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► **To cite this version:**

Qiong Wang, Anh Minh Tang, Yu-Jun Cui, Pierre Delage, Jean-Dominique Barnichon, et al..  
The effects of technological voids on the hydro-mechanical behaviour of compacted bentonite-  
sand mixture. Soils and Foundations, Japanese Geotechnical Society, 2013, 53 (2), pp.232-245.  
10.1016/j.sandf.2013.02.004 . hal-00829480

**HAL Id: hal-00829480**

**<https://hal-enpc.archives-ouvertes.fr/hal-00829480>**

Submitted on 3 Jun 2013

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1           The effects of technological voids on the hydro-mechanical  
2           behaviour of compacted bentonite-sand mixture

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## 26 **Abstract**

27 Compacted bentonite-based materials are often used as buffer materials in radioactive  
28 waste disposal. A good understanding of their hydro-mechanical behaviour is essential  
29 to ensure the disposal safety. In this study, a mixture of MX80 bentonite and sand was  
30 characterized in the laboratory in terms of water retention property, swelling pressure,  
31 compressibility and hydraulic conductivity. The effects of the technological voids or  
32 the voids inside the soil were investigated. The technological voids are referred to as  
33 the macro-pores related to different interfaces involving the buffer material, whereas  
34 the voids inside the soil is referred to as the common macro-pores within the  
35 compacted bentonite/sand mixture. The results obtained show that at high suctions,  
36 the amount of water absorbed in the soil depends solely on suction, whereas at low  
37 suctions it depends on both suction and bentonite void ratio. There is a unique  
38 relationship between the swelling pressure and the bentonite void ratio, regardless of  
39 the sample nature (homogeneous or not) and sand fraction. However, at the same  
40 bentonite void ratio, a higher hydraulic conductivity was obtained on the samples with  
41 technological voids. The effect of sand fraction was evidenced in the mechanical yield  
42 behaviour: at the same bentonite void ratio, the bentonite-sand mixture yielded at a  
43 higher pre-consolidation stress.

44

45 **Keywords:** Bentonite-sand mixture; Technological voids effects; Water retention  
46 property; Swelling pressure; Hydraulic conductivity; Compressibility.

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48

## 49 **1 INTRODUCTION**

50 Most designs of deep geological repository for high level radioactive wastes (HLW)  
51 are based on the multi-barrier concept with isolation of the waste from the  
52 environment. The multi-barrier concept includes the natural geological barrier (host  
53 rock), engineered barriers made up of compacted sand-bentonite mixtures (placed  
54 around waste containers or used as buffer and sealing elements) and metal canister.  
55 Compacted bentonite-based materials are relevant materials for this purpose thanks to  
56 their low permeability, high swelling and high radionuclide retardation capacities  
57 (Pusch, 1979; Yong et al., 1986; Villar and Lloret, 2008; Komine and Watanabe, 2010;  
58 Cui et al., 2011).

59 Engineered barriers are often made up of compacted bricks. When bricks are placed  
60 around waste canisters or to form sealing buffers, the so-called technological voids  
61 either between the bricks themselves or between bricks, canisters and the host rock  
62 are unavoidable. As an example, 10 mm thick gaps between bentonite blocks and  
63 canister and 25 thick mm gaps between the bentonite blocks and the host rock have  
64 been considered in the basic design of Finland (Juvankoski, 2010). These  
65 technological voids appeared to be equal to 6.6 % of the volume of the gallery in the

66 FEBEX mock-up test (Martin et al., 2006). Fractures that appear in the excavation  
67 damaged zone within the host rock in the near field constitute additional voids. In the  
68 French concept, the volume of the bentonite/rock gaps is estimated at 9 % of the  
69 volume of the gallery by the French waste management agency (ANDRA 2005). This  
70 value reaches 14 % in the SEALEX in-situ test carried out in the Tournemire  
71 Underground Research Laboratory (URL) run by IRSN (Institut de radioprotection et  
72 de sûreté nucléaire, the French expert national organisation in nuclear safety) in  
73 South-West of France (Barnichon and Deleruyelle, 2009).

74 Once placed in the galleries, engineered barriers are progressively hydrated by pore  
75 water infiltrating from the host-rock. This water infiltration is strongly dependent on  
76 the initial state of the compacted material (water content, suction and density, e.g. Cui  
77 et al. 2008). Indeed, it has been shown that water transfer in unsaturated swelling  
78 compacted bentonites or sand bentonite mixtures is strongly dependent on the  
79 imposed boundary conditions in terms of volume change. As shown in Yahia-Aissa et  
80 al. (2001), Cui et al. (2008) and Ye et al. (2009), the degree of swelling allowed  
81 significantly affects the amount of infiltrated water, with much water absorbed when  
82 swelling is allowed and a minimum amount of water absorbed when swelling is  
83 prevented. Volume change conditions also appeared to have, through microstructure  
84 changes, significant influence on the hydraulic conductivity.

85 In this regard, the degree of swelling allowed by the technological voids described  
86 above has a significant influence on the hydro-mechanical behaviour of the  
87 compacted bentonite and their effects need to be better understood. Swelling results in  
88 a decrease in dry density that may lead to a degradation of the hydro-mechanical  
89 performance of engineered barriers (Komine et al., 2009, Komine, 2010). As a result,  
90 the safety function expected in the design may no longer be properly ensured.  
91 Therefore, a better understanding of the effects of the technological voids is essential  
92 in assessing the overall performance of the repository.

93 In this study, a series of tests was performed on a compacted bentonite-sand mixture  
94 samples, aiming at investigating the effects of technological voids on their  
95 hydro-mechanical behaviour. Temperature effects were not considered and tests were  
96 carried out at constant ambient temperature ( $20\pm 1^\circ\text{C}$ ). Given that the paper deals with  
97 the hydration of engineered barriers in the repository, neither the drying process nor  
98 hysteresis effects were considered.

99 Firstly, the water retention curve was determined under both free swell and restrained  
100 swell conditions; secondly, the effects of a pre-existing technological void on both the  
101 swelling pressure and hydraulic conductivity were investigated; finally, the  
102 compressibility at different void ratios was studied by means of suction-controlled  
103 oedometer tests. An overall analysis of the effects of voids on the hydro-mechanical  
104 response of the engineered barrier was finally performed.

## 105 2 MATERIALS AND METHODS

### 106 2.1 Materials and sample preparation

107 A commercial MX80 Na-bentonite from Wyoming, USA was used. The bentonite  
108 powder was provided with an initial water content of 12.2% and was stocked in a  
109 hermetic container to maintain the water content constant, in a room at  $20\pm 1^\circ\text{C}$ . All  
110 tests were performed at this temperature.

111 This MX80 Na-bentonite is characterised by a high montmorillonite content (80%), a  
112 liquid limit of 575%, a plastic limit of 53% and a unit mass of the solid particles of  
113  $2.77 \text{ Mg/m}^3$ . The cation exchange capacity (CEC) is 76 meq/100g (83 % of Na). The  
114 grain size distribution (Figure 1) determined using a hydrometer (French standard  
115 AFNOR NF P94-057) on deflocculated clay shows that the clay fraction ( $< 2 \mu\text{m}$ ) is  
116 84%. The X-Ray diffractometer diagram of the clay fraction presented in Figure 2  
117 shows a peak at  $12.5 \text{ \AA}$ , typical of montmorillonite (this peak shifted from 12.5 to  
118  $16.9 \text{ \AA}$  when treated with glycol and to  $9.5 \text{ \AA}$  when dried). These data are comparable  
119 with that provided by Montes-H et al., (2003).

120 The sand used in the mixture was a quartz sand from the region of Eure and Loire,  
121 France, that passed through a 2 mm sieve. Figure 1 shows the sand grain size  
122 distribution curve determined by dry sieving (AFNOR NF P94-056). The curve is  
123 characterized by a uniformity coefficient  $C_u$  of 1.60 and a  $D_{50}$  close to 0.6 mm. The  
124 unit mass of the sand grains is  $2.65 \text{ Mg/m}^3$ .

125 A water having the same chemical composition as the pore water of the  
126 Callovo-oxfordian claystone from the ANDRA URL in Bure (France), called  
127 synthetic water, was used in the experiments. The corresponding chemical  
128 components (see Table 1) were mixed with distilled water in a magnetic stirrer until  
129 full dissolution.

130 The grain size distribution of the bentonite powder obtained by “dry” sieving is also  
131 presented in Figure 1, showing a well graded distribution around a mean diameter  
132 slightly larger than 1 mm. This curve is close to that of sand. The powder was  
133 carefully mixed with dry sand (70% bentonite - 30% sand in mass) giving a water  
134 content of 8.5% for the mixture. Prior to compaction, the mixture powder was put into  
135 a hermetic container connected to a vapor circulation system (see Figure 3) containing  
136 free water (100% relative humidity), so as to reach a target water content of 11%. The  
137 samples were weighed every two hours until the target water content was attained  
138 (after around two days).

139 A given quantity of mixture was then placed into a rigid ring (35 or 38 mm diameter)  
140 and statically compacted using an axial press at a constant displacement rate of  
141  $0.05 \text{ mm/min}$  to different target dry densities (values given in the following section).  
142 Once the target dry density reached, the displacement shaft was fixed for more than

143 15 h to attain axial stress stabilization (defined by changes in axial stress as low as  
144 0.05 MPa/h). This procedure minimized the sample rebound during unloading.

145 The results from Mercury intrusion porosimetry (MIP) tests on the bentonite/sand  
146 mixtures compacted to dry densities  $\rho_d = 1.67$  and  $1.97 \text{ Mg/m}^3$  and freeze dried are  
147 shown in Figure 4. A typical bimodal porosity (e.g. Ahmed et al. 1974, Delage et al.  
148 1996, Romero et al. 1999) was observed in both samples, defining intra-aggregate  
149 pores (micro-pores) with a mean size of  $0.02 \mu\text{m}$  and inter-aggregate pores  
150 (macro-pores) that depend on the dry density and range from  $10 \mu\text{m}$  (for  $\rho_d = 1.67$   
151  $\text{Mg/m}^3$ ) to  $50 \mu\text{m}$  ( $\rho_d = 1.97 \text{ Mg/m}^3$ ). As shown by Delage and Graham (1995) from  
152 the data of Sridharan et al. (1971), this confirms that compaction only affects the  
153 largest inter-aggregate pores while intra-aggregate pores remain unaffected (see also  
154 Lloret and Villar, 2007). In compacted bentonites, it has been shown that a further  
155 smaller sized pore population (ranging between 0.2 and 2 nm) corresponding to the  
156 intra-particle (interlayer) pores within the aggregates and not detectable by the MIP  
157 had to be also considered (Delage et al., 2006; Lloret and Villar, 2007).

## 158 **2.2 Experimental methods**

### 159 2.2.1 Water retention test

160 The water retention curve (WRC) of the bentonite/sand mixture was determined under  
161 both free swell and restrained swell conditions by using both the vapour equilibrium  
162 technique ( $s > 4.2 \text{ MPa}$ ) and osmotic technique ( $s < 4.2 \text{ MPa}$ ) for suction control.  
163 Three identical samples were used in parallel and the final water content calculated  
164 corresponds to the mean value. To apply suction by the vapour equilibrium technique  
165 under free swell conditions the as-compacted sample (35 mm diameter and 5 mm  
166 height) was placed into a desiccator containing a saturated salt solution at bottom. The  
167 sample mass was regularly measured to monitor the water content variation over time.  
168 In a standard fashion, equilibrium was considered reached when the mass stabilized.  
169 To apply the osmotic technique (Delage et al. 1998; Delage and Cui, 2008a and  
170 2008b), the sample was wrapped by a cylinder-shaped semi-permeable membrane and  
171 placed in a PEG 20 000 solution at a concentration corresponding to the required  
172 suction. The water content at equilibrium under each suction was determined by  
173 weighing.

174 Following Yahia-Aissa et al. (2001), the determination of the water retention curve  
175 under prevented swell conditions (constant volume conditions) was carried out on  
176 samples of 50 mm in diameter and 5 mm in height, placed into a specially designed  
177 rigid stainless steel cell allowing vapour exchanges through two metal porous disks  
178 put on both sides. To apply the osmotic technique, the semi-permeable membrane was  
179 placed between the porous stone and the soil sample (Figure 5a); all was then  
180 sandwiched between two perforated discs and immersed into a PEG solution at the  
181 required concentration. Water infiltrated into the soil through the porous stone and the

182 semi-permeable membrane until the target suction was reached. To apply suction with  
183 the vapour equilibrium technique, the sample sandwiched between two porous stones  
184 was installed between two external plates with valves (Figure 5b) that were connected  
185 to a suction control system using the vapour equilibrium technique. The water content  
186 at equilibrium under each suction was determined by weighing.

187 All the tests performed and the solutions used for suction control (Delage et al., 1998;  
188 Ye et al., 2009) are presented in Table 2. Samples were statically compacted at a dry  
189 density of  $1.67 \text{ Mg/m}^3$ , corresponding to the final dry density adopted in the in situ  
190 experiment at the Tournemire URL.

### 191 2.2.2 Hydration test with technological void (SP 01 - 04)

192 The effect of technological void on the swelling behaviour of the compacted  
193 sand-bentonite mixture was investigated using the device shown in Figure 6. In this  
194 system, a sample is placed inside an oedometer cell placed into a rigid frame  
195 comprising a load transducer that allows the measurement of vertical stress during  
196 hydration. The small vertical strain due to the deformability of the set-up is measured  
197 by a digital micrometer.

198 A technological void of 14% of the total cell volume that corresponds to the situation  
199 of the SEALEX in situ test at the Tournemire URL was set by choosing an initial  
200 diameter of the compacted sample smaller than that of the hydration cell. With a ring  
201 diameter of 38 mm, the annular technological void selected (14% of the total cell  
202 volume representing 17% of the initial sample volume) corresponded to a sample  
203 diameter of 35.13 mm.

204 The sample was hydrated by injecting synthetic water under constant pressure  
205 (0.1 MPa) through a porous disk in contact with the bottom face while the top face  
206 was put in contact with another porous stone so as to allowed free expulsion of either  
207 air or water (see Figure 6). The small water pressure (0.1 MPa) was adopted to avoid  
208 any effect on axial pressure measurement. Changes in axial stress, displacement and  
209 injected water volume over time were monitored. Once the axial stress stabilized  
210 (after more than 35 h , see Figure 9), water injection under 0.1 MPa was continued for  
211 24 h more in order to determine the hydraulic conductivity under permanent flow  
212 condition. Indeed, a linear relationship between flux and time was observed,  
213 confirming the observation of Dixon et al. (1992) about the validity of Darcy's law for  
214 saturated compacted bentonites.

215 Four tests with the same technological void of 14% (SP01 - SP04) were conducted on  
216 samples with the same initial water content of 11% and various initial dry densities  
217 obtained by changing the compaction pressure (between 65 and 85 MPa, giving rise to  
218 dry densities comprised between  $1.93$  and  $1.98 \text{ Mg/m}^3$ , see Table 3). An initial axial  
219 stress of 0.5 MPa was applied on the specimen before hydration to ensure good  
220 contact and satisfactory load measurement (see Figure 6). When water injection

221 started, the piston was fixed and the build-up of axial stress was monitored by the load  
222 transducer.

### 223 2.2.3 Suction controlled oedometer test (SO-01 SO-04)

224 Controlled suction oedometer compression tests were carried out on samples of 10  
225 mm in height and 38 mm in diameter by circulating vapour at controlled relative  
226 humidity at the base of the sample as shown in Figure 7 (tests SO-02/04). A high  
227 pressure oedometer frame was used so as to apply vertical stresses as high as 50 MPa  
228 (Marcial et al., 2002). Zero suction was applied by circulating pure water. Vertical  
229 strain was monitored using a digital micrometer (accuracy  $\pm 0.001$  mm).

230 Prior to compression, samples were hydrated under a low vertical stress of 0.1 MPa  
231 by applying a suction lower than the initial as-compacted value (estimated at 65 MPa  
232 from the water retention curve in Figure 8 at  $w = 11\%$ ).

233 As seen in Table 4, the testing program includes 3 standard tests (SO-02 to 04) carried  
234 out on 38 mm diameter samples with an initial dry density of  $1.67 \text{ Mg/m}^3$  under  
235 controlled suctions of 4.2, 12.6 and 38 MPa, respectively. Stabilisation of swelling  
236 under the imposed suctions and a vertical stress of 0.1 MPa were waited for prior to  
237 compression.

238 The configuration of test SO-01 ( $\rho_{di} = 1.97 \text{ Mg/m}^3$ , internal diameter of 35.13 mm), is  
239 similar to that described in Figure 6, with an annular void between the sample and  
240 ring corresponding to a 14% technological void. In this test, the sample was flooded  
241 with synthetic water, imposing zero suction through the liquid phase. The higher  
242  $1.97 \text{ Mg/m}^3$  density was chosen so as to correspond to the previous value of  $1.67$   
243  $\text{Mg/m}^3$  once the technological void clogged by the lateral sample swelling. Obviously,  
244 even though that the global density of sample SO-01 was equal to that of samples  
245 SO-02/04 after swelling, the density of sample SO-01 should not be homogeneous  
246 and should follow a rather axisymmetrical distribution, with lower values in the zone of  
247 former technological void clogged by soil swelling.

248

## 249 **3 EXPERIMENTAL RESULTS**

### 250 **3.1 Water retention curves**

251 Figure 8 presents the wetting path of the water retention curves (WRCs) obtained  
252 under both free swell and restrained swell conditions. For suctions higher than 9 MPa,  
253 the two curves are very similar while a significant difference can be identified in the  
254 range of suction below 9 MPa. When suction reached 0.01 MPa, the water content  
255 under free swell condition is 246.0%, a much higher value than that under restrained  
256 swell condition (25.4%). This confirms that the prevented swelling condition



257 significantly affects the retention property only in the range of low suctions  
258 (Yahia-Aissa et al. 2001, Cui et al. 2008, Ye et al. 2009).

259 The WRCs of samples of pure MX80 bentonite compacted to  $1.7 \text{ Mg/m}^3$  dry unit  
260 mass under both free swell and constant volume conditions determined by Marcial  
261 (2003) are also presented in Figure 8. In the higher suction range ( $s > 9 \text{ MPa}$ ), all data  
262 fall on the same curve, regardless of the imposed condition (swelling allowed or  
263 constant volume) and type and density of material (bentonite-sand mixture at  
264  $1.67 \text{ Mg/m}^3$  or pure bentonite at  $1.7 \text{ Mg/m}^3$ ). By contrast, at lower suctions  
265 ( $s < 9 \text{ MPa}$ ), the water content of the mixture under free swell condition is lower than  
266 that of the pure bentonite at the same suction value.

### 267 **3.2 Effects of the technological void (tests SP01-SP04)**

268 Figure 9 presents the results of the four tests (SP01-SP04) carried out to investigate  
269 the effect of technological void on the swelling pressure during water injection under  
270 a constant pressure of  $0.1 \text{ MPa}$ . As seen in Photo 1, some water escaping from the top  
271 of the cell was observed at the beginning of water injection during the initial increase  
272 of vertical stress (Figure 9). This phase of 25-30 min duration corresponded to the  
273 circulation of water in the annular gap between the sample and the ring. After this  
274 period, the gap was obviously filled by hydrated bentonite with no more outflow  
275 observed. After about 35 h, the vertical stress reached stabilization with final values of  
276  $2.07$ ,  $2.77$ ,  $2.44$ , and  $3.06 \text{ MPa}$  for tests SP01 ( $\rho_{di} = 1.93 \text{ Mg/m}^3$ ), SP02 ( $\rho_{di} = 1.96$   
277  $\text{Mg/m}^3$ ), SP03 ( $\rho_{di} = 1.96 \text{ Mg/m}^3$ ) and SP04 ( $\rho_{di} = 1.98 \text{ Mg/m}^3$ ), respectively. Note  
278 that even though the piston was fixed (Figure 6), small volume changes (vertical  
279 displacements between  $10$  and  $90 \mu\text{m}$ ) were recorded by the displacement transducer  
280 because of the deformability of the system.

### 281 **3.3 Controlled suction compression tests (SO-01, SO-02, SO-03 and SO-04)**

282 The changes in vertical strain with time during suction imposition for tests SO-01,  
283 SO-02, SO-03 and SO-04 are presented in Figure 10. In a standard fashion, higher  
284 vertical strain rates were observed at smaller suctions with final strains of  $1.2\%$  ( $e =$   
285  $0.69$ ),  $5.4\%$  ( $e = 0.73$ ),  $6.8\%$  ( $e = 0.75$ ) and  $18.0\%$  ( $e = 0.97$ ) obtained for suctions of  
286  $38 \text{ MPa}$ ,  $12.6 \text{ MPa}$ ,  $4.2 \text{ MPa}$  and  $0 \text{ MPa}$ , respectively.

287 The significantly faster hydration observed in test SO-01 (in which liquid water was  
288 used imposing a zero suction) was mainly due to the technological void that allowed  
289 water circulation around the sample. This first phase was comparable with that of tests  
290 SP-02/04 presented in Figure 9.

291 Figure 11 depicts the final void ratios obtained versus the imposed suctions in a  
292 semi-logarithmic plot. The points are reasonably located along a line and the  
293 following relationship can be derived:

$$294 \quad e = -0.048 \ln(s) + 0.848 \quad (\text{Eq.1})$$

295 where  $e$  is the void ratio at equilibrium and  $s$  is suction in MPa.

296 Once equilibrated at the desired suction, samples were submitted to controlled-suction  
297 compression. The compression curves are presented in Figure 12 in a diagram giving  
298 the changes in void ratio  $e$  with respect to vertical net stress ( $\sigma_v - u_a$ ) in which  $u_a$  is  
299 the air pressure, equal to the atmospheric pressure. Given the significant concerns  
300 about the validity of effective stress in unsaturated soils, it was preferred to use the  
301 independent variables approach involving the vertical net stress ( $\sigma_v - u_a$ ) and suction  
302 ( $s = u_w - u_a$ ), (Coleman 1962, Fredlund and Morgenstern, 1977, Gens 1996).

303 Initial void ratios were very different because of the significant dependence of initial  
304 swelling with respect to the suction imposed. Also, the sample SO-01 was not a  
305 homogeneous one, as commented above.

306 Each sample exhibited a slightly S-shaped compression curve. In a standard fashion,  
307 the compression curves are characterized by an initial linear branch with a low  
308 compressibility (pseudo-elastic domain) followed by a second branch with a higher  
309 compressibility (plastic domain) and a slight upward curvature at higher stresses.

310 As suggested by other authors (Keller et al., 2004; Tang et al., 2009), the points at  
311 high stresses were not used for determining the compression coefficient ( $C_c$ ) and the  
312 yield stress ( $\sigma_y$ ) delimitating the pseudo-elastic zone and the plastic one. Figure 13  
313 shows the changes in yield stress with respect to suction. Also plotted in this Figure  
314 are the data obtained by Marcial (2003) on pure bentonite samples. Figure 13  
315 confirms that suction decrease significant reduce the yield stress for both the mixture  
316 and pure bentonite samples. There is a linear relationship between yield stress and  
317 suction, and moreover, both curves are reasonably parallel. At a same suction, smaller  
318 yield stresses are observed for the mixture.

319 As also observed by Marcial (2003), the change in compression coefficient with  
320 respect to suction appeared to be non monotonic (Figure 14) with a decrease when  
321 suction was reduced from 38 MPa and 12.6 MPa, followed by an increase when  
322 suction was below 12.6 MPa. Comparison between pure bentonite and sand-bentonite  
323 mixture shows that at any suction, the latter appears to be more compressible with a  
324 larger compression coefficient.

### 325 **3.4 Hydraulic conductivity measurements**

326 The hydraulic conductivity of hydrated samples with initial technological void (tests  
327 SP2-SP4) was measured under constant head when applying the 0.1 MPa water  
328 pressure by recording the volume of injected water by means of a Pressure/Volume  
329 controller (no data were available for test SP01 due to a technical problem with the  
330 Pressure/Volume controller). The determination of hydraulic conductivity was done  
331 over the last 24 h once swelling stabilised. The hydraulic conductivity was also  
332 determined indirectly based on the consolidation curves during different compression  
333 stages of test SO-01 (see Figure 12) using Casagrande's method. As mentioned

334 before, the sample density was not homogeneous in those samples. Therefore, a non  
 335 uniform hydraulic conductivity can be expected for each sample. The measured  
 336 values correspond to the global hydraulic conductivity.

337 The changes in hydraulic conductivity with respect to dry density obtained from both  
 338 methods are presented in Figure 15 and compared with constant head permeability  
 339 measurements obtained by Gatabin et al. (2008) on homogeneous samples at similar  
 340 densities. The data obtained for the heterogeneous samples with both methods are in  
 341 good agreement. In a standard fashion, the hydraulic conductivity decreases with  
 342 density increase following a slope comparable to that obtained by Gatabin et al.  
 343 (2008). An in-depth examination shows that the samples tested here exhibit higher  
 344 hydraulic conductivity than that by Gatabin et al. (2008), with a difference of one  
 345 order of magnitude. This difference is suspected to be due to a preferential water flow  
 346 in the looser zone (initial technological voids) around the samples.  
 347

#### 348 **4 INTERPRETATION AND DISCUSSION**

349 In order to further analyse the effects of the technological void, various constitutive  
 350 parameters of the compacted mixture are now defined (see Figure 16), such as for  
 351 instance the bentonite void ratio ( $e_b$ ). It is supposed that the volume of bentonite ( $V_b$ )  
 352 in the mixture is equal to the difference between the total volume ( $V$ ) and the volume  
 353 of sand ( $V_s$ ).  $V_b$  is equal to the sum of the bentonite particle volume ( $V_{bs}$ ) and the  
 354 volume of void, namely intra-void volume ( $V_i$ ). The parameter  $e_b$  consists of two parts  
 355 (Eq.2), the intra-bentonite void ratio inside the soil ( $e_{bi}$ ) and the void ratio  
 356 corresponding to the technological void ( $e_{tech}$ ). Eq.3 and Eq. 4 define these two voids,  
 357 respectively.

$$358 \quad e_b = e_{bi} + e_{tech} \quad (\text{Eq.2})$$

$$359 \quad e_{bi} = \frac{V_i}{V_{bs}} \quad (\text{Eq.3})$$

$$360 \quad e_{tech} = \frac{V_{tech}}{V_{bs}} \quad (\text{Eq.4})$$

361 where  $V_{tech}$  is the volume of technological void. The value of  $e_{bi}$  can be deduced from  
 362 the initial dry unit mass of the mixture ( $\rho_{dm}$ ) using Eq.5 and Eq.6.

$$363 \quad e_{bi} = \frac{G_{sb}\rho_w}{\rho_{db}} - 1 \quad (\text{Eq.5})$$

$$364 \quad \rho_{db} = \frac{(B/100)\rho_m G_{ss}\rho_w}{G_{ss}\rho_w(1 + w_m/100) - \rho_m(1 - B/100)} \quad (\text{Eq.6})$$

365 where  $\rho_w$  is the water unit mass,  $G_{sb}$  is the specific gravity of bentonite,  $\rho_{db}$  is the

366 initial dry unit mass of bentonite in the mixture, which was calculated using Eq.6  
 367 (Dixon et al., 1985; Lee et al., 1999; Agus and Schanz, 2008; Wang et al., 2012),  $\rho_m$  is  
 368 the unit mass of the mixture,  $B$  (%) is the bentonite content (in dry mass) in the  
 369 mixture,  $G_{ss}$  is the specific gravity of sand,  $w_m$  is the water content of the mixture. In  
 370 this study the decrease of water unit mass ( $\rho_w$ ) during hydration (e.g. Skipper et al.,  
 371 1991; Villar and Lloret, 2004) was not considered and the value was assumed to be  
 372 constant ( $1.0 \text{ Mg/m}^3$ ),  $B = 70\%$ ,  $G_{ss} = 2.65$ .

373 To analyse the water retention property under free swell condition, a parameter  
 374 namely water volume ratio ( $e_w$ ) defined as the ratio of water volume ( $V_w$ ) to the  
 375 bentonite volume ( $V_{bs}$ ) is also adopted (Romero et al., 2011). This parameter can be  
 376 deduced from the water content of the mixture ( $w_m$ ) using the following equation:

$$377 \quad e_w = \frac{w_m G_{sb}}{B} \quad (\text{Eq.7})$$

378 In the following, the two parameters  $e_b$  and  $e_w$  are used to analyze all experimental  
 379 results obtained in order to evidence the effects of voids on the water retention  
 380 capacity, the swelling pressure, the compressibility and the hydraulic conductivity.

#### 381 **4.1 Water retention curves**

382 Figure 17a shows the changes in water volume ratio  $e_w$  of both the mixture and the  
 383 pure bentonite with respect to suction under free swell condition. Unlike in the water  
 384 content/suction plot (Figure 8), Figure 17a shows an excellent agreement with Marcial  
 385 (2003)'s data on pure bentonite, with a unique relationship between  $e_w$  and suction  
 386 along the wetting path with swelling. It confirms that water was only adsorbed in the  
 387 bentonite (volume  $V_{bs}$ ) and that the lower water content observed in the mixture at  
 388 same suction (Figure 8) is related to the lower volume of bentonite in the mixture.

389 The results from the hydration tests on pure compacted bentonites under restrained  
 390 swell condition with different void ratios (Marcial, 2003; Tang and Cui, 2010; Villar,  
 391 2005) are also presented in Figure 17. A phenomenon similar to that observed in the  
 392 water content/suction plane (Figure 8) can be identified: in the range of low suctions  
 393 ( $<9 \text{ MPa}$  for the MX80 bentonite), the water retention property of bentonite depends  
 394 strongly on the confining conditions; conversely, all curves become almost the same  
 395 in the range of high suctions (as also observed by Agus 2005 and Agus et al. 2010) As  
 396 suggested by Cui et al. (2002, 2008) and Ye et al. (2009), this confirms that the  
 397 exfoliation of clay particles from the aggregates into inter-aggregate pores caused by  
 398 hydration is moderate and can be accommodated at high suctions. By contrast, at  
 399 lower suctions, available pores become completely full by hydrated clay particles and  
 400 no more water can be adsorbed. This is not the case when swelling is allowed with  
 401 much more water adsorbed. Figure 17b is a zoom of Figure 17a at small water volume  
 402 ratios (between 0 and 1.5). The difference observed in the curves at constant volume

403 is due to differences in bentonite dry density  $\rho_{db}$ . When the full saturation is  
404 approached, samples with a higher bentonite void ratio (lower dry density) logically  
405 absorb more water for a given suction.

#### 406 **4.2 Hydration test with technological void**

407 The values of vertical stress measured on heterogeneous samples at the end of the  
408 hydration tests on samples with technological voids (SP 01-04) are presented in  
409 Figure 18 with respect to the bentonite void ratio. Note that the bentonite void ratios  
410 for tests SP 01-04 were determined by taken into account the system deformation  
411 mentioned above (i.e. vertical displacements between 10 and 90  $\mu\text{m}$ ). The data of  
412 swelling stresses measured in homogeneous samples under the same conditions of  
413 constant volume by other authors are also plotted for comparison (MX80 70/30  
414 bentonite/sand mixture from Karnland et al., 2008 and pure MX80 bentonite from  
415 Börgesson et al., 1996; Dixon et al., 1996; Karnland et al., 2008; Komine et al., 2009).

416 All data remarkably agree, providing a unique relationship between the vertical  
417 pressure and the bentonite void ratio, regardless of the sample nature (homogeneous  
418 or not). The correspondence with data from Karnland (pure bentonite and 70/30  
419 bentonite sand mixture) at bentonite void ratio close to 1 is particularly good. The  
420 following expression can be deduced for the relationship between the axial stress ( $\sigma_s$   
421 in MPa) and the bentonite void ratio  $e_b$  for the material studied here:

$$422 \quad \sigma_s = 2.250e_b^{-1.149} \quad (\text{Eq.8})$$

423 This good correspondence between the response in swelling stress of homogeneous  
424 samples and that in axial stress of a hydrated heterogeneous sample indeed confirms  
425 that the stress at equilibrium is not affected by the heterogeneity of the samples. The  
426 pressure ( $\sigma_s$  in MPa) only depends on the global bentonite void ratio ( $e_b$ ), regardless  
427 of the technological void and of the presence of sand.

428 In other words, during the hydration under constant global volume and in spite of their  
429 significant difference in form and dimension, the technological voids play the same  
430 role as the macro-pores of the homogeneous compacted bentonite in terms of filling  
431 voids by particle exfoliation, as commented above. The global final bentonite void  
432 ratio (or density) appears to be a relevant parameter allowing predicting the final axial  
433 stress obtained.

#### 434 **4.3 Compressibility**

435 The interpretation of the compressibility data was based on the well known features of  
436 the aggregate microstructure of compacted soils that have been recalled above,  
437 showing in particular that the compression at constant water content of unsaturated  
438 compacted soils initially occurs by the collapse of large inter-aggregate pores full of  
439 air with little effect on the aggregates themselves. As a consequence, it was observed

440 that the changes in suction during compression at constant water content are  
441 negligible, since suction changes are governed by intra-aggregate clay water  
442 interactions that are little affected during compression (Li, 1995; Gens et al., 1995;  
443 Tarantino and De Col, 2008).

444 The compression curves of the homogeneous samples in Figure 12 (SP2 to 4) are  
445 further interpreted by an approximated estimation of the changes in degree of  
446 saturation during compression. This estimation is based on the assumption that the  
447 order of magnitude of the initial water contents of the samples hydrated from the  
448 initial as-compacted suction (65 MPa) at given suctions (38, 12.6 and 4.2 MPa) prior  
449 to compression can be obtained from the wetting path of the water retention curve in  
450 Figure 17. Based on this assumption, the water contents after hydration were  
451 determined, equal to 12.8, 16.8 and 18.6 % for suctions of 38, 12.6 and 4.2 MPa,  
452 respectively. The corresponding degrees of saturation are 52, 63 and 68%,  
453 respectively.

454 The application of suctions as high as 4.2, 12.6 and 38 MPa generated a moderate  
455 swelling of the samples, with void ratio increasing from the initial value of 0.64 to  
456 0.75 at 4.2 MPa suction. In terms of microstructure, the changes corresponds to a  
457 moderate swelling of the aggregates within a structure still significantly desaturated  
458 with a maximum degrees of saturation of 68% at 4.2 MPa suction, indicating that the  
459 inter-aggregates pores remained full of air. During compression, the water content that  
460 was controlled within the aggregates did not suffer from any significant changes and  
461 the changes in degree of saturation could be estimated, as shown in Figure 19. The  
462 data show how the degree of saturation increase with increased stress and provide an  
463 estimation of the stress values at which saturation was reached (9, 14 and 27 MPa at  
464  $s = 4.2, 12.6$  and 38 MPa respectively). Once reported on the compression curves of  
465 Figure 12, we can observe that these stress values are located close to the inflection  
466 points observed on the curves, indicating that these points correspond to the saturation  
467 of the samples. In other words, the change in slope of the curves corresponds to the  
468 transition between two physical mechanisms, namely from the collapse of dry  
469 inter-aggregate pores to the expulsion of inter-aggregate adsorbed water. This is in  
470 agreement with the observation by Kochmanová and Tanaka (2011).

471 When the yield stress ( $\sigma_{v0}$ ) in Figure 13 is plotted versus the corresponding bentonite  
472 void ratio ( $e_b$ ) at the yield point (Figure 20), it appears that for both the mixture and  
473 pure bentonite, the yield stress increases sharply with decreasing bentonite void ratio.  
474 However, the curve of the mixture lies in the right of the pure bentonite's one,  
475 evidencing the role of sand in the compression behaviour. It can be concluded from  
476 Figure 20 that at the same bentonite void ratio, the mixture yields at a higher  
477 pre-consolidation stress.

#### 478 **4.4 Hydraulic conductivity**

479 The values of global hydraulic conductivities presented in Figure 15 showed possible

480 preferential flow pathway in the case of heterogeneous samples with initial  
481 technological voids. This observation can be made also in Figure 21 in which the data  
482 of Figure 15 are re-plotted versus the bentonite void ratio and compared to other data  
483 of the pure MX80 bentonite (Karnland et al., 2008; Dixon et al., 1996) and of the  
484 70/30 bentonite-sand mixture (Gatabin et al., 2008). The good agreement observed  
485 also confirms a negligible effect of sand on the hydraulic conductivity.

486 Note that the looser zone corresponding to the initial technological void is a weak  
487 zone with poorer mechanical resistance, at least on the short term. The question of the  
488 possible further changes that could occur on the long term is opened, given that some  
489 observations already showed that ageing effects are significant in compacted  
490 bentonite, both at microscopic scale (Delage et al. 2006) and macroscopic scale  
491 (Stroes-Gascoyne, 2010), showing a tendency towards density homogenisation.  
492 Further studies are needed to investigate the long term change in hydraulic  
493 conductivity of samples with initial technological voids.

494

## 495 **5 CONCLUSION**

496 The effects of voids on the hydro-mechanical properties of a compacted  
497 bentonite-sand mixture were studied. Water retention test, hydration test, suction  
498 controlled oedometer test and hydraulic test were performed on samples with different  
499 voids including the technological void and the void inside the soil. By introducing the  
500 parameters as bentonite void ratio and water volume ratio, the effects of voids on the  
501 water retention property, the swelling pressure, the compressibility and the hydraulic  
502 conductivity were analyzed.

503 Under different conditions (free swell and restrained swell), different water retention  
504 properties were observed depending on the suction value: at high suctions, the relation  
505 between the water volume ratio and the suction is unique, independent of the test  
506 conditions, indicating that the relatively limited exfoliated clay particles are mainly  
507 accommodated by the macro-pore of the soil. On the contrary, in the range of low  
508 suctions, the macro-pores available for accommodating exfoliated particles becomes  
509 limited in the case of restrained swell condition, explaining why less water is  
510 adsorbed in this case.

511 There is a unique relationship between the axial stress (for samples with technological  
512 void) or swelling pressure (constant volume condition) and the bentonite void ratio,  
513 regardless of the sample nature (homogeneous or not) and presence of sand,  
514 suggesting that the technological voids play the same role as the macro-pores of the  
515 homogeneous compacted bentonite. It also reveals that the swelling mechanisms of  
516 bentonite-sand mixture are the same as that of pure bentonite.

517 The change in slope of the compression curves corresponds to the transition between  
518 two physical mechanisms, namely from the collapse of dry inter-aggregate pores to

519 the expulsion of inter-aggregate adsorbed water.

520 At the same bentonite void ratio, bentonite/sand mixture yields at a higher  
521 pre-consolidation stress, evidencing the effect of sand on the compression behaviour.

522 Similar relationship between hydraulic conductivity and bentonite void ratio was  
523 observed for the bentonite-sand mixture and the pure bentonite without technological  
524 void; however, with the technological void in this study, the measured hydraulic  
525 conductivity for the same bentonite void ratio is generally higher, indicating the  
526 possible preferential flow pathway formed by the swollen soil that occupied the initial  
527 technological void.

528 From a practical point of view, the relationship elaborated between the  
529 hydro-mechanical behaviour with bentonite void ratio is helpful in designing the  
530 buffers/sealing elements with bentonite-based materials: if the bentonite proportion  
531 and the technological void are known, the specification of the buffer elements could  
532 be determined using the correlations elaborated in this study, according to the  
533 requirements in terms of swelling pressure and hydraulic conductivity. Then the water  
534 retention property and compressibility of the selected material can be evaluated. It  
535 should be however noted that the conclusion drawn here was based on the results of  
536 the bentonite/sand mixture with 70% of MX80 bentonite. Further experimental studies  
537 on other proportions and other bentonites are needed to generalise it.

## 538 **ACKNOWLEDGEMENTS**

539 The work was conducted in the framework of the SEALEX project of IRSN and the  
540 PHC Cai Yuanpei project (24077QE). The support of the National Nature Science  
541 Foundation of China (41030748) and that of the China Scholarship Council (CSC) are  
542 also greatly acknowledged.

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732 Table 1. Chemical composition of the synthetic water

Components	NaHCO <sub>3</sub>	Na <sub>2</sub> SO <sub>4</sub>	NaCl	KCl	CaCl <sub>2</sub> .2H <sub>2</sub> O	MgCl <sub>2</sub> .6H <sub>2</sub> O	SrCl <sub>2</sub> .6H <sub>2</sub> O
Mass (g) per Litter of solution	0.28	2.216	0.615	0.075	1.082	1.356	0.053

733

734 Table 2. Test conditions for water retention property

Suction control method	Suction (MPa)	constant volume	Free swell
LiCl	309	–	√
K <sub>2</sub> CO <sub>3</sub>	113	–	√
Mg(NO <sub>3</sub> ) <sub>2</sub>	82	–	√
Saturated salt solution	NaCl	38	√
	(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	24.9	√
	ZnSO <sub>4</sub>	12.6	√
	KNO <sub>3</sub>	9.0	√
	K <sub>2</sub> SO <sub>4</sub>	4.2	√
Concentration of PEG solution (g PEG/g Water)	0.302	1	√
	0.095	0.1	√
	0.030	0.01	√

735

736 Table 3. Specimens used for swelling pressure test

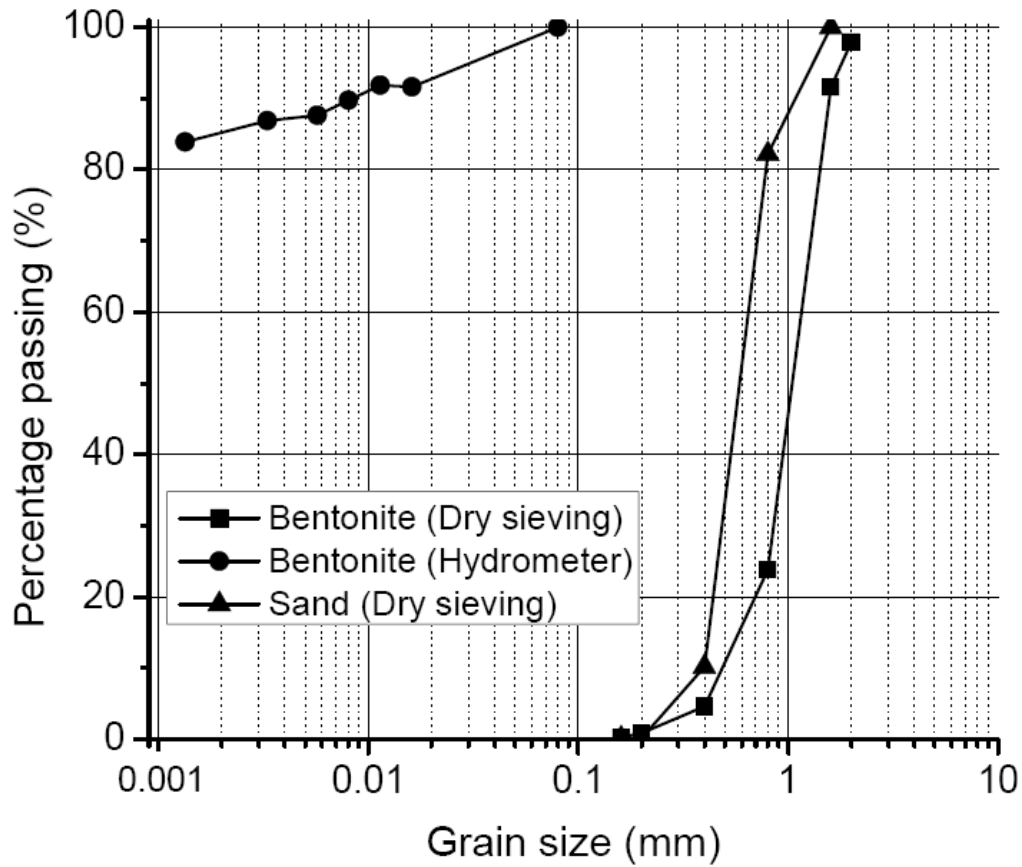
Tests	Compaction Stress (MPa)	Compacted dry density (Mg/m <sup>3</sup> )
SP01	65	1.93
SP02	70	1.96
SP03	80	1.96
SP04	85	1.98

737

738 Table 4 Specimens used for suction controlled oedometer test

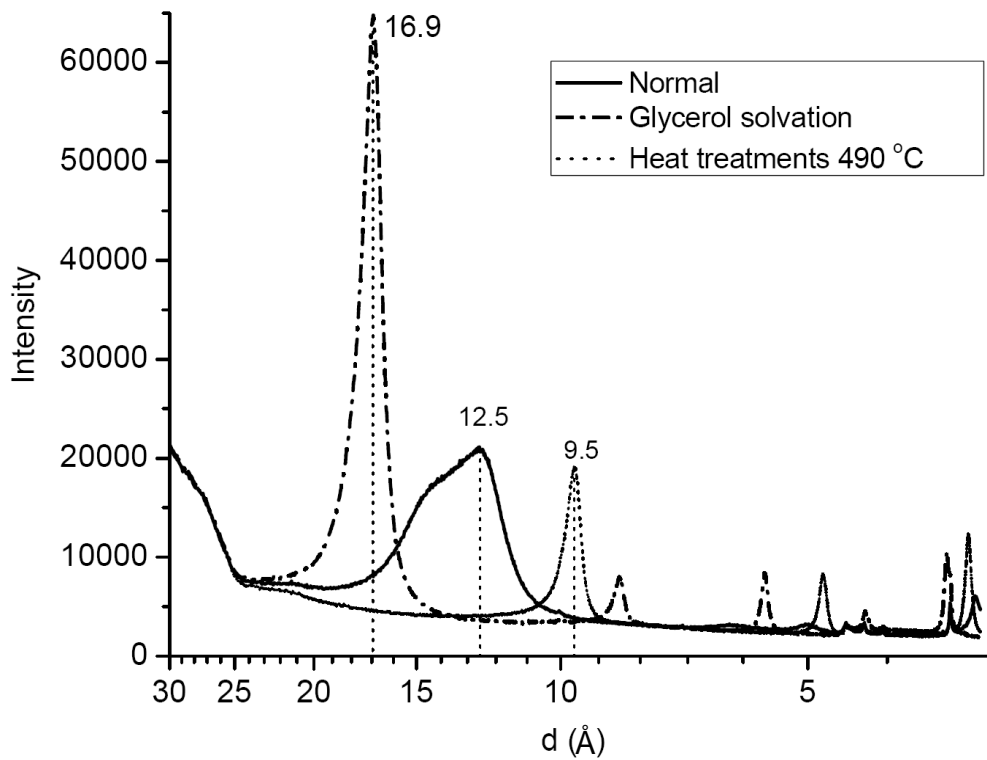
Tests	$\rho_{di}$ (Mg/m <sup>3</sup> )	D (mm)	s (MPa)
SO-01	1.97	35.13	0
SO-02	1.67	38.00	4.2
SO-03	1.67	38.00	12.6
SO-04	1.67	38.00	38

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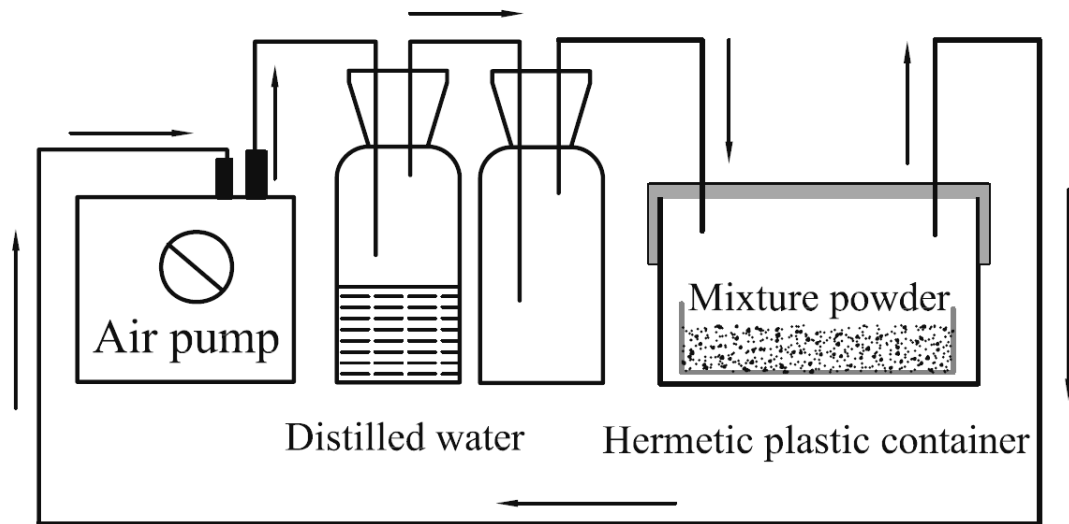
741 Figure 1. Grain size distribution of the MX80 bentonite and sand



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743 Figure 2. X-Ray curves of the MX80 bentonite

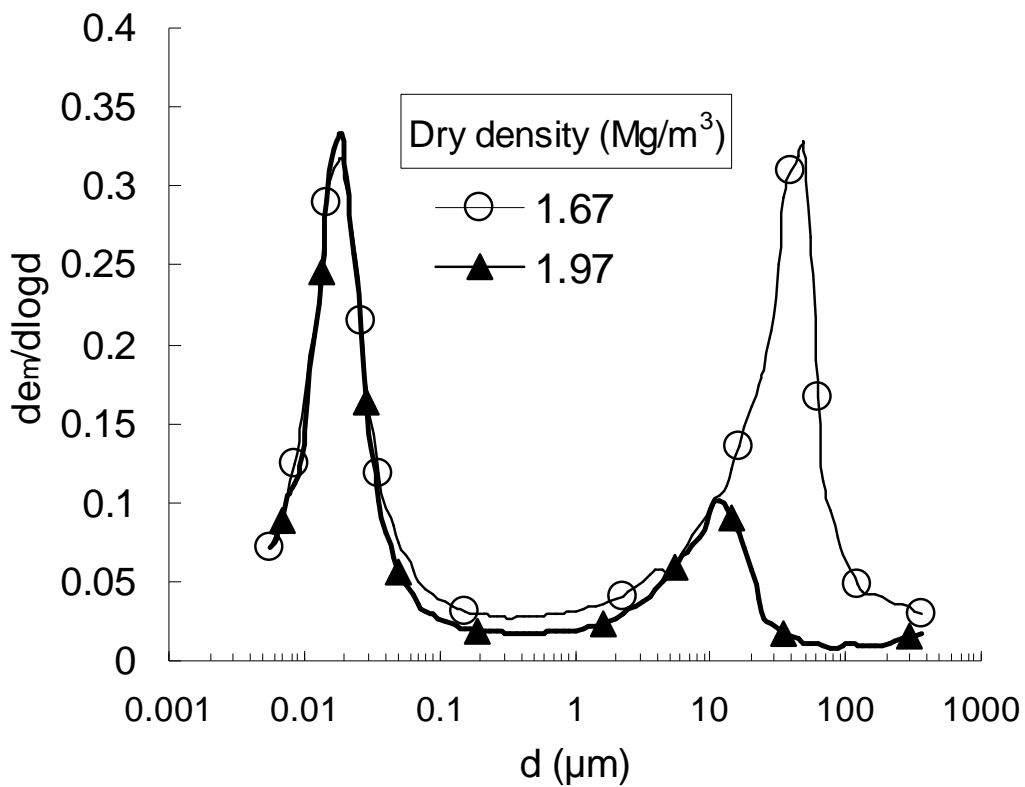
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746 Figure 3. Hermetic plastic container with a vapor circulation system for adjusting water  
747 content

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750 Figure 4. Pore size distribution of bentonite/sand mixture compacted to different dry density  
751 with a water content of about 11.0%

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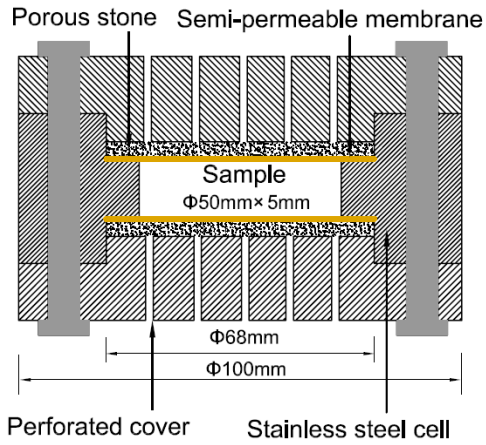
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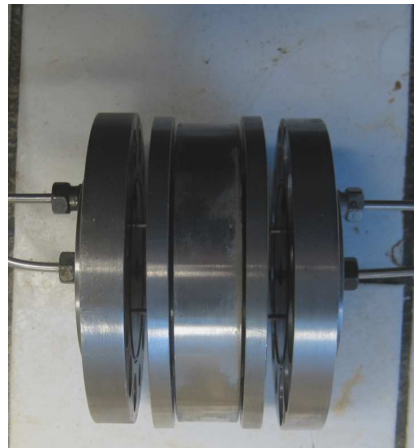
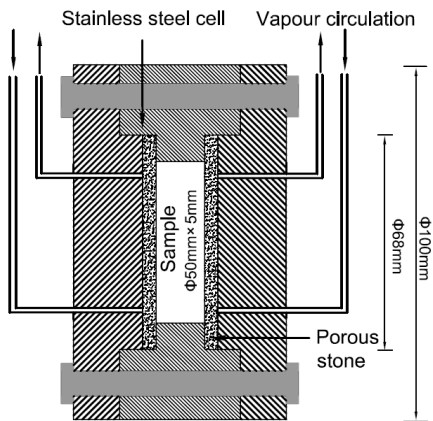
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(a)

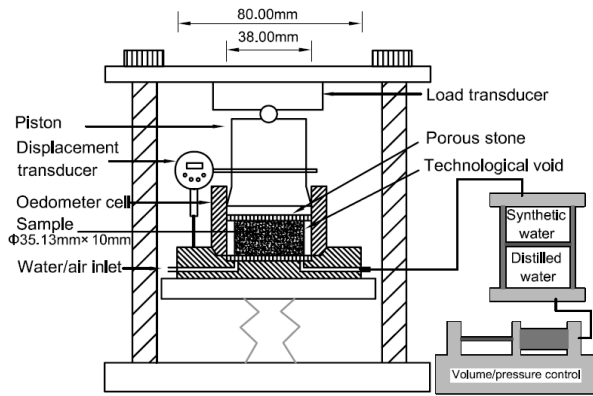


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(b)

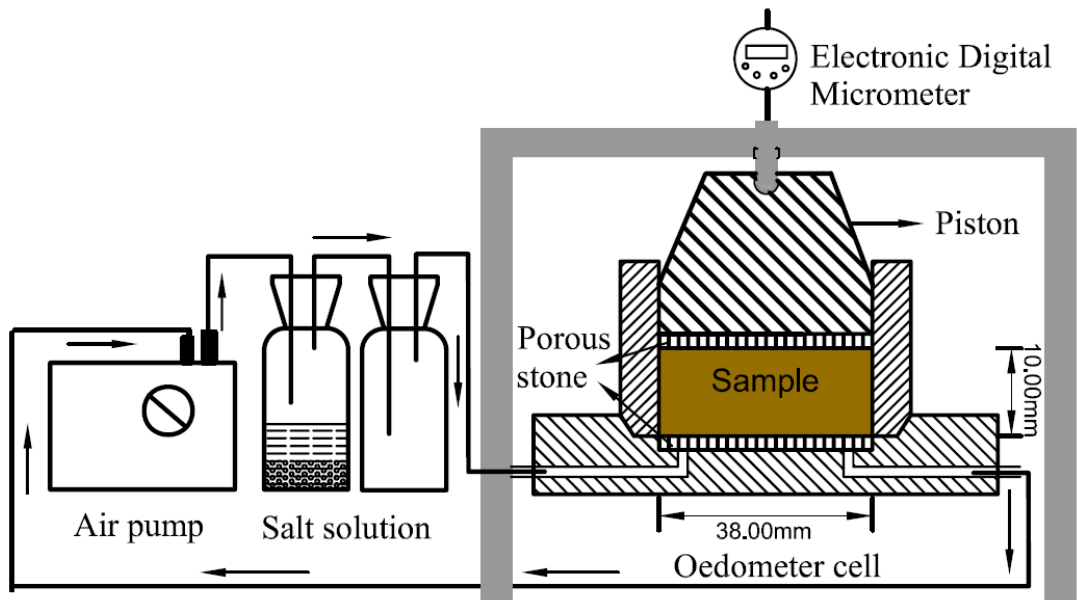
768 Figure 5. Constant volume cell for WRC determination. (a) Osmotic method; (b) Vapour  
769 equilibrium technique





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771 Figure 6. Schematic layout of hydration test with technological void



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773 Figure 7. Experimental setup of suction controlled oedometer test

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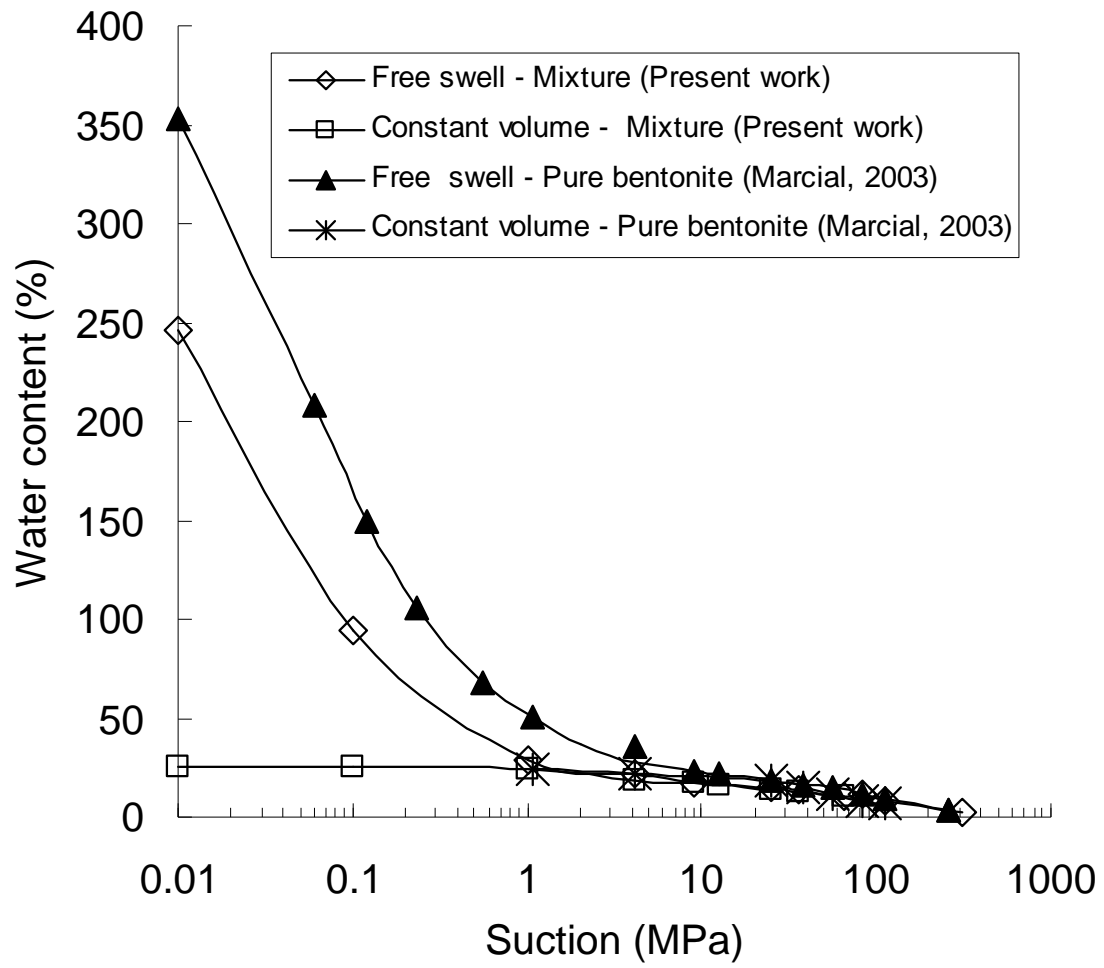
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788 Figure 8. WRCs of bentonite-sand mixture and pure bentonite

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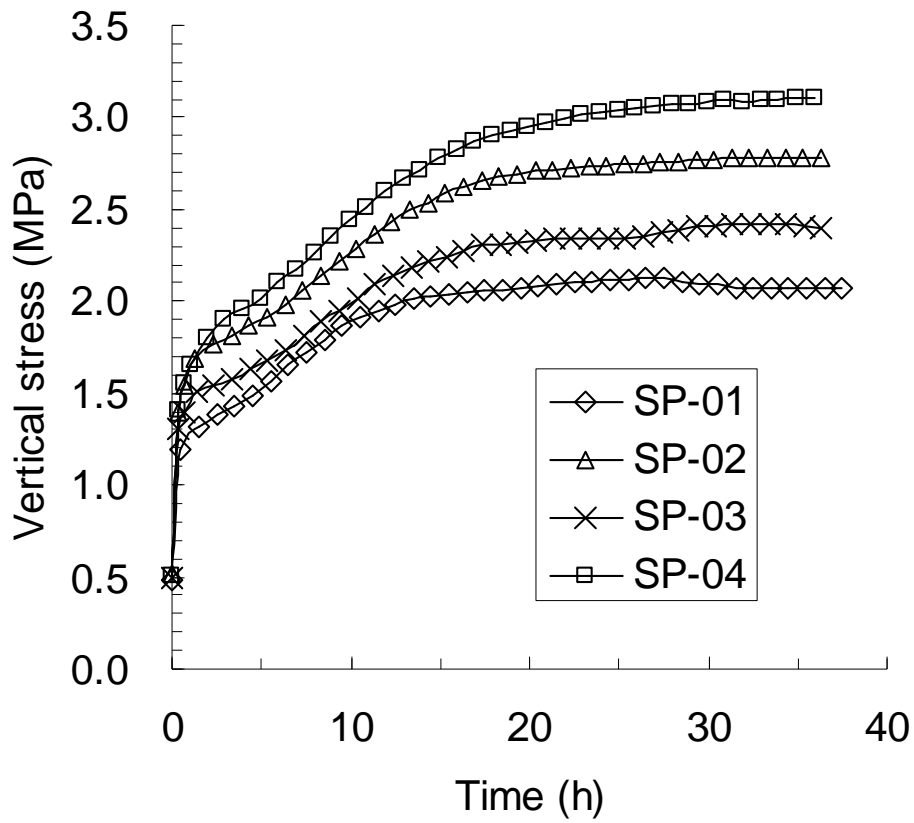
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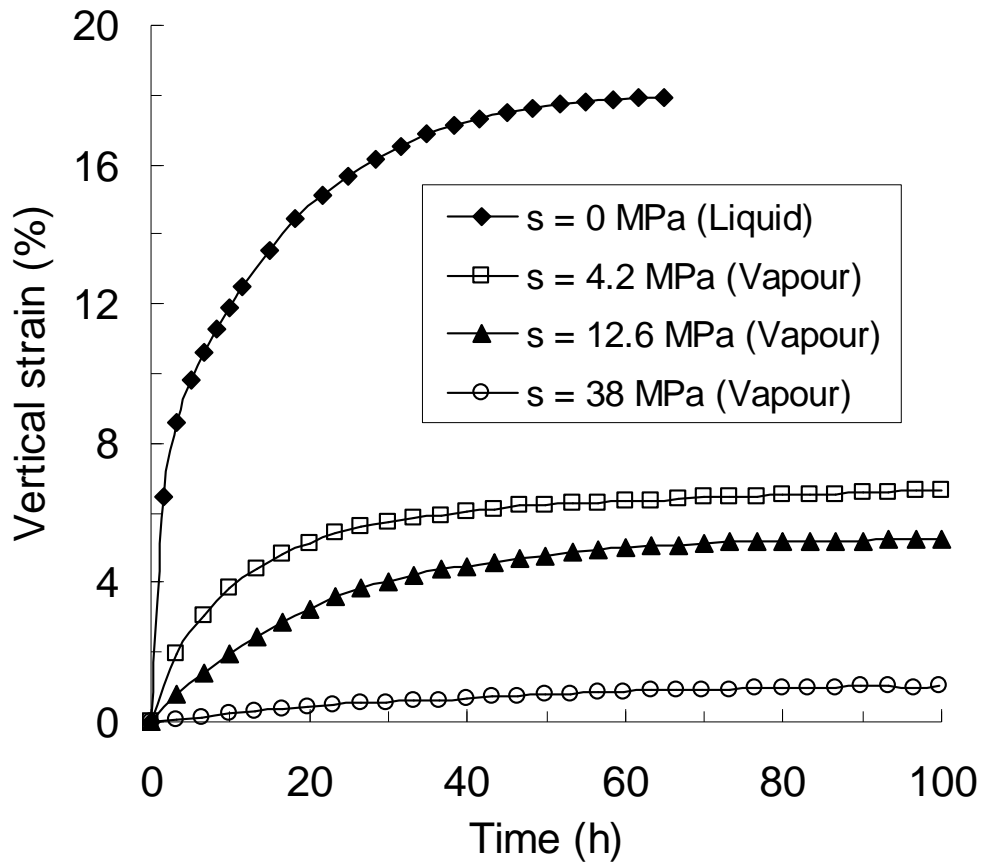
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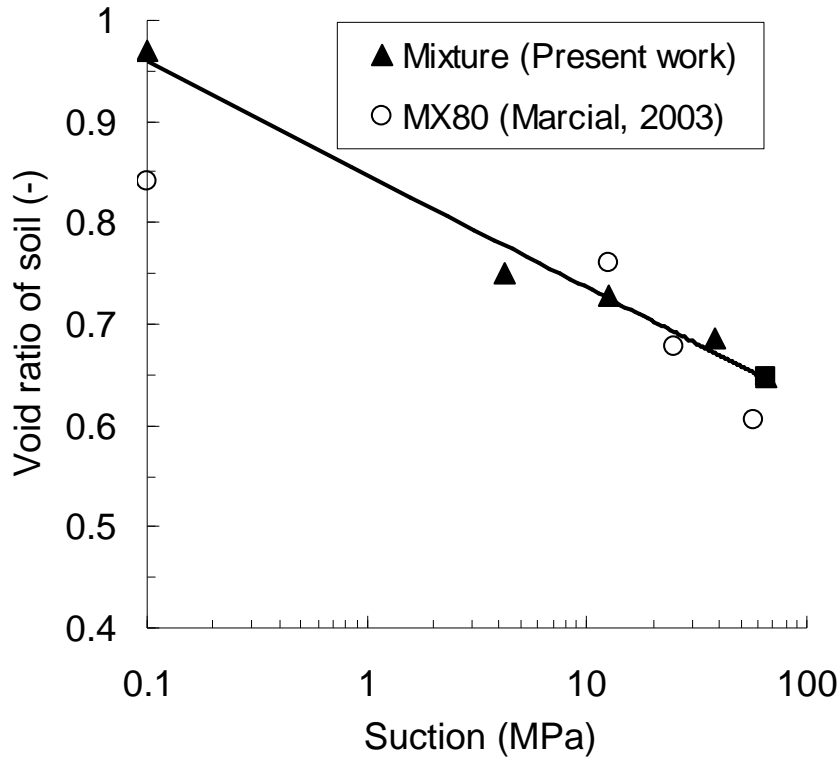
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796  
 797 Figure 9. Evolution of the vertical stress for all hydration tests with technological void  
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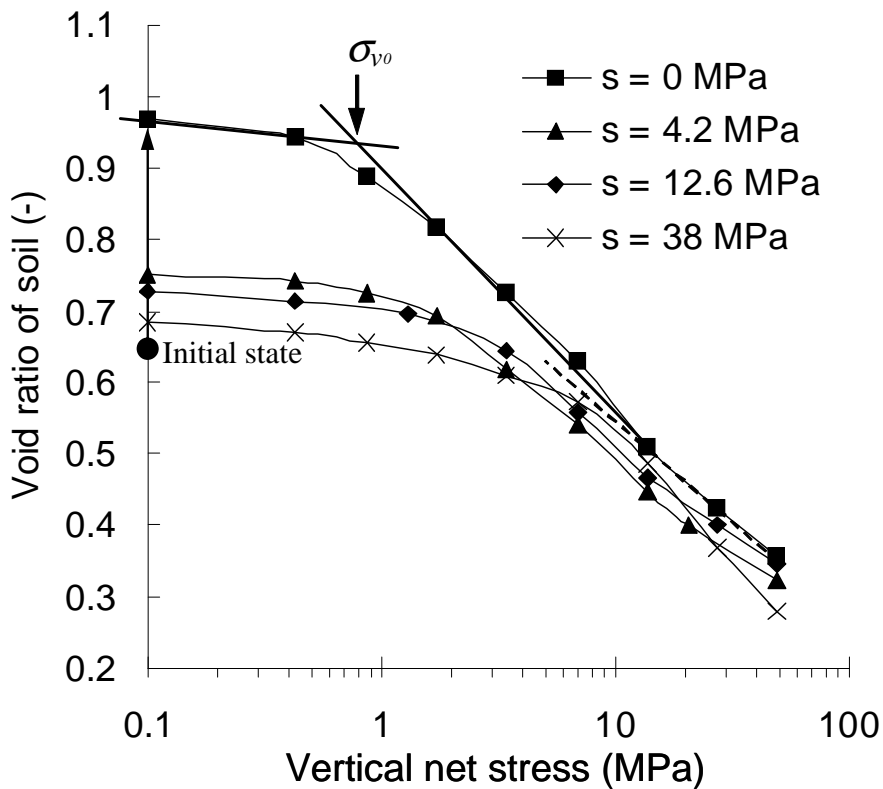


805  
 806 Figure 10. Evolution of vertical strain during suction imposition  
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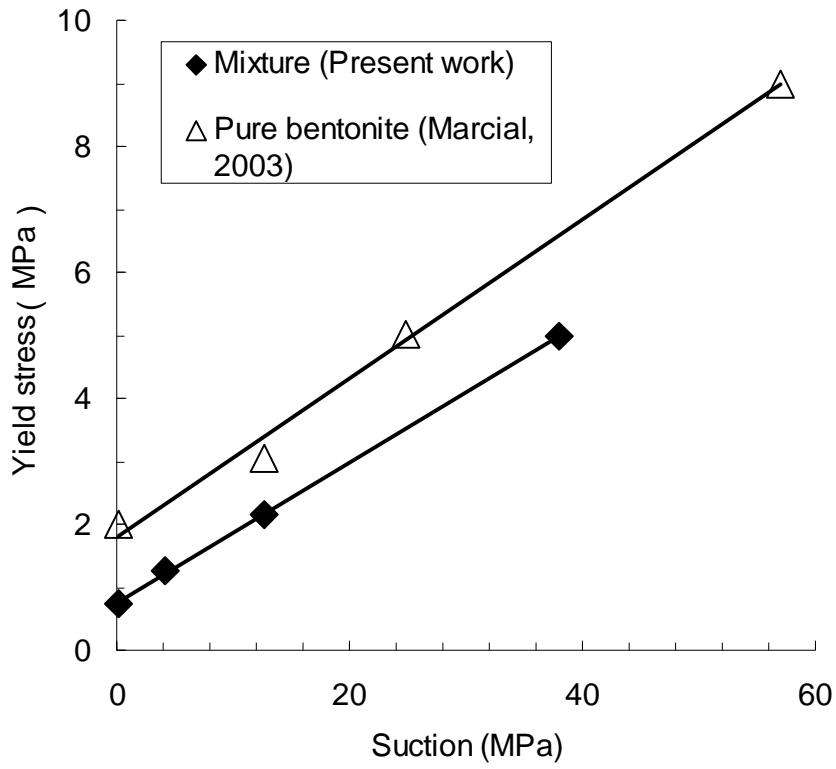
Figure 11. Relationship between void ratio and suction for the compacted sand bentonite mixture.



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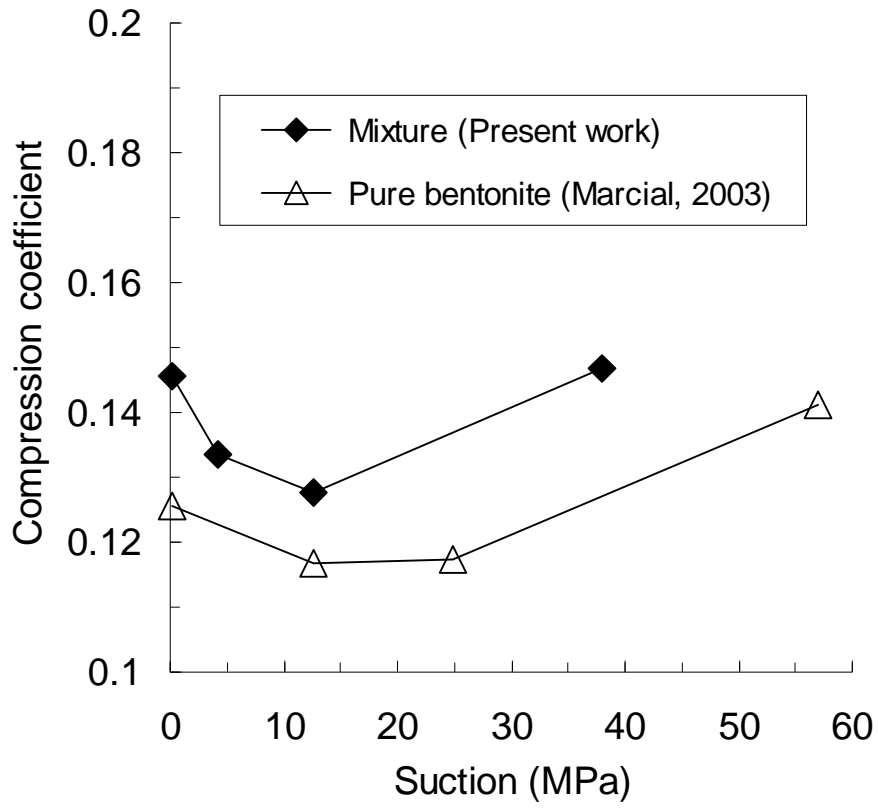
Figure 12. Void ratio of soil versus vertical net stress for different suctions

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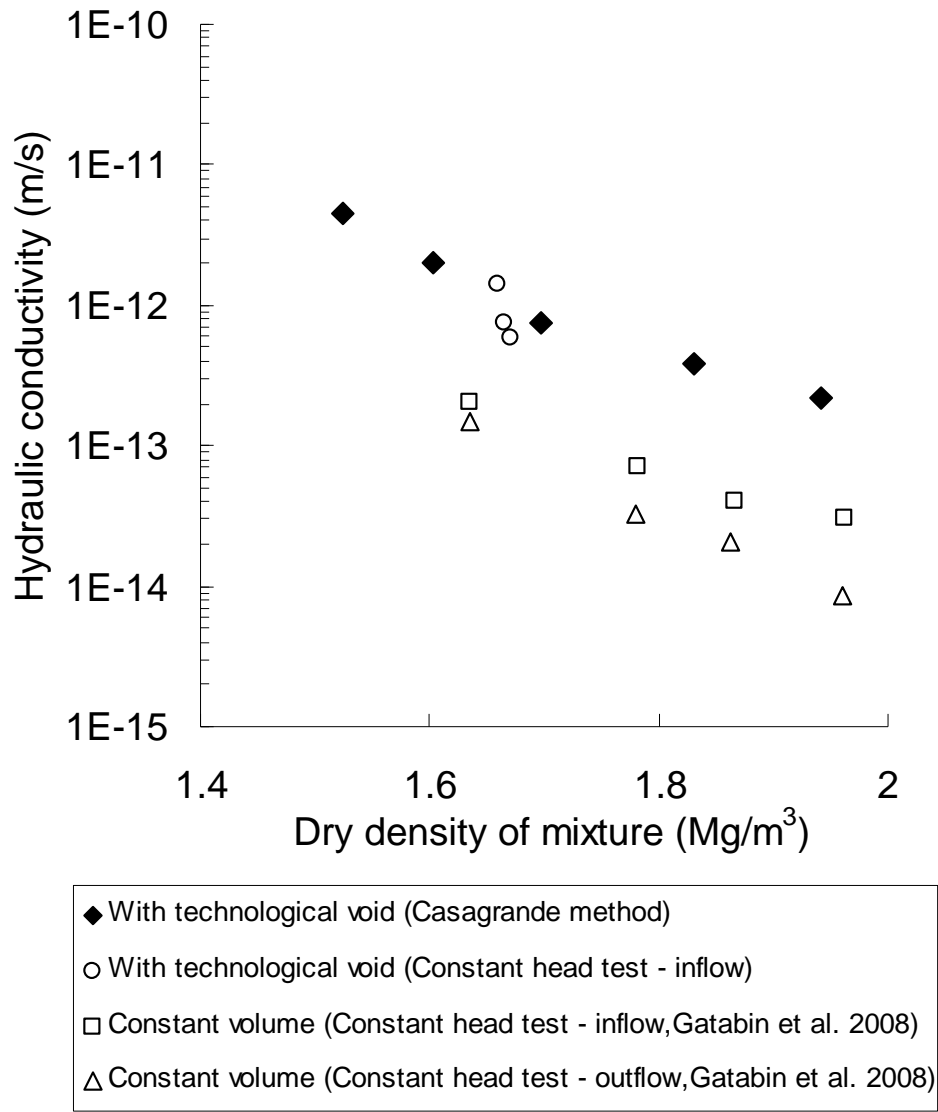
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Figure 13. Changes in yield stress with suction



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831 Figure 14. Changes in compression coefficient with suction



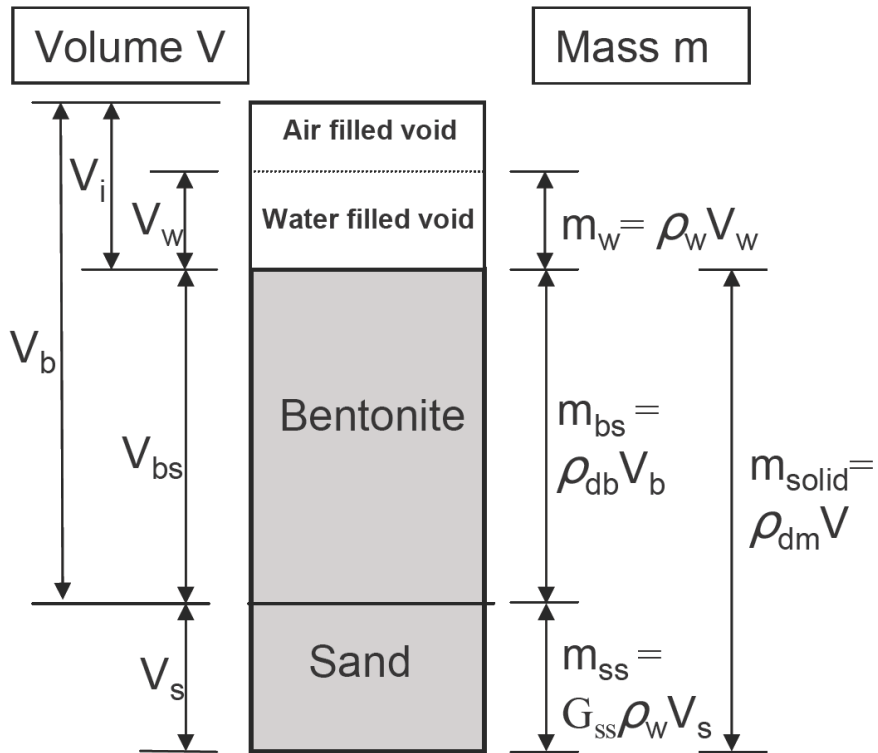
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833 Figure 15. Hydraulic conductivity versus dry density of mixture

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837 Figure 16. Composition of the bentonite/sand mixture

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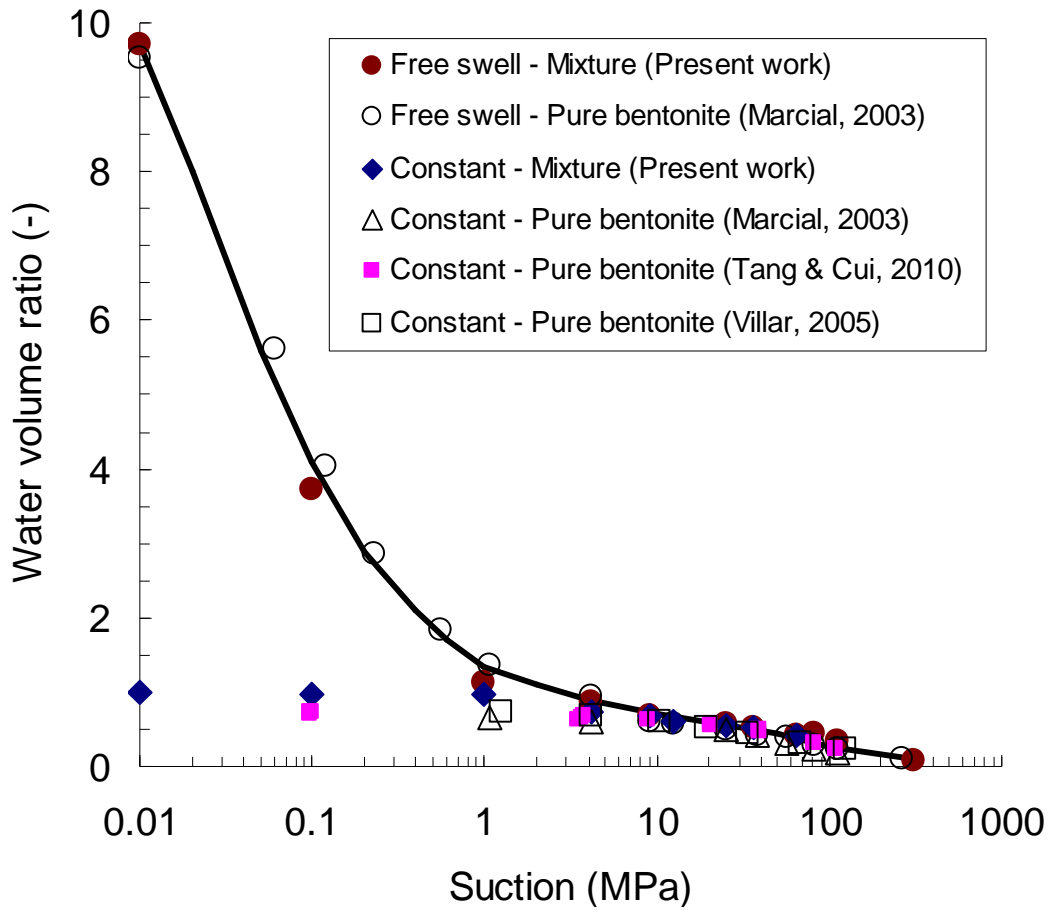
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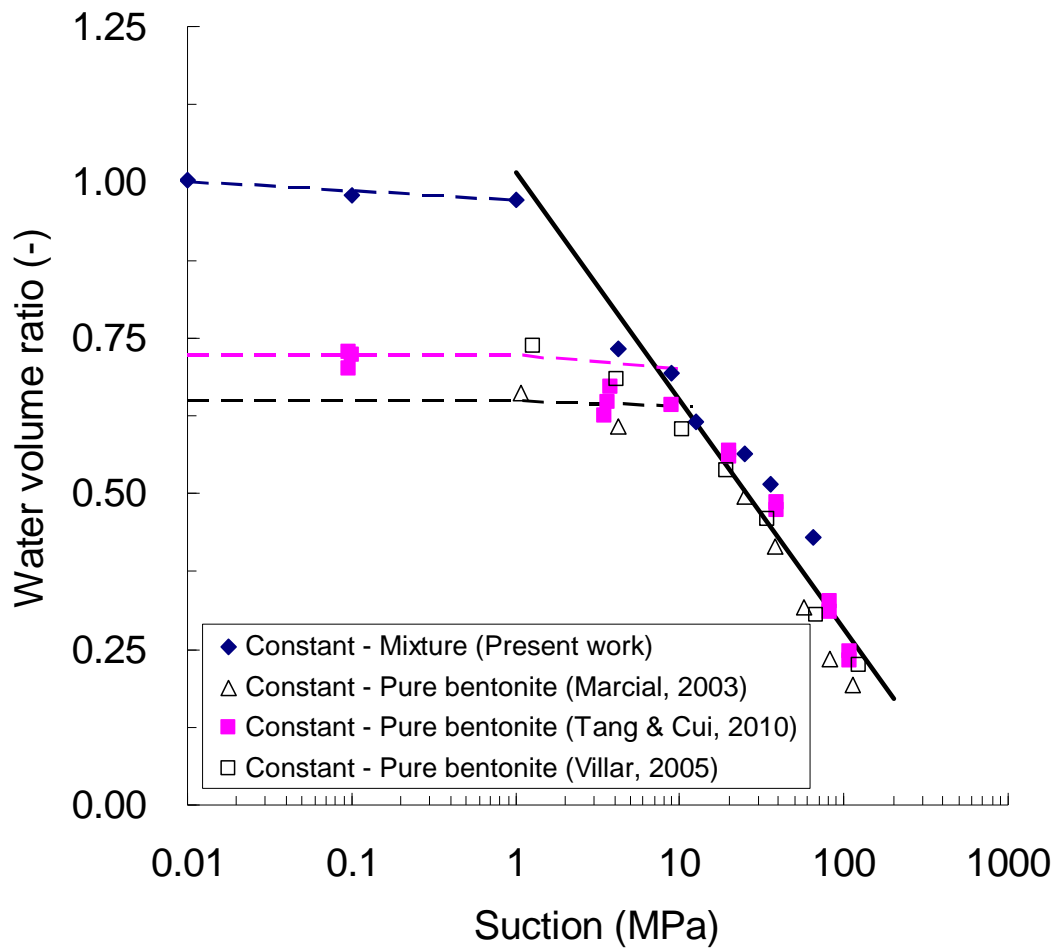


(a)

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850  $\rho_{db} = 1.70 \text{ Mg/m}^3$  (Marcial, 2003);

851  $\rho_{db} = 1.60 \text{ Mg/m}^3$  (Tang et al., 2010; Villar, 2005);

852  $\rho_{db} = 1.43 \text{ Mg/m}^3$  (Present work);

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b)

854 Figure 17. Water volume ratio ( $e_w$ ) Versus suction. a) full range of water volume ratio; b)

855 zoom on the range of low water volume ratio

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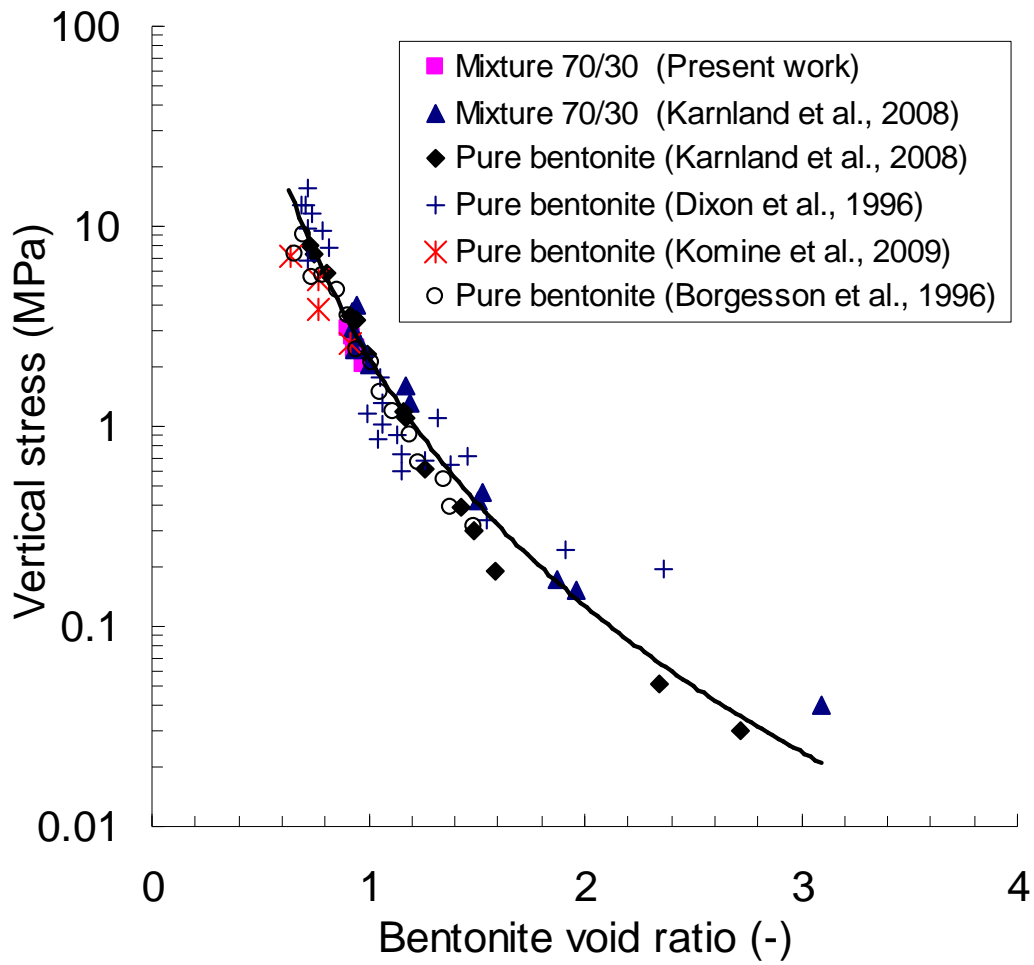
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866 Figure 18. Relationship between vertical stress and bentonite (MX 80) void ratio

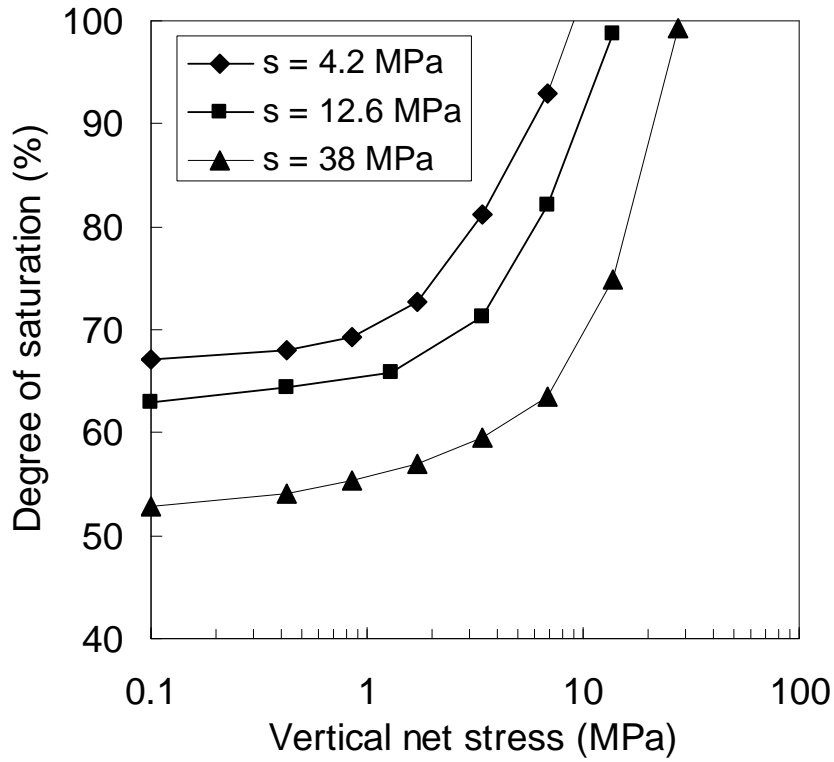
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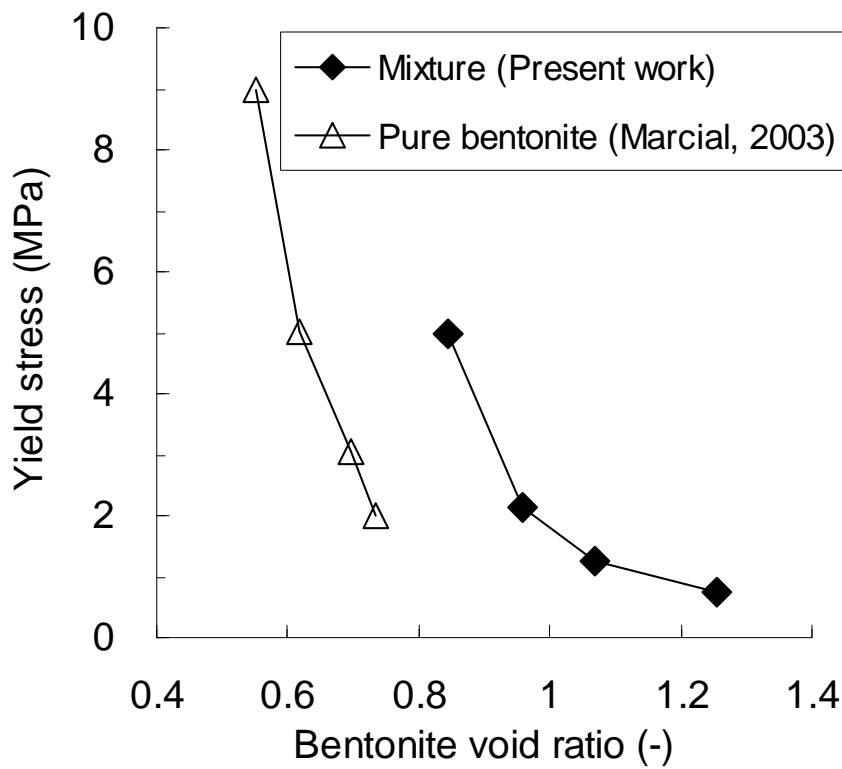
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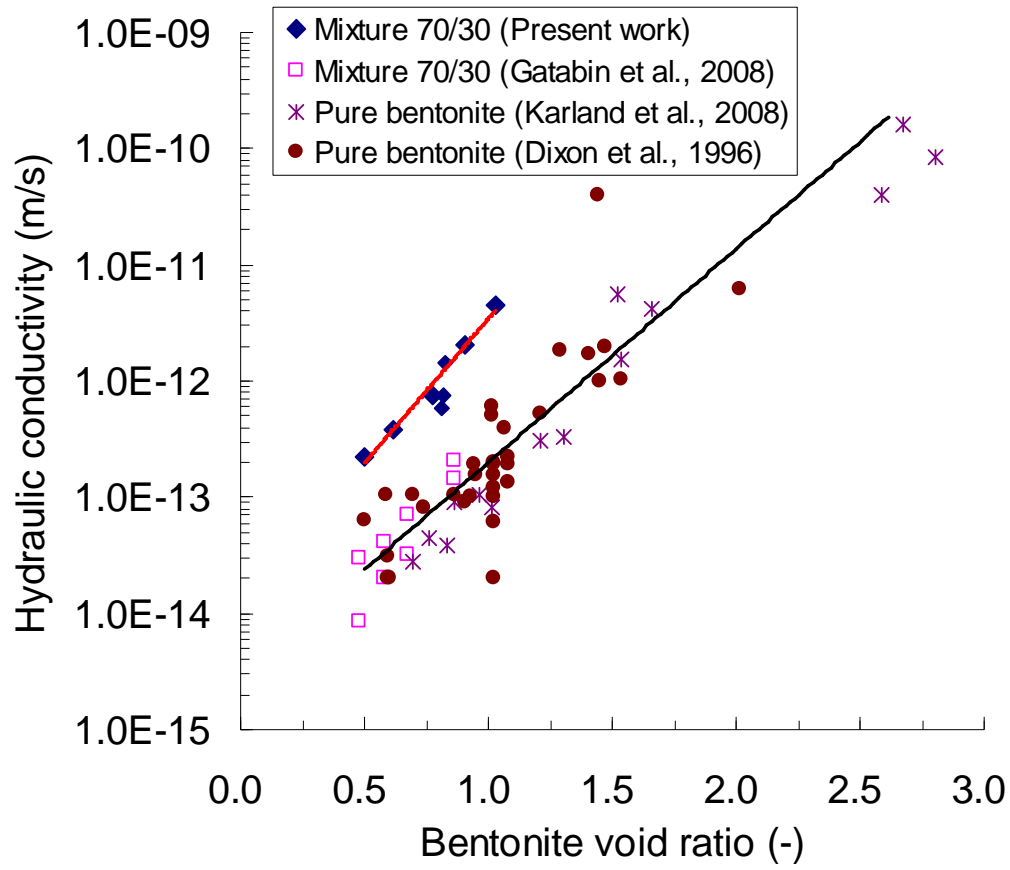
873 Figure 19. Changes in degree of saturation during compression



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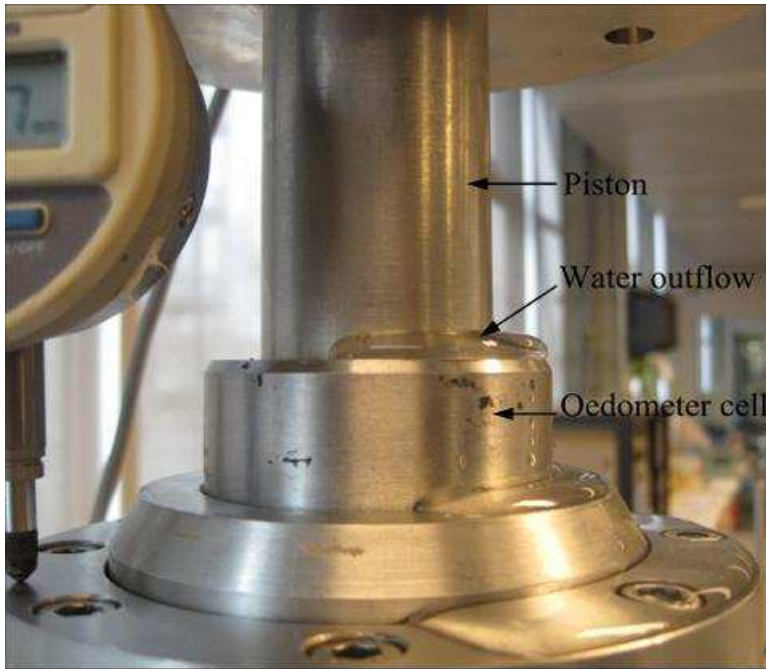
875 Figure 20. Relationship between yield stress and bentonite void ratio

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Figure 21. Hydraulic conductivity versus bentonite void ratio



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Photo 1. Water outflow through the technological void.