

Temperature Effects on the Unsaturated Permeability of the Densely Compacted GMZ01 Bentonite under Confined Conditions

Wei-Min Ye, Min Wan, Bao Chen, Yong-Gui Chen, Yu-Jun Cui, Ju Wang

► **To cite this version:**

Wei-Min Ye, Min Wan, Bao Chen, Yong-Gui Chen, Yu-Jun Cui, et al.. Temperature Effects on the Unsaturated Permeability of the Densely Compacted GMZ01 Bentonite under Confined Conditions. Engineering Geology, Elsevier, 2012, 126, pp.1-7. 10.1016/j.enggeo.2011.10.011 . hal-00693404

HAL Id: hal-00693404

<https://hal-enpc.archives-ouvertes.fr/hal-00693404>

Submitted on 2 May 2012

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

1 Temperature Effects on the Unsaturated Permeability of the Densely
2 Compacted GMZ01 Bentonite under Confined Conditions

3

4 W. M. YE^{a,b,*}, M. WAN^a, B. CHEN^a, Y. G. CHEN^a, Y. J. CUI^{a,c}, J. WANG^d

5 *a. Key Laboratory of Geotechnical and Underground Engineering of Ministry of Education, Tongji*
6 *University, Shanghai 200092, China*

7 *b. United Research Center for Urban Environment and Sustainable Development, the Ministry of*
8 *Education, Shanghai 200092, China*

9 *c. UR Navier, Ecole des Ponts ParisTech, France*

10 *d. Beijing Research Institute of Uranium Geology, Beijing 100029, China*

11

12 *To whom correspondence and reprint requests should be addressed; Tel.: +86 21 6598 3729; Fax:
13 +86 21 6598 2384, E-mail: ye_tju@tongji.edu.cn

14

15 **Abstract**

16 In this study, temperature controlled soil-water retention tests and unsaturated hydraulic conductivity
17 tests for densely compacted Gaomiaozi bentonite - GMZ01 (dry density of 1.70 Mg/m^3) were
18 performed under confined conditions. Relevant soil-water retention curves (SWRCs) and unsaturated
19 hydraulic conductivities of GMZ01 at temperatures of 40°C and 60°C were obtained. Based on these
20 results as well as the previously obtained results at 20°C , the influence of temperature on
21 water-retention properties and unsaturated hydraulic conductivity of the densely compacted
22 Gaomiaozi bentonite were investigated. It was observed that: (i) water retention capacity decreases as
23 temperature increases, and the influence of temperature depends on suction; (ii) for all the
24 temperatures tested, the unsaturated hydraulic conductivity decreases slightly in the initial stage of
25 hydration; the value of the hydraulic conductivity becomes constant as hydration progresses and
26 finally, the permeability increases rapidly with suction decreases as saturation is approached; (iii)
27 under confined conditions, the hydraulic conductivity increases as temperature increases, at a
28 decreasing rate with temperature rise. It was also observed that the influence of temperature on the
29 hydraulic conductivity is quite suction-dependent. At high suctions ($s > 60 \text{ MPa}$), the temperature
30 effect is mainly due to its influence on water viscosity; by contrast, in the range of low suctions ($s <$
31 60 MPa), the temperature effect is related to both the water viscosity and the macro-pores closing
32 phenomenon that is supposed to be temperature dependent.

33

34 **Key words** : GMZ bentonite; nuclear waste repository; temperature; water-retention property;
35 unsaturated permeability

36 **1 Introduction**

37 In a conceptual multi-barrier disposal radioactive waste repository (Figure 1), significant
38 Temperature- Hydraulic-Mechanical (THM) phenomena take place in the engineered barrier and in
39 the near field due to the combined actions of heating and hydration (Sanchez et al, 2004). The
40 hydraulic property of the compacted bentonite used as engineered barrier material is one of the key
41 properties for the design of such a disposal system. This explains the large number of studies that
42 have been performed in this area: Dixon et al (1987), Nachabe (1995) and Liu and Wen (2003) tested
43 the permeability of saturated compacted bentonites and analyzed the related influencing factors; Villar
44 (2000, 2002) and Komine (2004) reported different empirical relations between dry density and
45 saturated permeability of compacted bentonite; Komine (2004) and He and Shi (2007) predicted the
46 saturated permeability of bentonite based on the changes in porosity. For the unsaturated bentonite,
47 after an investigation to the unsaturated permeability of the mixture of the Kunigel V1 bentonite and
48 Hostun sand under confined conditions, Loiseau (2001) found that for suction lower than 23MPa, the
49 unsaturated permeability increases with suction decrease, while for suction higher than 23MPa, the
50 unsaturated permeability decreases as suction decreases. Under both confined conditions and
51 unconfined conditions, Cui et al. (2008) tested the unsaturated permeability of the mixture of
52 Kunigel-V1 bentonite/Hostun sand based on the instantaneous profile method, and found that as
53 suction decreases, the unsaturated permeability decreases to a certain value and then turns to increase.

54 Cho et al. (1999) reported that the influence of temperature on the permeability of bentonite is
55 mainly because the intrinsic permeability, viscosity and density of water are influenced by
56 temperature. Changes in viscosity of water with temperature have been found to be the most
57 important mechanism (Towhata et al, 1993; Cho et al, 2000; and Villar and Lloret, 2004).

58 GMZ bentonite has been selected as the potential buffer/backfill material for the construction of
59 the engineered barrier in the Chinese deep geological disposal program for high level radioactive
60 nuclear waste, thanks to its high montmorillonite content, high cation exchange capacity (CEC), large
61 specific surface and other desirable properties (Liu and Wen, 2003). Studies on the mineralogy and
62 chemical composition, mechanical properties, hydraulic behavior, swelling behavior, thermal
63 conductivity, microstructure and volume change behavior of the GMZ bentonite have been conducted
64 over years (Ye et al., 2010b). The investigation of the hydraulic properties of the GMZ bentonite has
65 been the gravity center of the recent studies. Liu and Wen (2003) tested the saturated permeability and
66 analyzed the related influencing factors of the compacted GMZ bentonite. Using the instantaneous
67 profile method, Ye et al. (2010a) tested the unsaturated permeability of the densely compacted
68 specimen, with a dry density of 1.7Mg/m^3 , under confined (constant-volume) conditions. Results
69 show that the unsaturated hydraulic conductivity of the compacted bentonite changes from 1.13×10^{-13}
70 m/s to 8.41×10^{-15} m/s (gravimetric water content from 12% to 28%) and it is not solely function of
71 suction. While under unconfined (free-swelling) conditions, the unsaturated hydraulic conductivity of
72 the Gaomiaozi bentonite is in a larger range of 1.0×10^{-12} - 1.0×10^{-15} m/s. Based on the
73 Kozeny-Carmen semi-empirical function, Niu et al (2009) proposed a semi-empirical equation for the
74 calculation of the unsaturated permeability of the GMZ bentonite with the consideration of
75 micro-structural changes.

76 As far as the influence of temperature effect is concerned, Ye et al. (2009b) reported that the
77 water retention capacity of the highly-compacted GMZ bentonite and bentonite-based mixtures
78 decreases as the temperature increases, regardless of the confining conditions.

79 In this paper, the soil-water retention curves (SWRCs) of the densely compacted Gaomiaozi

80 bentonite (GMZ01) under confined conditions and at various temperatures (20°C, 40°C and 60°C) are
81 presented. Based on the results obtained, the unsaturated permeability of the GMZ01 is investigated
82 by performing infiltration tests under controlled temperature.

83 **2. Materials**

84 The Gaomiaozi deposit is located in the northern Chinese Inner Mongolia autonomous region,
85 300 km northwest from Beijing (Ye et al., 2009a, 2010b). Some basic properties of the GMZ01
86 bentonite tested in this paper are listed in Table 1, which indicates that the GMZ01 bentonite has high
87 cation exchange capacity and high adsorption ability.

88 **3 Experimental Methods**

89 The instantaneous profile method has been adopted in this study. This method was successfully
90 used by many researchers to determine the unsaturated hydraulic conductivity of geomaterials (Daniel,
91 1982 ; Richards and Weeks, 1953; Hamilton et al., 1981; Watson, K.K., 1966; Meerdink et al., 1996;
92 Fujimaki and Inoue, 2003; Cui et al., 2008; Ye et al., 2010a). As an unsteady-state method, it can be
93 used either in the laboratory or in situ (Benson and Gribb 1997).

94 In order to apply this method to determine the unsaturated permeability of the GMZ01 bentonite
95 at different temperatures, on the one hand, the SWRCs of this soil should be determined at relevant
96 temperatures, and on the other hand, the corresponding suction profiles should be determined by
97 performing infiltration test at different temperatures with suction monitoring. For a given temperature,
98 the hydraulic gradient was determined using the suction profile; the water flux was determined using
99 the water content profile; the hydraulic conductivity was then calculated based on the generalized
100 Darcy's law. The detailed calculation procedure can be found in Ye et al. (2009a).

101

102 **3.1 Determination of SWRCs**

103 **3.1.1 Suction control**

104 The vapour equilibrium technique (for high suctions) and osmotic technique (for low suctions)
105 were employed for suction control in this study. At high suctions, the experimental setup used was
106 described by Ye et al (2005), as shown in Fig.2. Note that the vapor equilibrium technique was
107 employed by number of researchers for controlling total suction in unsaturated soil tests (Bernier et al,
108 1997; Blatz and Graham, 2000; Lloret et al, 2003; Chen et al, 2006).

109 In this study, the confined GMZ01 specimen was placed in a desiccator and the water vapour
110 above a saturated salt solution was circulated to provide the desired suction to the specimen. Saturated
111 salt solutions and their corresponding suctions imposed at 20, 40 and 60°C are shown in Table 3
112 (Tang and Cui, 2005).

113 For low suctions, the osmotic technique was used and the corresponding setup is shown in Fig 3
114 (Delage et al., 1992; 1998). Note that Tang et al. (2010) studied the temperature effect on the
115 calibration curve of PEG solutions and found that this effect is insignificant. Thus, in this study, the
116 osmotic technique was employed without temperature correction.

117

118 **3.1.2 Apparatus**

119 Custom-designed stainless steel cells with small holes in two ends (Fig.2, Ye, 2009a) were
120 employed for water retention test under confined conditions. The holes were designed as channels for

121 moisture exchange between the specimen in the cell and the circulating air (or PEG solution) around it.
122 For the temperature control, the setups were placed in ovens (Fig 3 and Fig 4), which have
123 temperature controlled to an accuracy of $\pm 0.1^\circ\text{C}$. Note that temperatures of 20, 40 and 60°C were
124 selected as the testing temperatures in this study.

125 **3.1.3 Specimen preparation**

126 The GMZ01 bentonite powder was compacted into a thin cylindrical specimen, which has a final
127 dimension of 20 mm in diameter and 6 mm in height. For the compaction, a press was used and the
128 compaction was carried out at a velocity of 0.1 mm/min. The final dry density and water content of
129 the compacted specimen were 1.70g/cm^3 and 10.65%, respectively.

130 **3.2 Infiltration test**

131 The schematic layout of the temperature controlled infiltration test is shown in Fig.5. A
132 custom-designed cylinder (Ye et al., 2009a, 2010a) is put in an oven with temperature controlled to an
133 accuracy of $\pm 0.1^\circ\text{C}$. The resistive relative humidity (RH) sensors (Cui et al, 2008) were used to
134 monitor the RH changes. Note that the same type of sensor was used by Ye et al. (2009a, 2010a). It
135 can be seen from Fig.5 that the sensors were installed every 30 mm along the length of the cell (4
136 sensors) with a fifth sensor in the upper base plate of the cell. As the sensors measure the air relative
137 humidity, no direct contact with soil specimen was allowed. For this reason, a small cavity was bored
138 in the soil for each transducer. This cavity had a dimension allowing introducing the transducer cap: a
139 porous stone of 2 mm thick and 5 mm in diameter. This porous stone separated the transducer from
140 the soil sample and allowed the air humidity transfer from the specimen to the transducer (Ye et al.,
141 2009a).

142 The distilled water was used in the infiltration test. The water absorbed by the specimen can be
143 quantified by calculating the water volume change in the left marked glass pipe, which can be
144 compensated by water from the right tube, in the U-shaped system outside the oven. Two drops of
145 silicone oil were added into the left pipe to prevent water evaporation. A soft tube was used for
146 connecting the U-shaped system to the inlet of the specimen in order to warm up the water to current
147 testing temperature before absorption. The humidity and temperature changes were recorded by the
148 data logging system.

149 A double-piston mould was used for the compaction of the specimen (Cui and Delage, 1996).
150 The powder of the GMZ01 bentonite was compacted in 5 layers. After the first layer (30 mm) was
151 compacted and the surface of specimen was carefully scarified for the integrity of the specimen, the
152 equal parts of the GMZ01 powder were added from two ends of the mould and then compacted to two
153 15 mm sub-layers. This procedure was repeated for the other 3 layers. The compaction was conducted
154 at a speed of 0.1 mm/min. The specimen has a final height of 150 mm, a dry density of 1.70 Mg/m^3 , a
155 suction about 90 MPa for 40°C temperature and 100MPa for 60°C temperature, and a degree of
156 saturation around 0.49 for 40°C temperature and 0.41 for 60°C temperature.

157 The unsaturated permeability test on the GMZ01 bentonite at 20°C was previously measured and
158 reported by Ye et al. (2010) and thus only the infiltration tests at temperatures of 40°C and 60°C were
159 performed in this study.

160

161 **4. Results and discussion**

162 **4.1 SWRCs**

163 The SWRCs of the highly-compacted GMZ01 specimen following wetting path at different

164 temperatures (20°C, 40°C and 60°C) under confined conditions are shown in Fig.5. Based on these
 165 results, an equation can be proposed to describe the water retention curves of the densely compacted
 166 GMZ01 bentonite (1.7 Mg/m³):

$$167 \quad w = \eta \frac{w_{sat}}{\{\ln[2.72 + (\psi/a)^b]\}^c} \quad (1)$$

168 with

$$169 \quad \eta = 1 - \frac{\ln(1 + \frac{\psi}{\psi_r})}{1 + \frac{1000}{\psi_r}}, \quad (2)$$

170 Where ψ (MPa) is the suction; ψ_r (MPa) is a reference suction (309 MPa in this study); w_{sat} is the

171 water content in the saturated state: $w_{sat} = 0.25 + 0.00018(T - 20 - 273.4)$; T (K) is the absolute

172 temperature; a (MPa), b and c are soil parameters: $a = -4.1474 \ln(T - 273) + 20.395$; $b = 0.8086$;

173 $c = 0.5864$.

174 Fig.6 indicates that, the water retention capacity decreases as temperature increases and the
 175 degree of the temperature influence depends on suction. This phenomenon can be analyzed separately
 176 at low and high suctions. At high suctions (> 4 MPa), changes of clay fabric and fluid in
 177 intra-aggregate spaces play a significant role in water retention capacity of GMZ bentonite.
 178 Intra-aggregate water moves into macro-pores (inter-aggregates pores) with temperature increase (Ye
 179 et al, 2009a). This process decreases the suction in the macro-pore level. As the suction is controlled,
 180 water flows out from the macro-pores, leading to a decrease of water retention capacity. At low
 181 suctions, capillary effect plays a decisive role in the water retention capacity. Increase of temperature
 182 causes changes in surface tension, which results in decrease of water content under constant suction
 183 conditions.

184 In order to quantitatively assess the influence of temperature on the water retention capacity of
 185 the bentonite under different suctions, a ratio k_T is defined as follows:

$$186 \quad k_T = \frac{w_{T1} - w_{T2}}{w_{T1}} \times 100\% \quad (3)$$

187 where w_{T1} and w_{T2} are water content at temperature $T1$ and $T2$ respectively for the same suction.

188 The relationship between the ratio k_T and suction for the GMZ01 bentonite at 40°C and 60°C are
 189 given in Fig.7. It can be observed that the effect of temperature on the water retention capacity is
 190 closely related to suction, particularly in the range from 30 to 60 MPa. This effect reaches a maximum
 191 at a suction around 40 MPa.

192 **4.2 Unsaturated permeability**

193 **4.2.1 Test at 40°C**

194 The relative humidity changes with hydration time in the infiltration test at 40°C are shown in
 195 Fig.8. Based on the SWRCs measured at 40°C (see Fig.6), the development of suction with hydration
 196 time can be obtained. Note that the conversion from relative humidity to suction was done using the

197 Kelvin's law. Fig 8 indicates that, for the relative humidity sensor located 3 cm from the hydration
198 water inlet at the bottom of the specimen, suction decreases rapidly in the first 200 h of hydration and
199 then decreases much more slowly. For suction measured at 6 cm, it begins to decrease rapidly after
200 100 h hydration and gradually decreases after 800 h hydration. As it is relatively far from the water
201 inlet, suctions measured at 12 cm and 15 cm from the bottom of the specimen start to decrease rapidly
202 after 200 and 300 h of hydration, respectively. The slope of the curve of suction versus time decreases
203 as the distance from the inlet increases. The test was stopped after about 1670 h hydration, when the
204 sensor at 3 cm distance from the inlet indicated that zero suction (100% relative humidity) was
205 achieved at this height.

206 The relationship between the unsaturated hydraulic conductivity and suction is shown in Fig.9. It
207 can be observed that at 40°C temperature, the unsaturated hydraulic conductivity of the GMZ01 with
208 a dry density of 1.7 Mg/m³ is on the whole between 1.64×10⁻¹³m/s and 1.34×10⁻¹⁴m/s. During the
209 initial stages of hydration, the hydraulic conductivity gradually decreases with suction decrease, and
210 the hydraulic conductivity reaches the minimum value of 1.34×10⁻¹⁴m/s when the suction drops to
211 45 MPa; the hydraulic conductivity keeps steady in the range of suction from 20 MPa to
212 60MPa; but when suction drops to a level lower than 20 MPa, the unsaturated hydraulic conductivity
213 increases rapidly and reaches 1×10⁻¹³m/s.

214 4.2.2 Test at 60°C

215 The unsaturated hydraulic conductivity of the confined GMZ01 determined at 60°C is shown in
216 Fig.10. It can be seen that the values are generally between 1.79×10⁻¹⁴m/s and 1.19×10⁻¹³m/s. As the
217 infiltration of water progresses, suction drops from 80 MPa to 55 MPa, while the unsaturated
218 hydraulic conductivity decreases slightly. With suction reduction from 55 MPa to 20 MPa, the
219 hydraulic conductivity remains almost constant despite of the suction changes. For suction lower than
220 20 MPa, the hydraulic conductivity rapidly increases with decreasing suction and reaches a final value
221 of 1×10⁻¹³m/s.

222 When the soil suction is decreased from the initial value (about 80 MPa) to zero, the hydraulic
223 conductivity first decreases from 2×10⁻¹⁴m/s to 7×10⁻¹⁵m/s and then increases to 1×10⁻¹³m/s, which is
224 close to the saturated hydraulic conductivity. As in the first stage, water transfer is primarily governed
225 by the network of large pores and these large pores are progressively decreasing in quantity and in
226 size, resulting in hydraulic conductivity decreases. After completion of this large-pore clogging by gel
227 creation, a normal conductivity increase with suction decrease is observed (Ye et al., 2009a).

228 4.3 Influence of temperature on the unsaturated hydraulic conductivity

229 To further assess the influence of temperature on the unsaturated permeability of the highly
230 compacted GMZ01 bentonite, the unsaturated hydraulic conductivity of the confined specimen at
231 20°C (Ye et al, 2009a) are compared to those measured at 40°C and 60°C (Fig.11). It can be seen that
232 under confined conditions, the unsaturated hydraulic conductivity of the highly compacted GMZ01
233 bentonite increases with temperature rise. Moreover, the rate of change also decreases as temperature
234 increases. The temperature effect becomes more significant at higher suctions (above 20 MPa). In the
235 range of lower suctions (less than 20 MPa), it is observed that the lower the suction the less the
236 temperature effect. The possible explanation is that for lower suctions the moisture absorbed by the
237 bentonite is mainly associated with microstructure changes and the temperature effect on the
238 microstructure is not significant.

239 The influence of temperature on the hydraulic conductivity is mainly related to the influence of

240 temperature on the water viscosity and the pore structure of the bentonite. To remove the influence of
241 temperature on water viscosity, the relative hydraulic conductivity is introduced to allow for a better
242 analysis of the influence of temperature on hydraulic conductivity. Relationships between the relative
243 permeability and degree of saturation (S_r) of the confined GMZ01 at 40°C and 60°C are given in
244 Fig.12. It can be observed that when S_r is higher than 0.57, the hydraulic conductivity at 60°C is
245 similar to that observed at 40°C. This means that in this range of degree of saturation the influence of
246 temperature on permeability is mainly due to the influence on water viscosity. On the contrary, when
247 S_r is lower than 0.57, the relative permeability at 40°C is found higher than that at 60°C. Interestingly,
248 this threshold corresponds to a suction of 60 MPa, and from Figs 9, 10 and 11 it can be observed that
249 when $s > 60$ MPa the hydraulic conductivity decreases with suction decrease. As mentioned above, in
250 this suction range hydration leads to progressive macro-pores closing thus to a decrease in hydraulic
251 conductivity. This macro-pore closing process can be assumed to be more significant at higher
252 temperature because of softer clay aggregates and lower water viscosity, explaining a lower hydraulic
253 conductivity at 60°C than at 40°C. As the relative hydraulic conductivity has been found independent
254 of temperature when $S_r > 0.57$ (Fig. 12), it can be supposed that the macro-closing process ended
255 when $S_r > 0.57$; in other words, the influence of temperature on pore structure became insignificant in
256 this range.

257 It is also important to note that the obtained results could be affected by the possible density
258 gradient along the specimen as identified by Dixon et al. (2002) and Villar et al. (2008). This density
259 gradient can be formed owing to the expansion of the hydrated bentonite that intrudes into the drier
260 area under the effect of swelling pressure. If it occurs, the computation of degree of saturation without
261 considering this gradient is not correct and the water retention curve considered is also inappropriate.
262 In other words, the simultaneous profile method meets its limitation. Because in this study, no specific
263 analyses were conducted after the infiltration tests, this phenomenon can not be verified. Further
264 studies will be performed to **investigate this aspect**.

265

266 **5 Conclusions**

267 The SWRCs of the highly compacted GMZ01 confined specimens on wetting path and at
268 different temperatures (20°C, 40°C and 60°C) show that the water retention capacity decreases as
269 temperature increases; and the influence of temperature depends on suction. The ratio k_T can be used
270 to quantitatively describe the influence of temperature on water retention capacity of bentonite at
271 different suctions.

272 Under confined conditions and at 40°C temperature, the unsaturated hydraulic conductivity of
273 the GMZ01 bentonite at a dry density of 1.7Mg/m³ is between 1.64×10^{-13} m/s and 1.34×10^{-14} m/s. At
274 60°C temperature, the value is slightly lower, between 1.19×10^{-13} m/s and 1.79×10^{-14} m/s.

275 For all the temperatures considered, the unsaturated hydraulic conductivity decreases slightly in
276 the first stage of hydration. The value of the hydraulic conductivity becomes constant as hydration
277 progresses. Finally, the hydraulic conductivity increases rapidly with suction decreases when
278 saturation is approached. This phenomenon may be explained by the changes in the soil
279 microstructure.

280 Under confined conditions, the hydraulic conductivity increases as temperature increases, at a
281 rate that decreases with temperature rise. Also, the influence of temperature on the hydraulic
282 conductivity is quite suction-dependant. At high suctions ($s > 60$ MPa) or low degrees of saturation

283 (Sr < 0.57), the temperature effect is mainly due to its influence on water viscosity; on the contrary, in
284 the range of low suctions ($s < 60$ MPa) or high degrees of saturation (Sr > 0.57), the temperature
285 effect is related to both the water viscosity and the macro-pores closing phenomenon that is supposed
286 to be temperature dependent. Note that further studies are needed to investigate the possible dry
287 density gradient effect on the hydraulic conductivity determined based on the simultaneous profile
288 method.

289

290 **ACKNOWLEDGEMENTS**

291 The authors are grateful to the National Natural Science Foundation of China (Projects No.
292 41030748, No.40772180 and No.40728003), Kwang-Hua Fund for College of Civil Engineering at
293 Tongji University, China Atomic Energy Authority (Project [2007]831), and Shanghai municipality
294 (Leading Academic Discipline Project - B308).

295

296 **References**

- 297 Benson C.H. and Gribb M.M. 1997. Measuring unsaturated hydraulic conductivity in the laboratory
298 and field. In *Unsaturated soil engineering practice*. Edited by S.L. Houston and D.G. Fredlund.
299 American Society of Civil Engineers (ASCE), Reston, Va. pp. 113-168.
- 300 Bernier F., Volckaert G., Alonso E.E. and Villar, M.V. 1997. Suction-controlled experiments on
301 Boom clay. *Engineering Geology*, 47(4): 325-338
- 302 Blatz J. and Graham J. 2000. A system for controlled suction in triaxial tests. *Geotechnique*, 50(4):
303 465-469
- 304 Chen B., Qian L.X., Ye W.M., Cui Y.J. and Wang J. 2006. Soil-water characteristic curves of
305 Gaomiaozhi bentonite. *Chinese Journal of Rock Mechanics and Engineering*, Vol.25(4): 788-793.
- 306 Cho W.J., Lee J.O. and K.S. Chun. 1999. The temperature effects on hydraulic conductivity of
307 compacted bentonite. *Applied Clay Science* 14, 47-58.
- 308 Cho W.J., Lee J.O. and Kang C.H. 2000. Influence of temperature elevation on the sealing
309 performance of the potential buffer material for a high-level radioactive waste repository. *Annals*
310 *of Nuclear Energy*, Vol. 27: 1271-1284.
- 311 Cui Y. J. & Delage P. 1996. Yielding and plastic behaviour of an unsaturated compacted silt.
312 *Géotechnique* 46 (2): 291-311.
- 313 Cui Y. J., Tang A.M., Loiseau C, Delage P. 2008. Determining the unsaturated hydraulic conductivity
314 of a compacted sand-bentonite mixture under constant-volume and free-swell conditions. *Physics*
315 *and Chemistry of the Earth*, Vol. 33:462-471.
- 316 Daniel D.E. 1982. Measurement of hydraulic conductivity of unsaturated soils with thermocouple
317 psychrometers. *Soil Science Society of America Journal* 20 (6), 1125-1129.
- 318 Delage P., Suraj de Silva G.P.R. and Vicol T. 1992. Suction controlled testing of non saturated soils
319 with an osmotic consolidometer. *Proceedings 7th International Conference on Expansive Soils*,
320 Dallas, 206-211.
- 321 Delage P., Howat M. and Cui Y.J. 1998. The relationship between suction and swelling properties in a
322 heavily compacted unsaturated clay. *Engineering Geology*, vol.50 (1-2): 34-48.
- 323 Dixon D.A., Cheung S.C.H., Gray M.N. and Davidson B.C. 1987. The hydraulic conductivity of
324 dense clay soils. *Proceedings of the 40th Canadian Geotechnical Conference, Regina*,
325 Saskatchewan - Canada:389-396.

- 326 Dixon D., Chandler N., Graham J. and Gray M.N. 2002. Two large-scale sealing tests conducted at
 327 Atomic Energy of Canada's underground research laboratory: the buffer-container experiment and
 328 the isothermal test. *Can. Geotech. J.* 39: 503-518.
- 329 Fujimaki H. and Inoue M. 2003. A flux-controlled steady-state evaporation method for determining
 330 unsaturated hydraulic conductivity at low matric pressure head values. *Soil Science*, 168(6):
 331 385-395.
- 332 Hamilton D.C., Gloeckler G., Krimigis S.M. and Lanzerotti L.J. 1981. Composition of nonthermal
 333 ions in the Jovian magnetosphere. *Journal of Geophysical Research*, 86(A10): 8301-8318.
- 334 He J. and Shi J. Y. 2007. Calculation of saturated hydraulic conductivity of bentonite. *Chinese Journal
 335 of Rock Mechanics and Engineering*, Suppl. 2: 3920-3925 (in Chinese).
- 336 Komine H. 2004. Simplified evaluation on hydraulic conductivities of sand-bentonite mixture
 337 backfill. *Applied clay science*, Vol.26 (1-4) :13-19.
- 338 Liu, Y.M. and Wen, Z.J. 2003. An investigation of the physical properties of clayey materials used in
 339 nuclear waste disposal at great depth. *Mineral Rocks* 23 (4), 42–45 in Chinese.
- 340 Lloret A., Villar M.V., Sanchez M., Gens A., Pintado X. and Alonso E.E. 2003. Mechanical
 341 behaviour of heavily compacted bentonite under high suction changes. *Geotechnique*, 53(1):
 342 27-40.
- 343 Loiseau C. 2001. Transferts d'eau et couplages hydromécaniques dans les barrières ouvragées. PhD
 344 Thesis. CERMES/ENPC, France.
- 345 Meerdink J.S., Benson C.H. and Khire M.V. 1996. Unsaturated hydraulic conductivity of two
 346 compacted barrier soils. *Journal of Geotechnical Engineering*, 122(7): 565-576.
- 347 Nachabe H.M. 1995. Estimating hydraulic conductivity for models of Soils with Macropores. *Journal
 348 of Irrigation and Drainage Engineering*, Vol.121 (1): 95-102.
- 349 Niu W.J., Ye W.M., Chen B. and Qian L.X. 2009. The Equations of Unsaturated Permeability
 350 Considering the Micro- structure. *Exploration Engineering (Rock & Soil Drilling and Tunneling)*,
 351 Vol. 36(6):34-39 (in Chinese).
- 352 Richards S.J. and Weeks L.V. 1953. Capillary conductivity values from moisture yield and tension
 353 measurements on soil columns. *Soil Science Society of America Proceedings*, 17: 206-209.
- 354 Sánchez M. 2004. Thermo-Hydro-Mechanical coupled analyses in low permeability media. PhD
 355 Thesis, Universitat Politècnica de Catalunya, Spain.
- 356 Tang A.M., Cui Y.J. 2005. Controlling suction by the vapour equilibrium technique at different
 357 temperatures and its application in determining the water retention properties of MX80 clay
 358 *Canadian Geotechnical Journal*, Vol.42:1-10.
- 359 Tang A.M., Cui Y.J., Qian L.X., Delage P. and Ye W.M. 2010. Calibration of the osmotic technique
 360 of controlling suction with respect to temperature using a miniature tensiometer. *Canadian
 361 Geotechnical Journal*, Vol. 47(3/1): 359-365.
- 362 Towhata I., Kuntiwattanakul P., Seko I. and Ohishi K. 1993. Volume change of clays induced by
 363 heating as observed in consolidation tests. *Soils Found.* Vol. 33 (4), 170–183.
- 364 Villar M.V. 2000. Caracterización termo-hidro-mecánica de una bentonita de Cabo de Gata: Ph.D.
 365 Thesis. Universidad Complutense de Madrid. Madrid (in Spanish).
- 366 Villar M.V. 2002. Thermo-hydro-mechanical characterisation of a bentonite from Cabo de Gata. A
 367 study applied to the use of bentonite as sealing material in high level radioactive waste
 368 repositories. *Publicación Técnica ENRESA*, Madrid, Spain.

- 369 Villar M.V. and Lloret A. 2004. Influence of temperature on the hydro-mechanical behaviour of a
370 compacted bentonite . *Applied Clay Science*, Vol. 26(1/4): 337-350.
- 371 Villar M.V., Sánchez M., Gens A., 2008. Behaviour of a bentonite barrier in the laboratory:
372 experimental results up to 8 years and numerical simulation. *Physics and Chemistry of the Earth*
373 33, S476-S485.
- 374 Watson K.K. 1966. An instantaneous profile method for determining the hydraulic conductivity of
375 unsaturated porous materials. *Water Resources Research*, 2(4): 709-715.
- 376 Ye W.M., Cui Y.J., Qian L.X. and Chen, B. 2009a. An experimental study of the water transfer
377 through confined compacted GMZ bentonite, *Engineering Geology*, v 108, n 3-4, p 169-176
- 378 Ye W.M., Niu W.J., Chen B., Chen Y.G. 2010a. Unsaturated Hydraulic Conductivity of Densely
379 Compacted Gaomiaozi Bentonite Under Unconfined Conditions, *Journal of Tongji University*
380 (Natural Science), Vol 38(10): 1439-1443, in Chinese.
- 381 Ye W.M., Wan M., Chen B., Chen Y. G., Cui Y. J. and Wang J. 2009b. Effect of temperature on
382 soil-water characteristics and hysteresis of compacted Gaomiaozi bentonite. *Journal of Central*
383 *South University of Technology*. Vol.16, No.5: 821-826.
- 384 Ye W.M., Tang Y.Q. and Cui Y.J. 2005. Measurement of soil suction in laboratory and soil-water
385 characteristics of Shanghai soft soil. *Chinese Journal of Geotechnical Engineering*, 27(3):347-349
386 (in Chinese).
- 387 Ye W.M., Chen Y.G., Chen B., Wang Q. and Wang J. 2010b. Advances on the knowledge of the
388 buffer/backfill properties of heavily compacted GMZ bentonite. *Engineering Geology*, Vol
389 116(1-2): 12-20.

390
391

Table 1 Basic Properties of GMZ01 bentonite

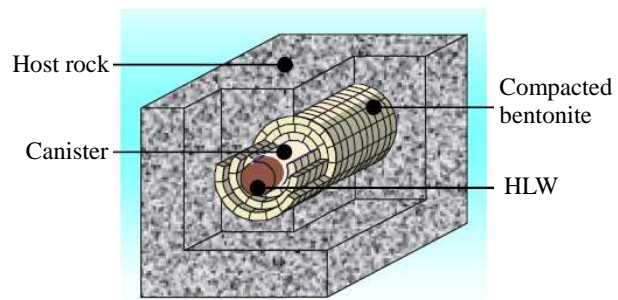
Property	Description
Specific gravity of soil	2.66
pH	8.68–9.86
Liquid limit (%)	276
Plastic limit (%)	37
Total specific surface area/ ($\text{m}^2 \cdot \text{g}^{-1}$)	570
Cation exchange capacity/ ($\text{mmol} \cdot \text{g}^{-1}$)	0.773 0
Main exchanged cation/ ($\text{mmol} \cdot \text{g}^{-1}$)	$\text{Na}^+(0.433\ 6)$, $\text{Ca}^{2+}(0.291\ 4)$, $\text{Mg}^{2+}(0.123\ 3)$, $\text{K}^+(0.025\ 1)$
Main minerals	Montmorillonite(75.4%), quartz (11.7%), feldspar (4.3%), cristobalite (7.3%)

392
393
394

Table 2 Salt solution and corresponding suction at different temperatures (MPa)(Tang 2005)

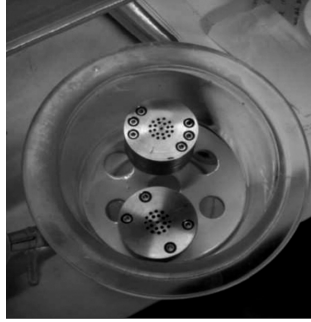
Salt solution	20°C	40°C	60°C
LiCl_2	309.0	–	340
MgCl_2	150.0	162.4	187.7
K_2CO_3	113.0	122.0	144.8
$\text{Mg}(\text{NO}_3)_2$	82.0	103.1	139
NaNO_2	57.0	–	
NaNO_3	39.0	49.5	61.6
NaCl	38.0	40.6	44.2
$(\text{NH}_4)_2\text{SO}_4$	24.9	32.2	
KCl	21.0	27.8	33.4
ZnSO_4	12.6	–	
KNO_3	9.0	–	
K_2SO_4	4.2	5.1	5.5

395



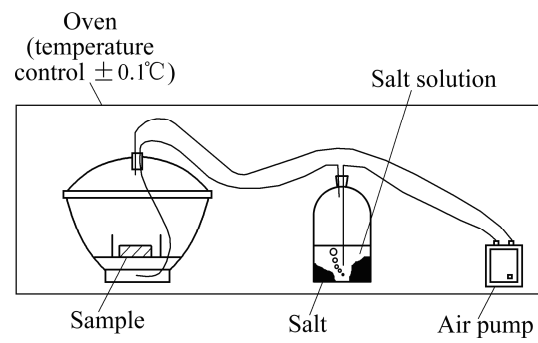
396
397
398
399

Fig. 1. Schematic view of a high level nuclear waste repository (Sanchez, 2004)



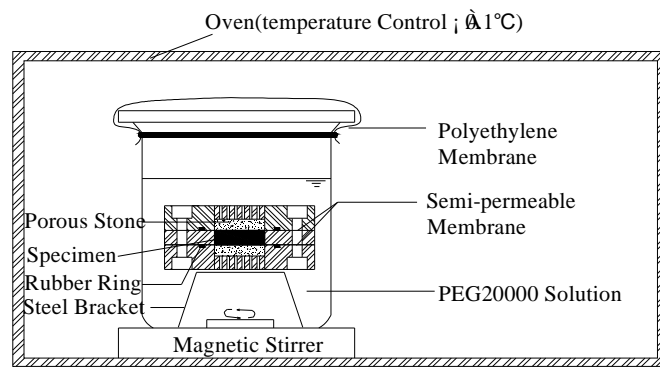
400
401
402

Fig. 2. Constant-volume hydration cell



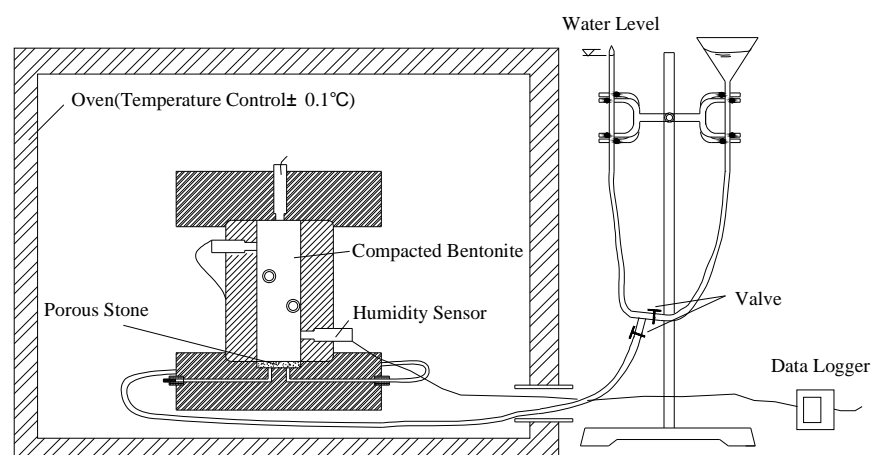
403
404
405

Fig. 3. Setup for the water retention curve determination using the vapor equilibrium technique



406
407
408

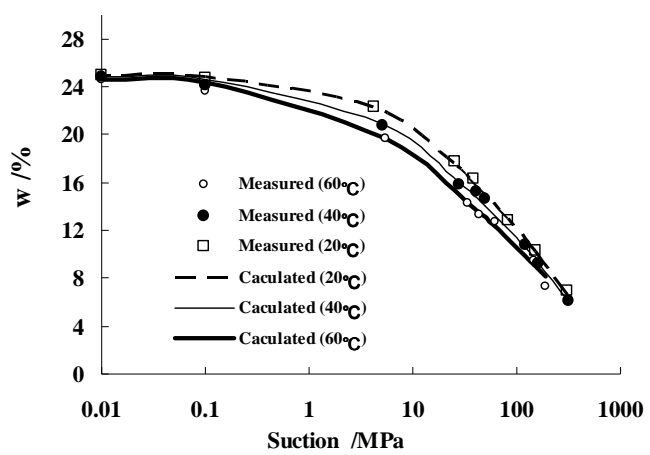
Fig. 4. Setup for the water retention curve determination using the osmotic technique



409

410

Fig. 5. Schematic layout of the temperature controlled infiltration test

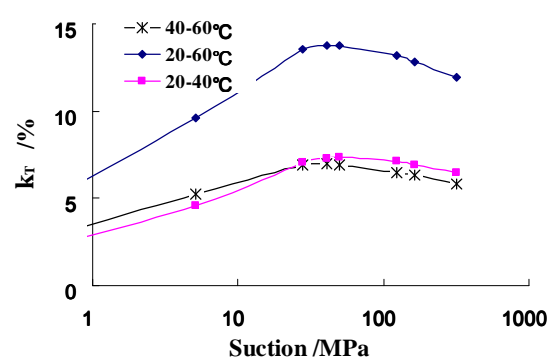


411

412

413

Fig. 6. Water retention curves of the confined specimen at different temperatures

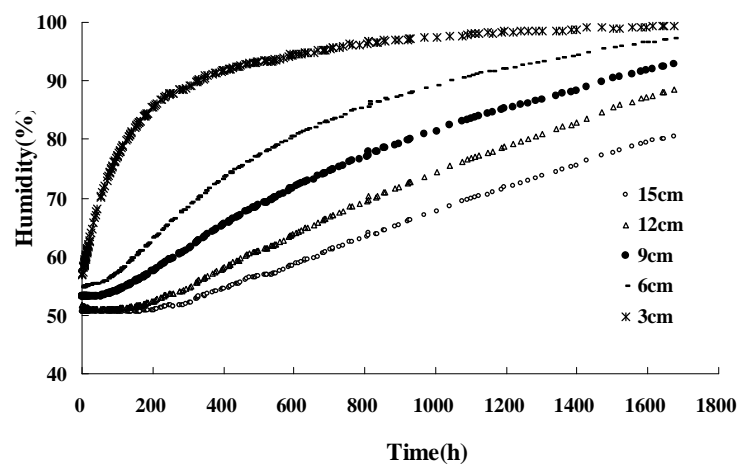


414

415

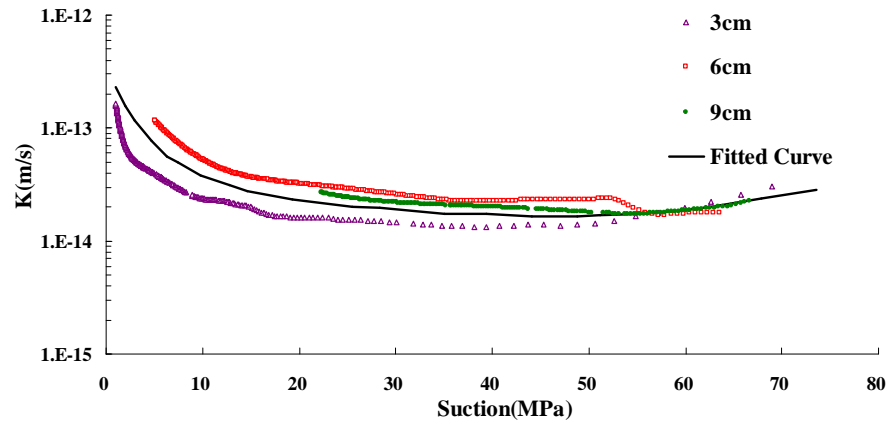
416

Fig. 7. Change of K_T with suction



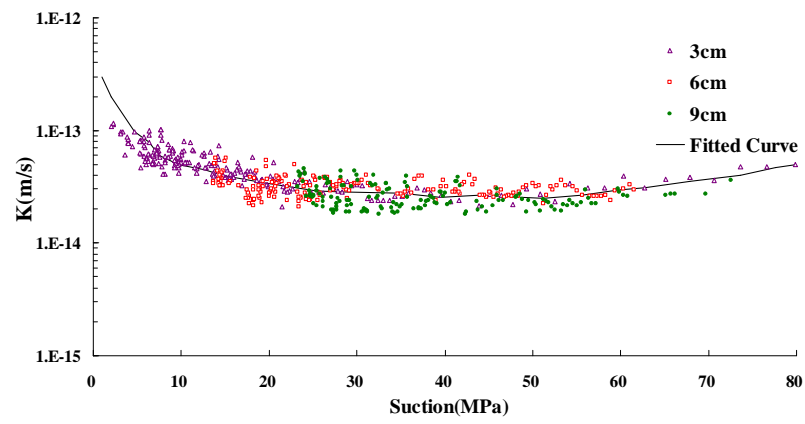
417
418

Fig. 8. Evolution of the relative humidity of confined GMZ01 with time at 40°C



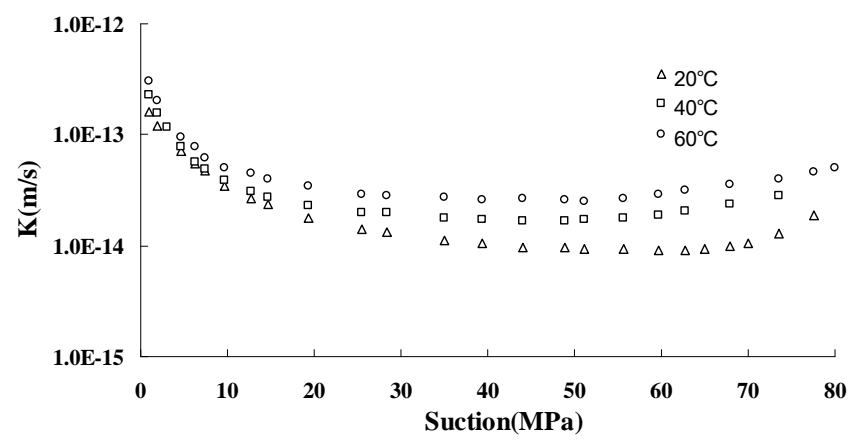
419
420

Fig. 9. Change of unsaturated hydraulic conductivity with suction for the confined GMZ01 at 40°C



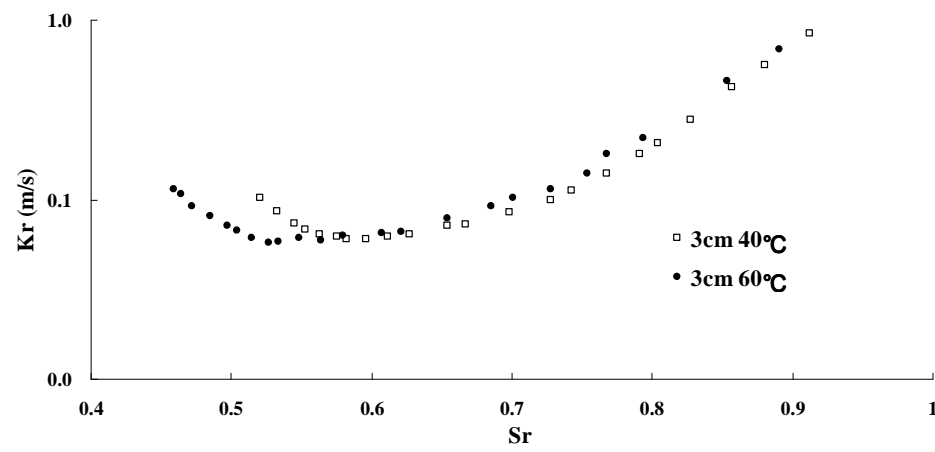
421
422

Fig. 10. Change of unsaturated hydraulic conductivity with suction for the confined GMZ01 at 60°C



423
424
425
426

Fig. 11. Evolution of unsaturated hydraulic conductivity with suction for the confined GMZ01 at different temperatures



427
428
429

Fig. 12. Relationship between Kr and Sr of the confined GMZ01 at 40°C and 60°C