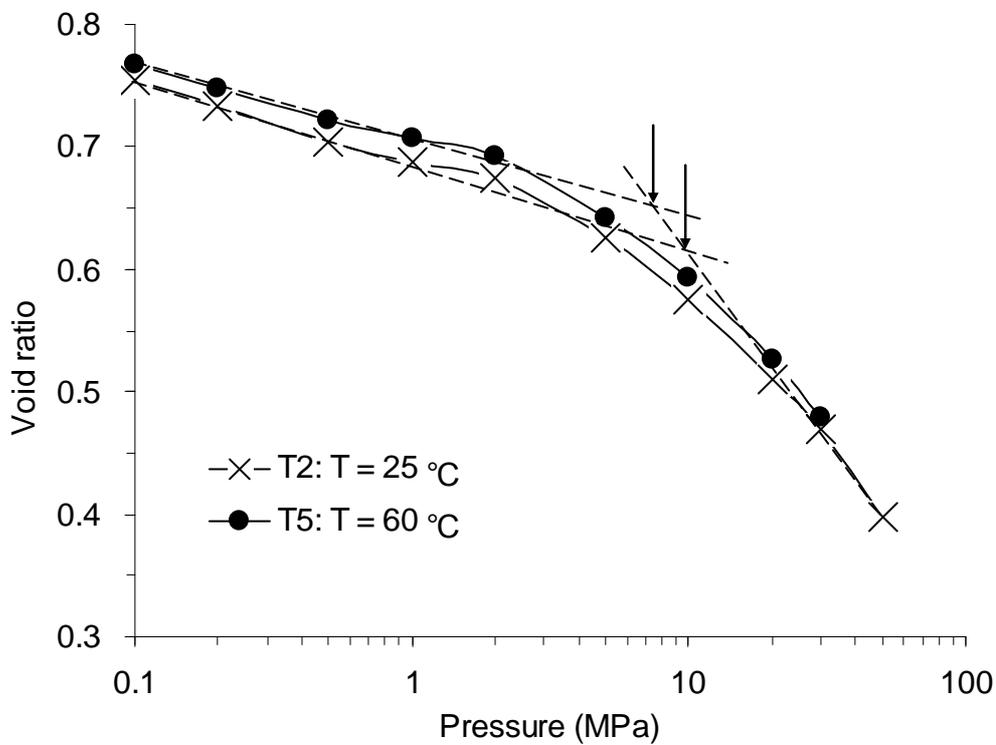
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(a)  $s = 110$  MPa

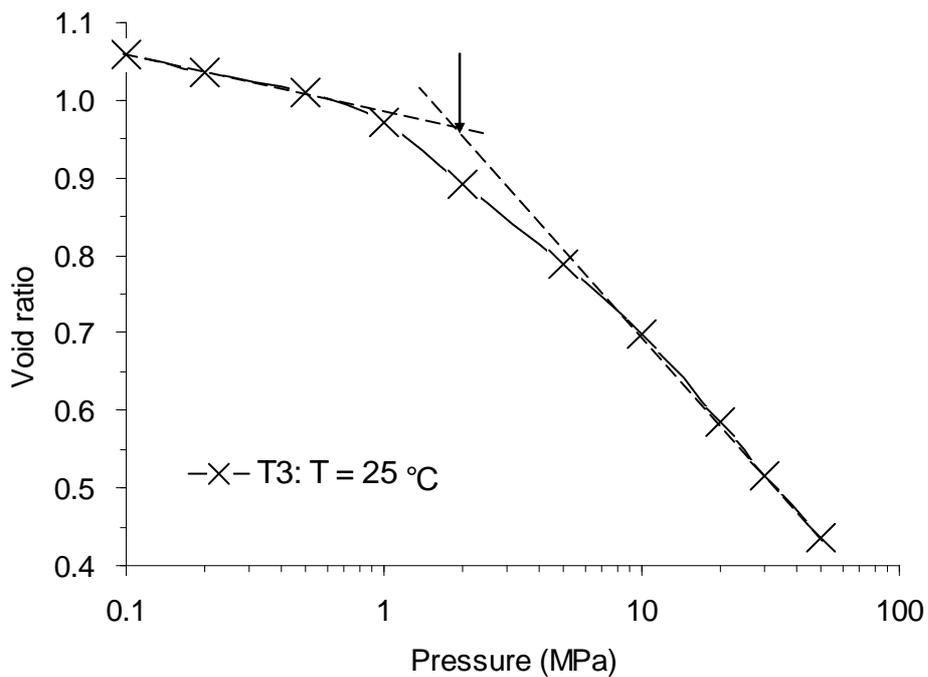


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(b)  $s = 39$  MPa

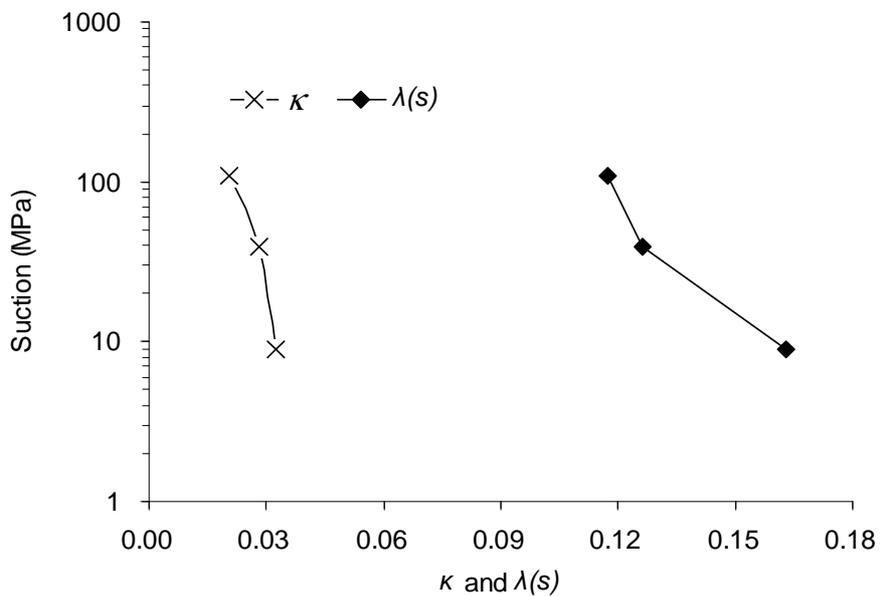
Behaviour of GMZ bentonite



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(c)  $s = 9$  MPa

Fig. 7. Results of mechanical loading at constant suction and temperature: tests T1-T6

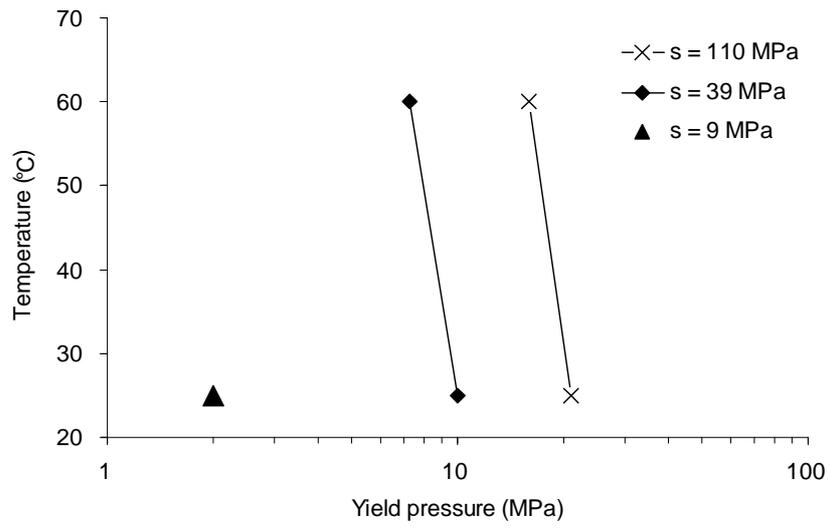


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Fig. 8. Compressibility parameters  $\kappa$  and  $\lambda(s)$  versus suction for tests at 25 °C

# Behaviour of GMZ bentonite

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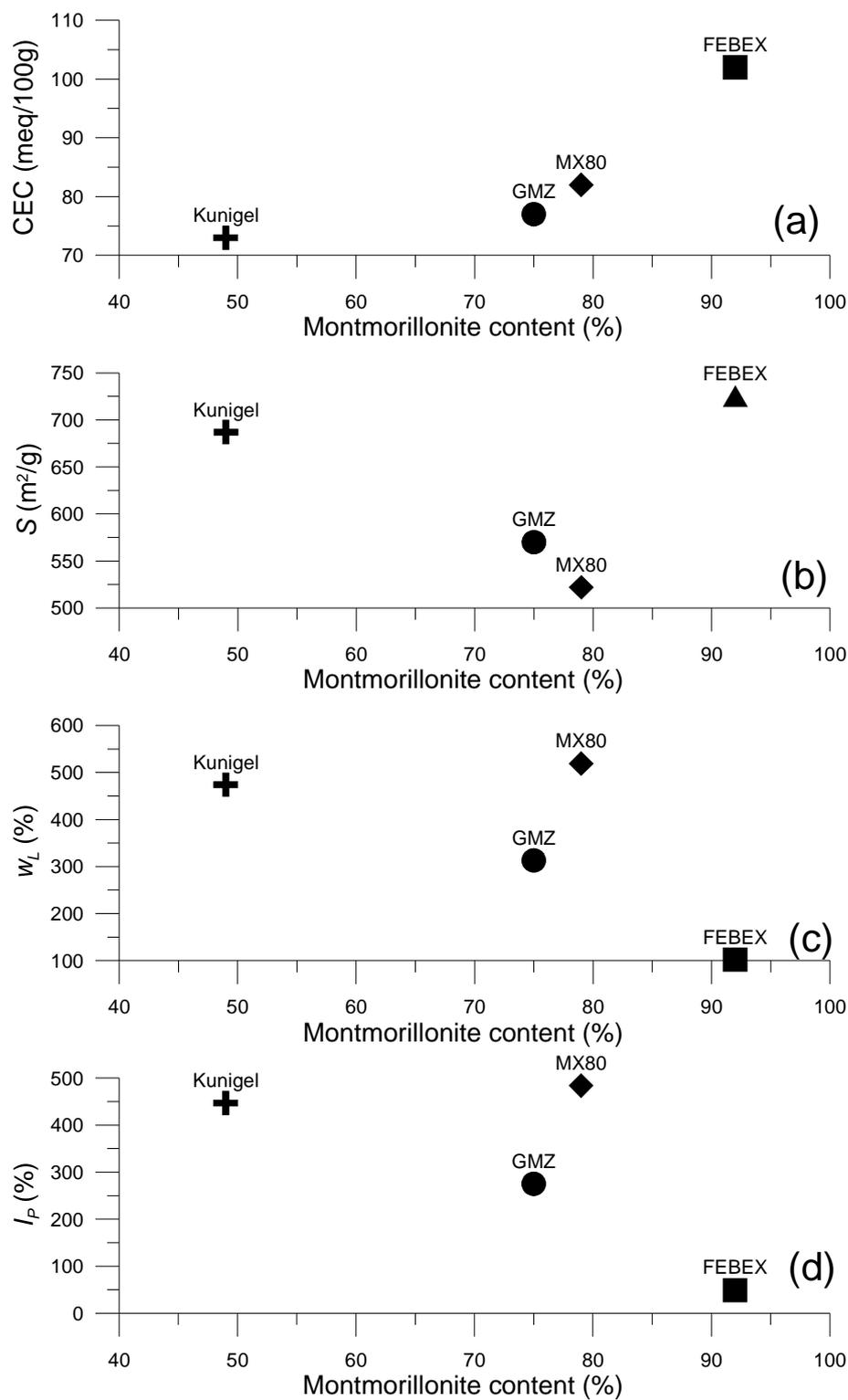


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3 **Fig. 9. Yield pressure  $p_0$  versus temperature**

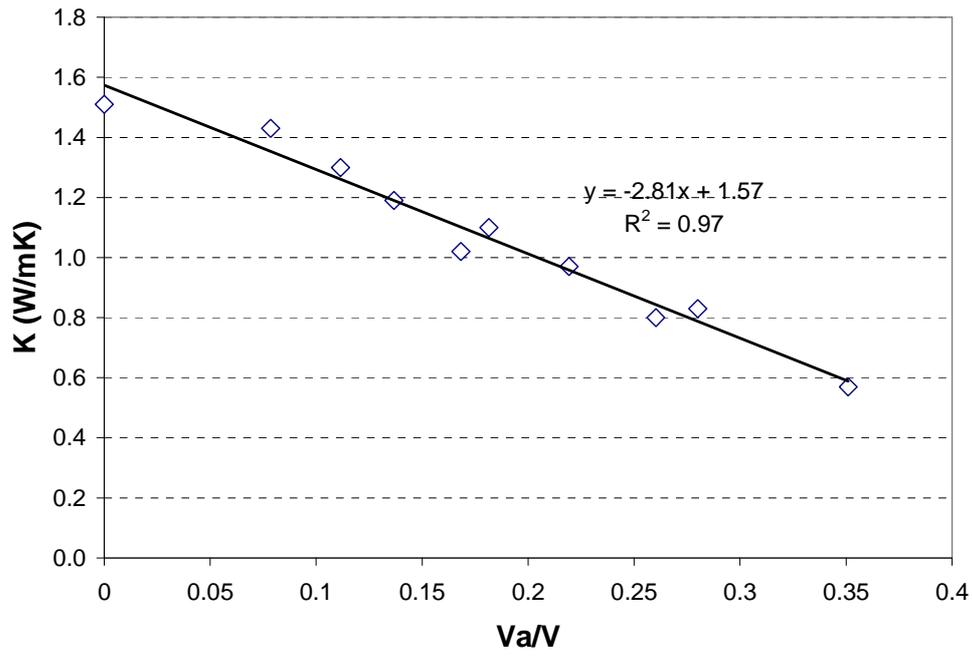
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Behaviour of GMZ bentonite



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 2 **Fig. 10. Correlation between the montmorillonite content with (a) Cations Exchange Capacity, CEC; (b)**  
 3 **specific surface area, S; (c) Liquid limit, w<sub>L</sub>; and (d) Plasticity index, I<sub>p</sub>**  
 4

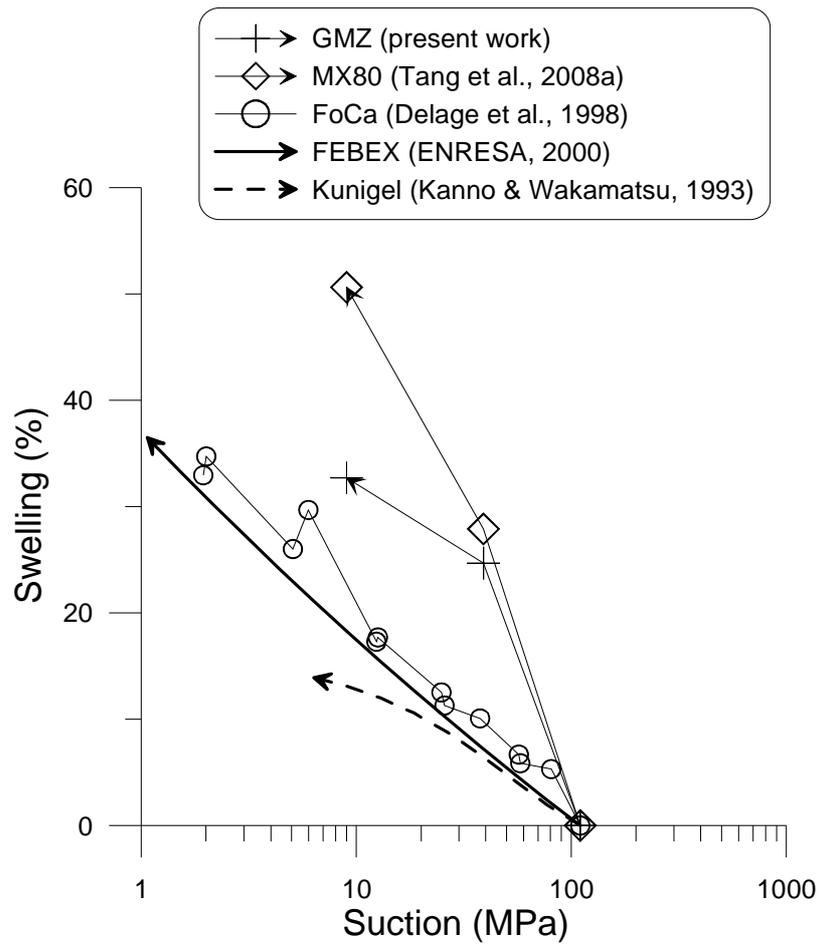
### Behaviour of GMZ bentonite



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**Fig. 11. Variations of thermal conductivity with air-volume fraction for GMZ bentonite (after Wen, 2006)**

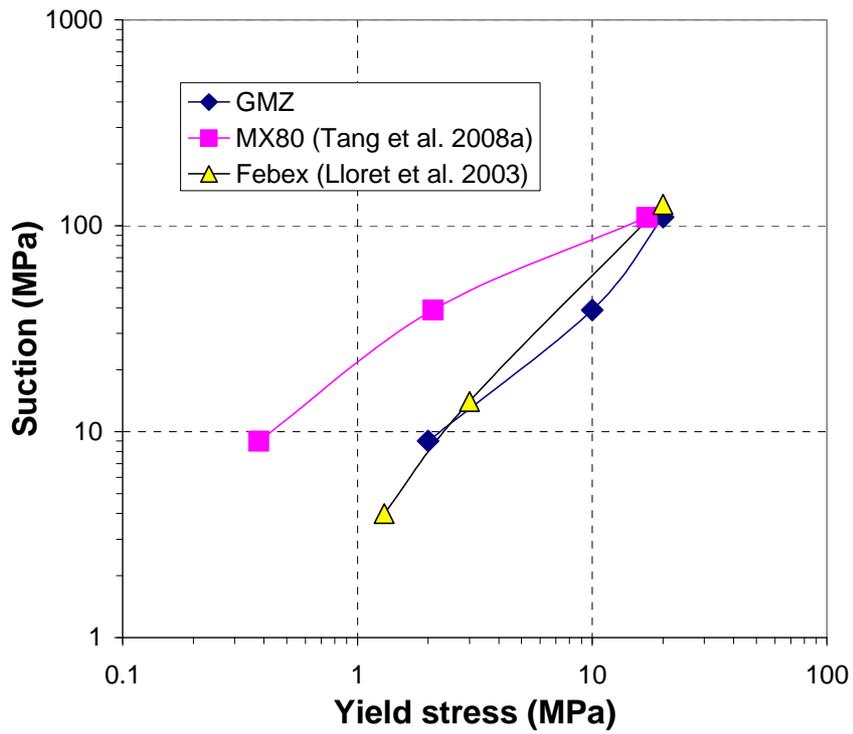
Behaviour of GMZ bentonite



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Fig. 12. Swelling of various compacted bentonite from a initial suction of 110 MPa

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Fig. 13. Relationship between yield stress and the applied suction for various bentonites

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