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1 Investigation of the hydro-mechanical behaviour of compacted
2 bentonite/sand mixture based on the BExM model

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30 **Abstract:**

31 This study focuses on the hydro-mechanical behaviour of a MX80 bentonite/sand
32 mixture. Barcelona Expansive Model (BExM) was used to describe this behaviour. For
33 this purpose, experimental data obtained in the laboratory were analysed, allowing
34 determination of the parameters used in the model. These parameters were then used to
35 simulate the hydro-mechanical (H-M) responses of the material from other tests with
36 different stress paths. It was observed that the model reproduced well the main feature
37 of swelling pressure development and micro-structural volume change during suction
38 decrease. On the other hand, the simulations also showed some limitations of the model
39 which is based on the consideration of two levels of soil structure or double structure:
40 the pore size distribution curve determined by the technique of mercury intrusion
41 porosimetry (MIP) in the range of low suctions (4.2 and 1 MPa) being revealed to be
42 tri-modal, the BExM model cannot capture this aspect to correctly describe the
43 macro-structural and micro-structural void ratio changes. Moreover, because the BExM
44 model lumps clay intra-particle spaces and inter-particles voids together as micro-pores,
45 it leads to overestimation of the micro-structural water content compared to the
46 experimental value.

47

48 **Keywords:** bentonite/sand mixture; hydro-mechanical behaviour; constitutive
49 modeling; volume change; microstructure.

50

51 **1 INTRODUCTION**

52 Compacted bentonite-based materials have been proposed as engineering barriers in the
53 deep geological repository for high-level radioactive wastes (HLW) in several
54 countries. Thanks to their low permeability, high swelling and high radionuclide
55 retardation capacities [1-3], they are expected to limit the release of radionuclide to the
56 surrounding host rock [4]. After installation in the repository, the engineering barriers
57 will simultaneously undergo the intrusion of groundwater from the host rocks or
58 geological barriers, and the stress changes mainly due to the bentonite swelling.
59 Therefore, the hydro-mechanical performance of engineering barriers is a key issue in
60 assessment of the overall repository safety.

61 Various laboratory studies have been conducted on the H-M behaviour of
62 bentonite-based materials [5-9]. Based on the experimental results, a number of
63 constitutive models have been developed such as the model of Gens and Alonso [10],
64 the model of Alonso et al. [11] and the model of Cui et al. [12], etc. To the authors'
65 knowledge, the elasto-plastic model developed by Alonso et al. [11], namely Barcelona
66 Expansive Model (BExM), is the most widely used one in describing the mechanical
67 behaviour of unsaturated expansive soils.

68 In the BExM model, the authors incorporate the microstructure effects by introducing
69 two levels of soil structure: a microstructure level that corresponds to the active clay
70 minerals with prevailing physico-chemical effects, and a macrostructure level that
71 accounts for the larger scale structure of the soil. The coupling between the two levels is

72 described by means of the interaction functions capable of describing, in a
73 phenomenological fashion, the occurrence of macro-structural elasto–plastic strains as
74 a consequence of micro-structural strains.

75 Because of the complexity of the model, there have been few experimental works that
76 allow the determination of the full set of its parameters, especially for the
77 bentonite-based materials. In this study, the hydro-mechanical behaviour of compacted
78 MX80 bentonite/sand mixture was investigated based on the BExM model. The
79 determination of the model parameters was first conducted by matching the model
80 equations with the laboratory experimental results. The parameters thus determined
81 were then used to simulate the H-M behaviour of the material in the swelling pressure
82 and water retention tests. The performance and limitation of the model were further
83 analysed by comparing the model and experimental results and by considering the
84 microstructure changes upon wetting or suction decrease.

85 **2 BARCELONA EXPANSIVE MODEL**

86 As mentioned previously, Barcelona Expansive Model (BExM) proposed by Alonso et
87 al. [11] accounts for two levels of soil structure [10, 13]: micro- and macro-structural
88 levels. The micro-structural level corresponds to the aggregates of active clay particles
89 with intra-aggregate pores, whereas the macro-structural level corresponds to the larger
90 scale soil structure [14-15]. Following this concept, the void ratio (e) can be split into
91 two parts:

$$92 \quad e = e_m + e_M \quad (1)$$

93 where e_m and e_M are micro- and macro-structural void ratios, respectively.

94 The micro-structural pores are assumed to be always saturated, thus the Terzaghi's
 95 effective stress concept holds: any given changes in suction (s) induce the same volume
 96 change as that induced by the same changes in mean net stress (p). The volume change
 97 in this level is reversible and independent of macro-structural effects [10]. Thereby, the
 98 micro-structural elastic volumetric strain is calculated as follows:

$$99 \quad d\varepsilon_{vm}^e = \frac{de_m}{1 + e_m} = \frac{d(p + s)}{K_m} \quad (2)$$

$$100 \quad \text{with } K_m = \frac{\exp[\alpha_m(p + s)]}{\beta_m} \quad (3)$$

101 where K_m is the micro-structural modulus; it increases with increase in p or s . α_m and β_m
 102 are model parameters which define the micro-structural bulk modulus K_m .

103 In the macro-structural level, both elastic and plastic strains can develop as a result of
 104 stress/suction changes. The macro-structural elastic volumetric strain is expressed as a
 105 function of mean net stress and suction:

$$106 \quad d\varepsilon_{vM}^e = \frac{de_M}{1 + e_M} = \left(\frac{\kappa}{1 + e_M} \right) \frac{dp}{p} + \left(\frac{\kappa_s}{1 + e_M} \right) \frac{ds}{s + p_{atm}} \quad (4)$$

107 where κ and κ_s are the macro-structural elastic compressibility parameters for changes
 108 in stress and in suction, respectively, p_{atm} is the atmospheric pressure.

109 The variation of pre-consolidation mean net stress (p_0) with suction is given by an LC
 110 (Loading Collapse) yield curve function in the (p, s) plane (Figure 1):

$$111 \quad \frac{p_0}{p_c} = \left(\frac{p_0^*}{p_c} \right)^{\frac{\lambda(0) - \kappa}{\lambda(s) - \kappa}} \quad (5)$$

112 with $\lambda(s) = \lambda(0)[r + (1 - r)\exp(-\beta s)]$ (6)

113 where p_c is a reference stress, p_0^* is the net mean yield stress at zero suction, $\lambda(0)$ is the
 114 macro-structural compressibility parameter for changes in p at zero suction (saturated
 115 state), $\lambda(s)$ is the macro-structural compressibility parameter for changes in p at suction
 116 s , r is a parameter that defines the minimum compressibility of soil and β is a parameter
 117 that controls the rate of compressibility decrease with increasing suction.

118 The micro-structural deformations-induced plastic strains are described by two
 119 additional yield curves SI (suction increase) and SD (suction decrease) in Figure 1. The
 120 SI yield curve is defined by the expression $p + s_I = 0$ and the SD yield curve is defined
 121 by the expression $p + s_D = 0$ where s_I , s_D are both hardening parameters. For a reason of
 122 simplicity, it is assumed that the SI and SD yield curves are always activated thereby
 123 inducing irreversible macro-structural deformations. Under this assumption the SI and
 124 SD curves are masked by the Neutral Line (NL). Note that Alonso et al. [15], Sánchez
 125 et al. [16], Tang and Cui, [17] also considered the NL solely to separate micro-structural
 126 swelling from micro-structural compression. Upon hydro-mechanical loadings, the NL
 127 moves following the current stress (p) and current suction (s). Therefore, the following
 128 two parts of irreversible volumetric strains are taken into account:

129 1) When the yield curve LC is reached by a mechanical loading:

130
$$d\varepsilon_{vML}^p = \frac{\lambda(s) - \kappa}{1 + e_M} \frac{dp_0}{p_0}$$
 (7)

131 2) As mention above, the SI and SD yield curves are assumed to be always activated,
 132 the macro-structural plastic strain induced by micro-structural strain is:

133
$$d\varepsilon_{vMSI}^p = f_I d\varepsilon_{vm}^e \quad (8)$$

134
$$d\varepsilon_{vMSD}^p = f_D d\varepsilon_{vm}^e \quad (9)$$

135 where f_I and f_D are the interaction functions between micro- and macro-structural levels
 136 in case of suction increase and suction decrease, respectively.

137 Regarding the hardening law for LC yield curve, the yield stress at zero suction (p_0^*) is
 138 expressed as a function of the total macro-structural strain (ε_{vM}^p).

139
$$\frac{dp_0^*}{p_0^*} = \frac{(1 + e_M) d\varepsilon_{vM}^p}{\lambda(0) - k} \quad (10)$$

140 Note that the increment of the total macro-structural plastic strain ($d\varepsilon_{vM}^p$) is the sum of
 141 the increment of the macro-structural plastic strain resulted by hydraulic and mechanic
 142 loading ($d\varepsilon_{vML}^p$) and that resulted by the micro-structural interactions ($d\varepsilon_{vMSI}^p$ or
 143 $d\varepsilon_{vMSD}^p$), as follows:

144
$$d\varepsilon_{vM}^p = d\varepsilon_{vML}^p + d\varepsilon_{vMSI}^p + d\varepsilon_{vMSD}^p \quad (11)$$

145 **3 PARAMETERS DETERMINATION**

146 The model parameters were determined on the basis of the experimental results
 147 obtained on the MX80 bentonite/sand mixture. The soil microstructure was
 148 investigated using mercury intrusion porosimetry (MIP) by Wang et al. [18], and the
 149 results allow determining the initial micro- and macro-structural void ratios (e_m and e_M).
 150 Montes-H et al. [20] investigated the swelling of a single clay aggregate under relative
 151 humidity changes using the technique of environmental scanning electron microscopy
 152 (ESEM) in conjunction with a digital image analysis. The observed volume changes

153 were used to calibrate the variation of e_m with suction changes. The volume changes
154 upon wetting and loading were studied by carrying out suction controlled oedometer
155 tests [18]. The results obtained were used for the determination of the model parameters
156 related to the hydro-mechanical behaviour. It is important to note that the notation “ p ”
157 used in the BExM refers to “mean stress”. As the results from oedometers tests were
158 considered for parameters’ determination. In the following, the notation “ p ” used refers
159 to the vertical stress in oedometer condition.

160 Figure 2 depicts the pore size distribution (PSD) curve of the compacted MX80
161 bentonite/sand mixture having an initial suction of 65 MPa and a void ratio of 0.635.
162 The incremental pore volume was represented by the change of void ratio e divided by
163 the change of the logarithm of pore diameter d : $de/d\log d$, corresponding to the total
164 volume of the pores having similar entrance pore diameter d . A clear double structure
165 can be observed, defining a population of intra-aggregate pores (micro-pores) with a
166 mean size of 0.02 μm and a population of inter-aggregate pores (macro-pores) with a
167 mean size of 50 μm . The inter-aggregates pores were found to be dependent on dry
168 density, while the intra-aggregate pores remain unaffected by the compaction [8].
169 Based on this evidence, a delimiting value of 2 μm between macro-pores and
170 micro-pores for the MX80 bentonite/sand mixture was defined by Wang et al. [18] from
171 the PSD curves of different dry densities. Thus, the micro-structural and
172 macro-structural void ratios can be determined using the limit pore diameter of 2 μm :
173 $e_m = 0.391$ and $e_M = 0.244$, as noted in Figure 3.

174 Regarding the micro-structural volume change, Montes-H et al. [20] examined the

175 swelling potential of a single MX80 aggregate at different relative humidity states using
176 environmental scanning electron microscopy (ESEM) and the technique of digital
177 image analysis. From an initial relative humidity of 2.5%, corresponding to 537 MPa
178 suction, various relative humidity values were applied. The deformations are shown in
179 Figure 3 versus suction (deduced from the corresponding relative humidity and
180 temperature applied). Note that the result at the relative humidity of 95% was not taken
181 into account due to the “water over-saturation of aggregate” appeared in the experiment
182 [20]. The data show that wetting from the initial suction of 537 MPa to a suction of 13.5
183 MPa (90% relative humidity) induced a micro-structural volumetric swelling of 21%.

184 Based on the evidence that the swelling of mixture is totally controlled by bentonite and
185 sand being inert [18,21,22], the experimental data obtained from MX80 bentonite by
186 Montes-H et al. [20] were used to calibrate parameters α_m and β_m which define the
187 micro-structural bulk modulus K_m (Eq. (2) and (3)). The changes of mixture void ratio
188 were determined from the corresponding void ratio of pure bentonite based on the
189 expressions shown in [18], (Eq (5) and (6)). The following parameters were used to fit
190 the micro-structural volumetric strain to the experimental data: $\alpha_m = 0.083 \text{ MPa}^{-1}$ and
191 $\beta_m = 0.011 \text{ MPa}^{-1}$. Starting from the initial suction of $s_0 = 65 \text{ MPa}$ (black dot in Figure 3)
192 with the initial micro-structural void ratio of $e_m = 0.391$, both the wetting and drying
193 paths were considered: e_m reduced to 0.301 at suction = 537 MPa and increased to
194 0.474 at suction = 0.1 MPa. With the parameters thus determined, the model can
195 satisfactorily fit the experimental results (Figure 3).

196 The volume changes of compacted MX80 bentonite/sand mixture upon wetting and

197 loading were investigated by carrying out suction controlled oedometer tests (Wang et
198 al. [18]). The stress paths followed are presented in Figure 4. Three tests were
199 conducted on samples with an initial dry density of 1.67 Mg/m^3 ($e = 0.635$) under
200 controlled suctions. From the initial state ($p_{ini} = 0.1 \text{ MPa}$, $s = 65 \text{ MPa}$), suctions of 38
201 MPa, 12.6 MPa, 4.2 MPa were first applied by the vapour equilibrium technique under
202 a low vertical stress of 0.1 MPa, allowing the development of vertical swelling strain.
203 After completion of the swelling strain at each suction, loading (up to 30 MPa) was
204 applied under constant suction condition. An additional test at zero suction was
205 conducted by considering an annular void between sample and ring. The sample with a
206 diameter smaller than that of the oedometer cell was used for this purpose (see [18] for
207 more details).

208 The final void ratio values after suction equilibrium following wetting path are
209 presented in Figure 5. Due to the annular void that allowed the sample swell in the
210 radial direction, the sample undergoes first a stress path close to the isotropic conditions.
211 The significant interaction between micro- and macro-structural levels in this condition
212 leads to larger volumetric strain as compared to the oedometer condition for other tests.
213 Therefore, these results for 38 MPa, 12.6 MPa, 4.2 MPa suction were used to calibrate
214 the parameters related to the macro-structure changes due to suction decrease. Upon
215 wetting, the macro-structural behaviour involves two mechanisms: (i) elastic
216 volumetric strain (Eq. (4)) which depends on parameter κ_s ; (ii) plastic volumetric strain
217 induced by the micro- and macro-structural interaction (Eq. 9) which depends on f_D . For
218 simplicity, the elastic volumetric strain (Eq. (4)) was assumed to be insignificant for the

219 high expansive soil considered, and a small value of $\kappa_s = 0.001$ was given. Note that the
220 suction-induced macro-structural elastic deformation was ignored (i.e. $\kappa_s = 0$) in the
221 work of Alonso et al. (2005). The micro-structural void ratio was calculated using the
222 parameters determined above (α_m and β_m). The f_D was then determined by matching the
223 void ratio values in Figure 5 with Eq. 4 and Eq.9: $f_D = 0.8-1.1 \tanh [20 \times (p/p_0 - 0.25)]$.

224 The parameters that control the hydro-mechanical behaviour can be obtained based on
225 the compression curves at different constant suctions. The compression curves at
226 4.2 MPa, 12.6 MPa and 38 MPa suction are depicted in Figure 6. From these curves the
227 values of $\lambda(4.2)$, $\lambda(12.6)$, $\lambda(38)$, $p_0(4.2)$, $p_0(12.6)$, $p_0(38)$ and κ can be determined. By
228 using data of $\lambda(s)$, parameters $\lambda(0)$, γ , β can be obtained through Eq. (6) and the
229 following values were obtained: $\lambda(0) = 0.14$, $r = 0.82$, $\beta = 0.07$. With these parameters
230 determined, p_0^* , p_c were then determined by fitting the data in terms of $p_0(s)$: $p_0^* = 0.92$,
231 $p_c = 0.005$. Afterwards, the f_I (in Eq.8) was obtained by matching the experimental
232 compression curves: $f_I = 0.05-1.1 \tanh [20 \times (p/p_0 - 0.25)]$. Note that during the
233 mechanical loading, the following volumetric strains were taken into account: ε_{vm}^e (Eq.
234 2), ε_{vM}^e (Eq. 4), ε_{vML}^p (Eq. 7) and ε_{vMSI}^p (Eq.8).

235 A summary of the model parameters thus determined and the initial conditions is given
236 in Table 1.

237 **4 SIMULATION AND INTERPRETATION**

238 **4.1 Swelling pressure development during suction decrease**

239 The evolution of swelling pressure during suction decrease was simulated by applying

240 the back compaction method [23]. Following this method, the computation of swelling
241 induced stress can be performed in two stages at a certain suction and stress state
242 (Figure 7): 1) to calculate the micro-porosity change and the macro-volume change
243 potential by allowing swell in the first stage; 2) to press the swelling strain back and
244 calculate the resulting stress after the compression process. From the initial state ($p_{ini} =$
245 0.1 MPa, $e = 0.635$, $s = 65$ MPa), the simulation decreased the suction of the sample to
246 0.1 MPa in a series of steps at constant volume conditions. In each step, the back
247 compaction process was considered as an inverse process of swelling. Thus, the
248 predicted increase in swelling pressure can be obtained. The deformation under both
249 swelling process and compression process was assumed to be elasto-plastic. The SI and
250 SD yield curves were always activated; the loading induced plastic deformation of
251 macro-pores occurs during wetting when the yield curve LC was reached.

252 The predicted swelling pressure induced by suction decrease within the soil sample is
253 presented in Figure 8, along with the swelling pressure measured at different suctions
254 (Figure 8). The swelling pressure evolution observed in the laboratory can be well
255 reproduced by considering the occurrence of two concurrent phenomena: initially,
256 when suction is reduced the bentonite aggregates swell and a net pressure increment is
257 developed to maintain a constant volume condition. During this initial stage, the stress
258 path is far from the LC yield curve (Figure 8). However, the progressive wetting may
259 bring the stress state to the LC yield curve and the overall macrostructure is prone to
260 undergo collapse. Both phenomena co-exist during the wetting path. As noted by
261 Gens & Alonso [10] and Alonso et al. [15], if collapse strains tend to dominate over

262 other contributions to the total volumetric deformation, the stress path will closely
263 follow the LC yield locus. A continuous increasing swelling pressure observed in this
264 study indicates that the macro-pores collapse was fully compensated by the
265 micro-structural swelling; thus no decrease in macro-pores was observed.

266 **4.2 Microstructure changes during suction decrease**

267 During the swelling pressure simulation under constant volume conditions, the changes
268 of macro- and micro-structural void ratios were calculated at the end of each stage, as
269 shown in Figure 9. The measured values from the MIP results were also presented. The
270 correspondence between the measured and predicted deformations is reasonably good
271 for both micro- and macro-pores, except in the case of suction of 4.2 and 1 MPa where
272 the macro-pores quantity increased again with further suction decrease. The
273 discrepancy was caused by the complexity of microstructure at these suctions (Figure
274 10): when saturation is approached ($s < 4.2$ MPa), the macro-pores observed at higher
275 suction are filled by the swollen bentonite, however, a large quantity of fissure-like
276 (with very large aspect ratio) 2-dimension pores (2-D pores in Audiguier et al. [24])
277 with mean entrance diameter of 50 μm appeared due to the division of aggregates
278 (Figure 11a), leading to the increase of macro-pores. Moreover, a new pore group of
279 2-D pores of about 1 μm diameter was formed due to the fissuring of aggregates (Figure
280 11b), leading to a tri-modal pore size distribution [19]. Note that the MIP results
281 obtained from wetted samples by Romero et al. (2011) also showed the complexity of
282 the microstructure changes during wetting, with a new pore population appearing
283 between micro- and macro-pores [25]. Obviously, the two-level soil structure,

284 micro-structural (intra-aggregate) and macro-structural (inter-aggregate), defined in the
285 BExM model cannot describe this phenomenon.

286 **4.3 Water retention property**

287 As mentioned previously, the BExM model assumes that the micro-pores remain
288 always saturated, thus the Terzaghi's effective stress concept holds. Following this
289 assumption, the amount of water in the micro-pores can be calculated based on the
290 micro-structural void ratio. The changes in micro-structural water content (w_{em}) upon
291 wetting were calculated and are presented in Figure 12, together with the experimental
292 water retention curve (WRC, including both micro-structural and macro-structural
293 waters) determined using vapour equilibrium and osmotic techniques at constant
294 volume conditions [18,19]. The model depicts well the two regions with different water
295 retention mechanisms: intra-aggregate and inter-aggregate region. The simulated
296 micro-structural water content curve and the measured WRC intersect at about 4-5 MPa,
297 indicating that from this point on, the suction–water content relationship was controlled
298 by the inter-aggregate pores. Note that this threshold suction is also close to that
299 observed by Yahia-Aissa et al. [26] on FoCa 7 clay (3-4 MPa) and Cui et al. [27] on the
300 mixture (7/3 by dry mass) of Kunigel V1 bentonite/Hostun sand (4-5 MPa).

301 On the other hand, the estimated micro-structural water content (w_{em}) was found to be
302 higher than the water content corresponding to the WRC in the intra-aggregate region.
303 This discrepancy is due to the micro-pores that were unsaturated in reality but assumed
304 to be saturated in the BExM model. By considering the two levels of soil structure [10],
305 the BExM model lumps the intra-particles (inter-layer) space and the inter-particles

306 space together as intra-aggregates pores. Actually, the intra-particles pores can be
307 considered as saturated in the range of suctions of practical interest because it requires
308 an extremely high level of suction (of the order of 10^5 kPa) to remove water from the
309 inter-layer space. However, air can enter the intra-aggregate pores ($< 2 \mu\text{m}$ for the
310 bentonite/sand mixture as shown in Figure 3) at a suction of about 140 kPa, and hence
311 the corresponding voids can become unsaturated [28], leading to the discrepancy
312 between the experimental and estimated value of micro-structural void ratio. It should
313 be noted that in spite of this assumption, the model can predict well the main features of
314 volumetric strain, swelling pressure evolution etc. of expansive soils. For the
315 desaturation of micro-pores, the authors think that the model could be improved by
316 considering degree of saturation as proposed by Romero et al (2011)[25].

317 **5 CONCLUSION**

318 The hydro-mechanical behaviour of a compacted MX80 bentonite/sand mixture was
319 investigated within the framework of the Barcelona Expansive Model (BExM). The
320 model parameters were first determined based on the experimental results obtained.

321 The changes of swelling pressure, micro-structural volume change and micro-structural
322 water content were then simulated and compared with the experimental results.

323 The swelling pressure observed under constant volume was well reproduced by the
324 model. A continuous increasing swelling pressure observed indicates that the
325 macro-pores collapse was fully compensated by the micro-structural swelling.

326 The macro- and micro-structural void ratio changes upon wetting under constant

327 volume condition were well reproduced in the range of high suctions. However, the
328 model cannot well describe the changes in the range of low suctions (4.2 and 1 MPa).
329 Further examination showed that the pore size distribution curve in the low suction
330 range is tri-modal, different from the assumption of bi-modal distribution in the BExM
331 model.

332 The model depicts well the two regions of different water retention mechanisms:
333 intra-aggregate and inter-aggregate regions. However, the predicted micro-structural
334 water content was found higher than the water content corresponding to the WRC in the
335 intra-aggregate region. This discrepancy is due to the micro-pores assumed to be
336 always saturated in the BExM model, but unsaturated in reality.

337 On the whole, the main features of the hydro-mechanical behaviour of bentonite/sand
338 mixture can be described by the BExM model, demonstrating the performance of this
339 model in representing the H-M behaviour of bentonite-based materials. However,
340 further considerations should be done when applying the model such as the formation
341 of a third pore population under suction decrease and the de-saturation of
342 intra-aggregate pores at high suctions.

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347 **REFERENCES**

- 348 [1] Pusch, R. Highly compacted sodium bentonite for isolating rock-deposited radioactive waste
349 products. *Nucl. Technol. (United States)*, 45(2) (1979):153-157
- 350 [2] Yong, R.N., Boonsinsuk, P., and Wong, G. Formulation of backfill material for a nuclear fuel
351 waste disposal vault. *Canadian Geotechnical Journal*, 23(2) (1986):216-228.
- 352 [3] Villar, M.V., Lloret, A. Influence of dry density and water content on the swelling of a
353 compacted bentonite. *Applied Clay Science*, 39(1-2) (2008):38-49.
- 354 [4] Cho, W.J., Lee, J.O., Kwon, S. Analysis of thermo-hydro-mechanical process in the engineered
355 barrier system of a high-level waste repository. *Nuclear Engineering and Design*.
356 240(2010):1688-1698.
- 357 [5] Delage, P., Howat, M. D., & Cui, Y. J. The relationship between suction and swelling
358 properties in a heavily compacted unsaturated clay. *Engng Geol.* 50(1) (1998): 31 – 48.
- 359 [6] Lloret, A., Villar, M. V., Sanchez, M., Gens, A., Pintado, X. & Alonso, E. E. Mechanical
360 behaviour of heavily compacted bentonite under high suction changes. *Géotechnique* 53(1)
361 (2003): 27-40
- 362 [7] Romero, E., Villar, M. V. & Lloret, A. Thermo-hydro-mechanical behaviour of heavily
363 overconsolidated clays. *Engng Geol.* 81(3) (2005): 255 – 268.
- 364 [8] Lloret, A. & Villar, M. V. Advances on the knowledge of the thermo-hydromechanical
365 behaviour of heavily compacted « FEBEX » bentonite. *Physics and Chemistry of the Earth*
366 32(8 – 14) (2007): 701 – 715.
- 367 [9] Agus, S.S., Arifin, Y. F., Tripathy, S., Schanz, T. Swelling pressure–suction relationship of
368 heavily compacted bentonite–sand mixtures. *Acta Geotechnica*, DOI:10.1007/s11440-
369 012-0189-0.
- 370 [10] Gens, A. & Alonso, E. E. A framework for the behaviour of unsaturated expansive clays. *Can.*
371 *Geotech. J.* 29(6) (1992): 1013 – 1032.
- 372 [11] Alonso, E. E., Vaunat, J. & Gens, A. Modelling the mechanical behaviour of expansive clays.
373 *Engng Geol.* 54(1) (1999): 173 – 183.
- 374 [12] Cui Y.J., Yahia-Aissa M. and Delage P. A model for the volume change behaviour of heavily
375 compacted swelling clays. *Engineering Geology* 64 (2-3) (2002), 233-250.
- 376 [13] Alonso, E. E., Gens, A., Josa, A. (1990). A constitutive model for partially saturated soils.
377 *Geotechnique*, 40 (3): 405–430.
- 378 [14] Kröhn, K. P. New conceptual models for the resaturation of bentonite. *Applied Clay Science*,
379 23(1 – 4) (2003): 25 – 33.
- 380 [15] Alonso, E. E., Alcoverro, J., Coste, F., et al. The FEBEX benchmark test: case definition and
381 comparison of modelling approaches. *International Journal of Rock Mechanics & Mining*
382 *Science* 42(5-6) (2005): 611 – 638.

- 383 [16] Sánchez, M., Villar, M. V., Gens, A., Olivella, S. & do N. Guimaraes, L. Modelling the effect of
384 temperature on unsaturated swelling clays. Proc. of the 10th International Symposium on
385 Numerical Models in Geomechanics (Numog X), Rhodes, Greece, (2007): 57-62.
- 386 [17] Tang, A. M., Cui, Y. J. Modelling the thermomechanical volume change behaviour of
387 compacted expansive clays. *Géotechnique*, 59 (2009): 185-195
- 388 [18] Wang, Q., Tang, A. M., Cui, Y.J., Delage, P., Barnichon, J.D., & Ye, W.M. The effects of
389 technological voids on the hydro-mechanical behaviour of compacted bentonite-sand mixture.
390 *Soils and Foundations*, Vol.53, No.2 (2013) in Press.
- 391 [19] Wang, Q., Tang, A. M., Cui, Y.J., Delage, P., Barnichon, J.D., & Ye, W.M. Hydraulic
392 conductivity and microstructure changes of compacted bentonite/sand mixture during
393 hydration. (2012) submitted to *Engineering Geology*.
- 394 [20] Montes-Hernandez, G, Duplay, J., Martinez, L. & Mendoza, C. Swelling-shrinkage kinetics of
395 MX80 bentonite. *Applied Clay Science*, 22(6) (2003): 279 – 293.
- 396 [21] Karnland, O., Nilsson, U., Weber, H., and Wersin, P. Sealing ability of Wyoming bentonite
397 pellets foreseen as buffer material-Laboratory results. *Physics and Chemistry of the Earth*,
398 Parts A/B/C, 33(2008), S472-S475.
- 399 [22] Wang Q., Tang A.M., Cui Y.J., Delage P., Gatmiri B. Experimental study on the swelling
400 behaviour of bentonite/claystone mixture. *Engineering Geology* 124 (2012), 59-66.
- 401 [23] Xie, M. L., Wang, W. Q., De-jonge, J., and Kolditz O. Numerical Modelling of Swelling
402 Pressure in Unsaturated Expansive Elasto-Plastic Porous Media. *Transport in Porous Media*,
403 66 (2007):311–339
- 404 [24] Audiguier, M., Geremew, Z., Cojean, R. Relations enter les microstructures de deux sols
405 argileux de la région parisienne et leur sensibilité au retrait gonflement. SEC2008, Sécheresse
406 et constructions, Paris, France, 1-3 sept. Editions du LCPC(2008), 235-243.
- 407 [25] Romero, E., G. Della Vecchia, C. Jommi,. An insight into the water retention properties of
408 compacted clayey soils. *Géotechnique*. 61 (4) (2011): 313-328.
- 409 [26] Yahia-Aissa, M.,Delage, P., Cui, Y.J. In: Adachi, Fukue (Ed.), Suction–water Relationship in
410 Swelling Clays, *Clay Science for Engineering*, IS-Shizuoka Int Symp on Suction, Swelling,
411 Permeability and Structure of Clays. In Balkema, (2001): 65–68.
- 412 [27] Cui, Y. J., Tang, A. M., Loiseau, C., Delage, P. Determining water permeability of compacted
413 bentonite–sand mixture under confined and free-swell conditions. *Physics and Chemistry of*
414 *the Earth*, 33(2008): S462–S471.
- 415 [28] Sharma, R.S. Mechanical behaviour of unsaturated highly expansive clays. University of
416 Oxford. PHD thesis (1998).
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440 Table 1. Parameters used in the simulation

Initial state		Hydro-mechanical behaviour	
e	0.635	κ	0.006
e_m	0.391	κ_s	0.001
e_M	0.244	$\lambda(0)$	0.14
s_0	65 MPa	p_c	0.005
p_{ini}	0.1 MPa	r	0.82
p_0^*	0.92 MPa	β	0.07
		α_m	0.083 MPa ⁻¹
		β_m	0.011 MPa ⁻¹
		$f_D = 0.8-1.1 \tanh [20 \times (p/p_0 - 0.25)]$.	
		$f_I = 0.05-0.8 \tanh [20 \times (p/p_0 - 0.25)]$	

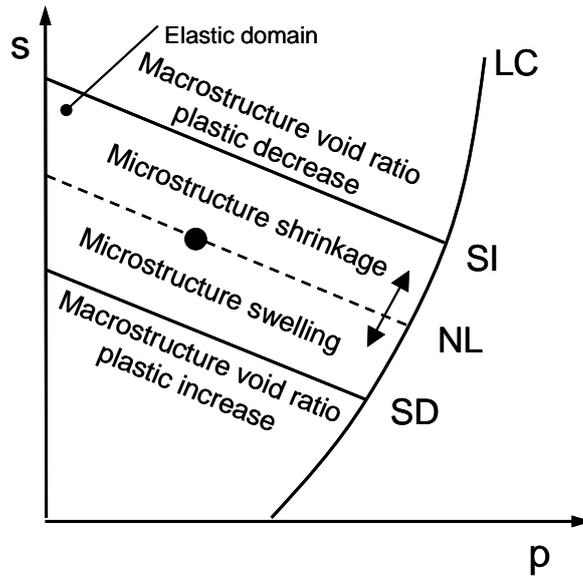
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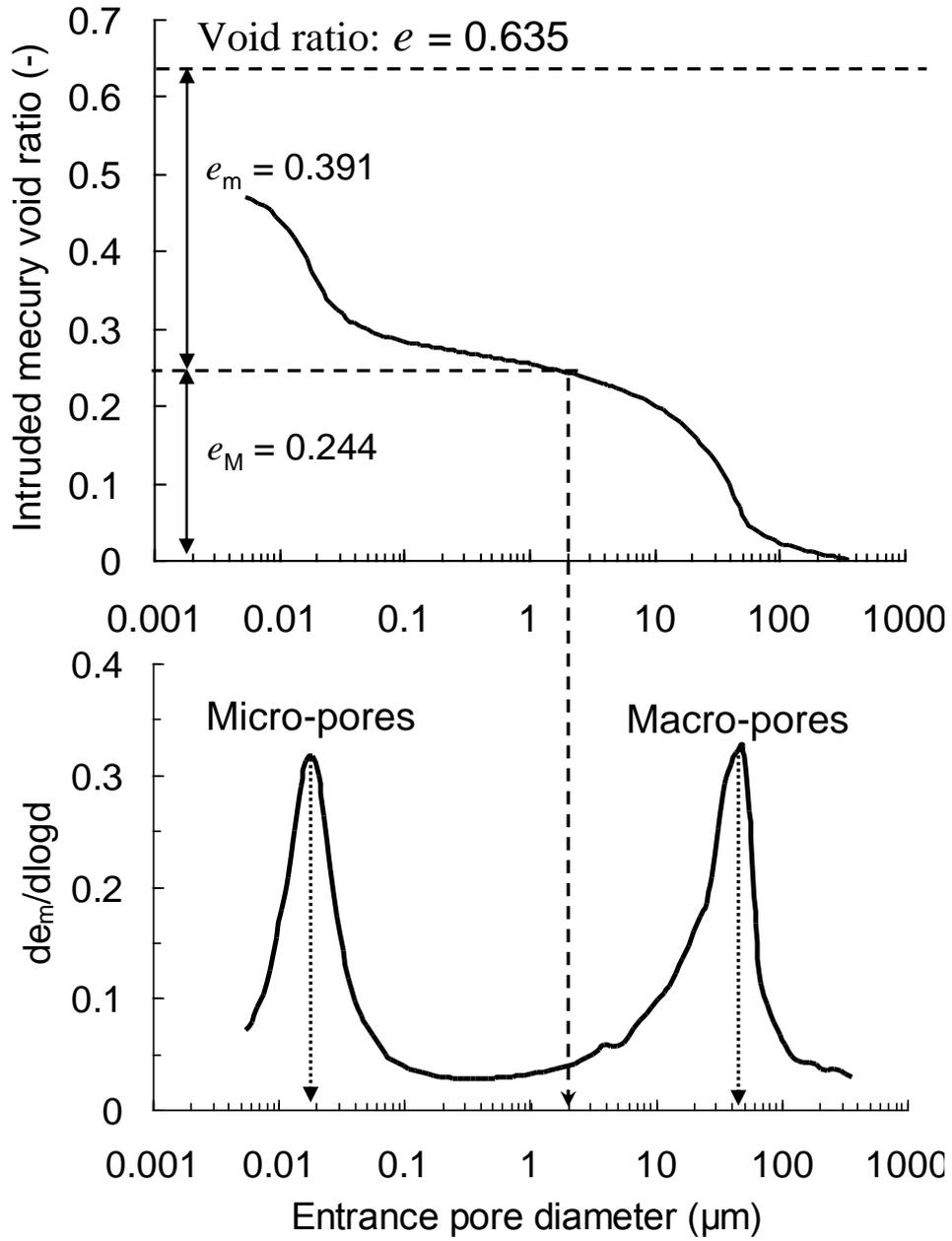
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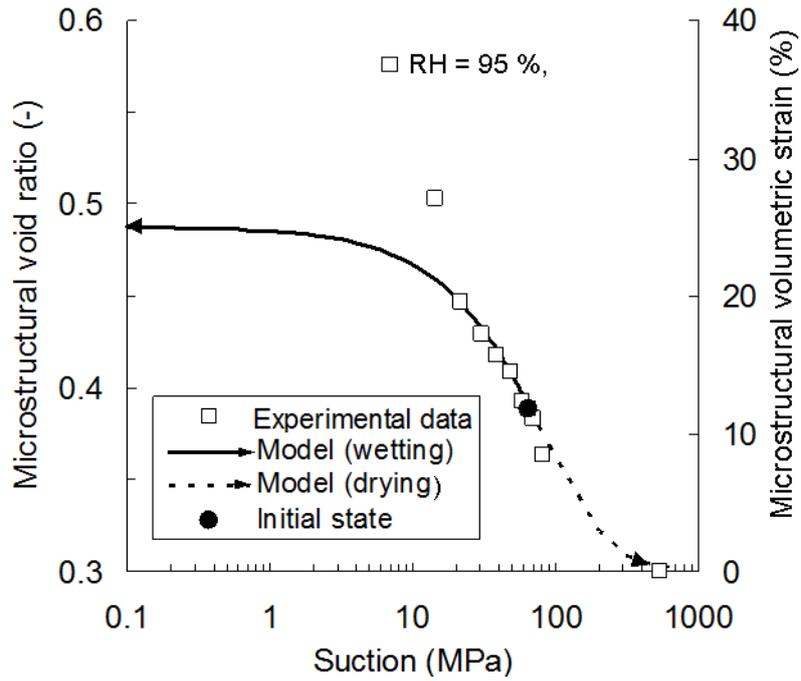
447 Figure 1. BExM yield loci in the p - s plane (after Alonso et al. 2005)



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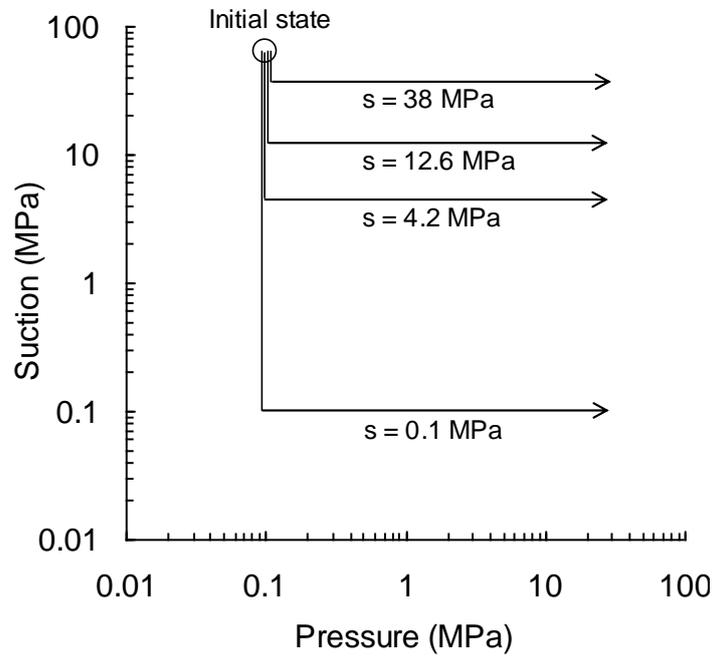
449 Figure 2. Pore size distribution of the compacted MX80/sand mixture

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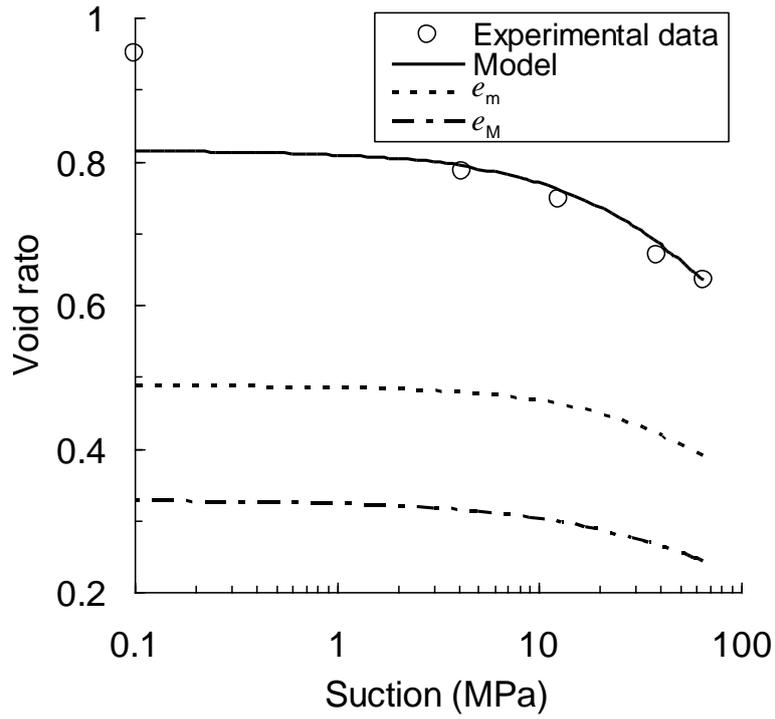
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Figure 3. Micro-structural volumetric strain of MX80 bentonite and micro-structural void ratio of mixture versus suction



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457 Figure 4. Stress paths followed in the suction controlled oedometer tests

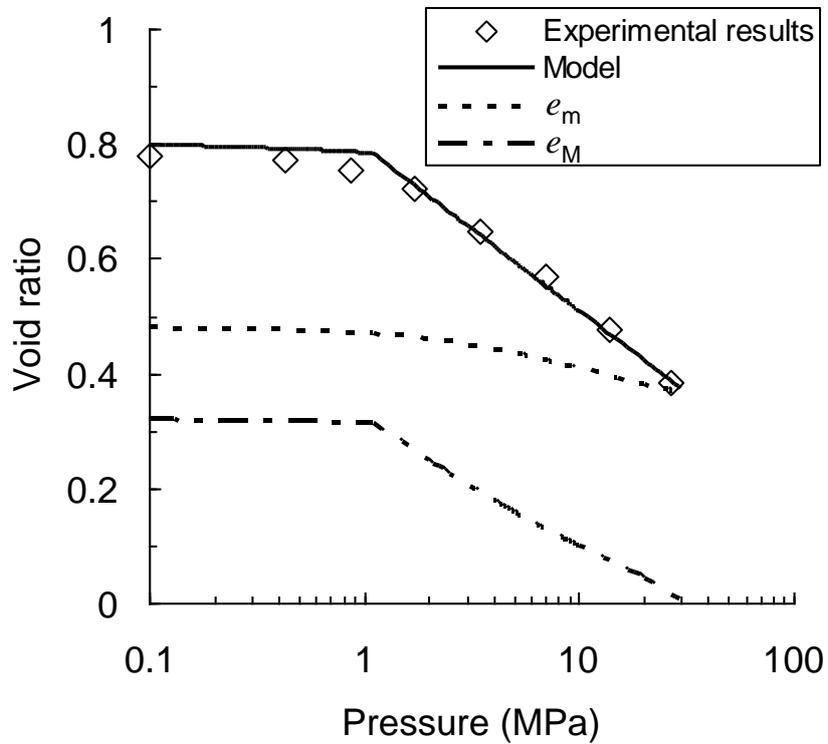


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459 Figure 5. Void ratio changes upon wetting under a vertical stress of 0.1 MPa

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(a) $s = 4.2$ MPa

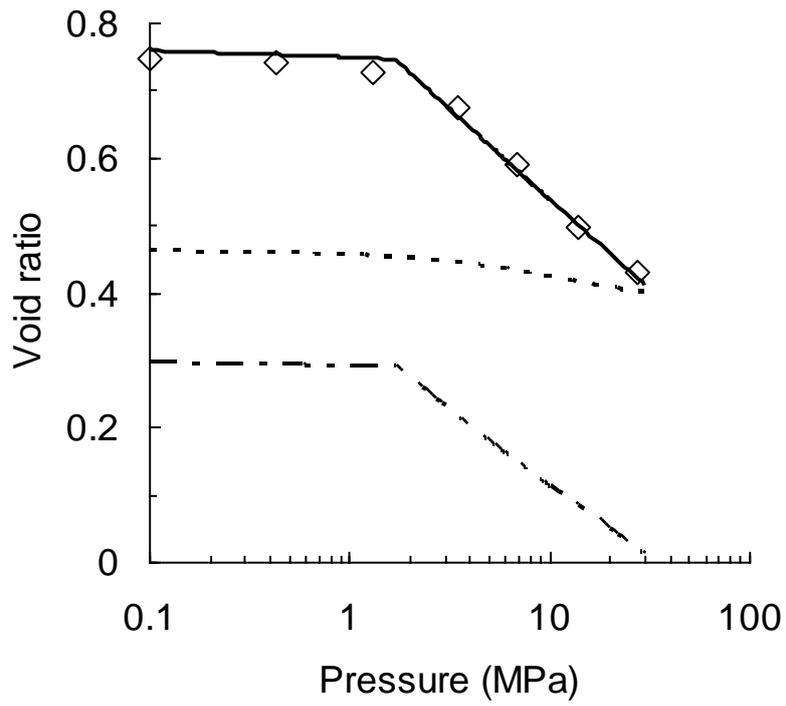
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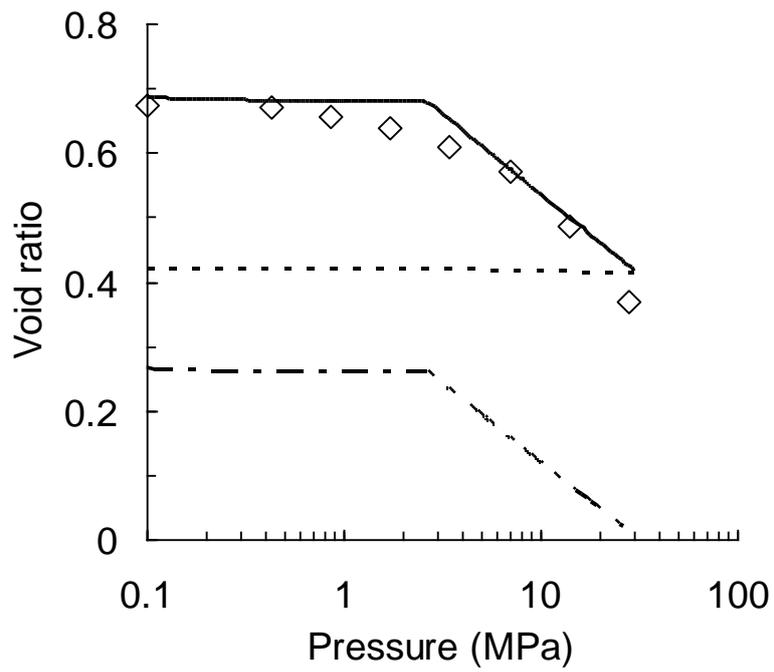
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(b) $s = 12.6$ MPa

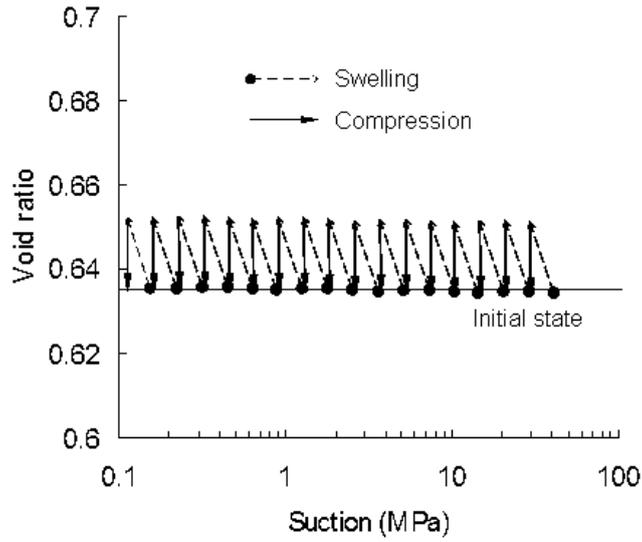


(c) $s = 38$ MPa

Figure 6. Void ratio changes upon mechanical loading at constant suction

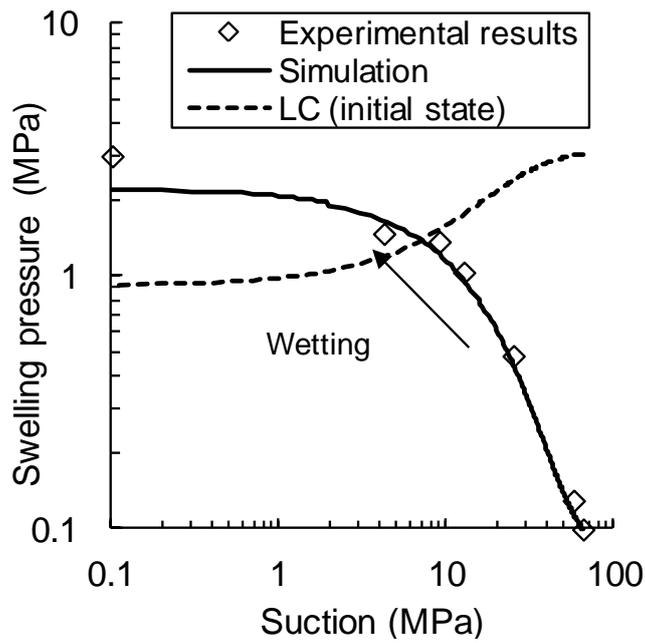
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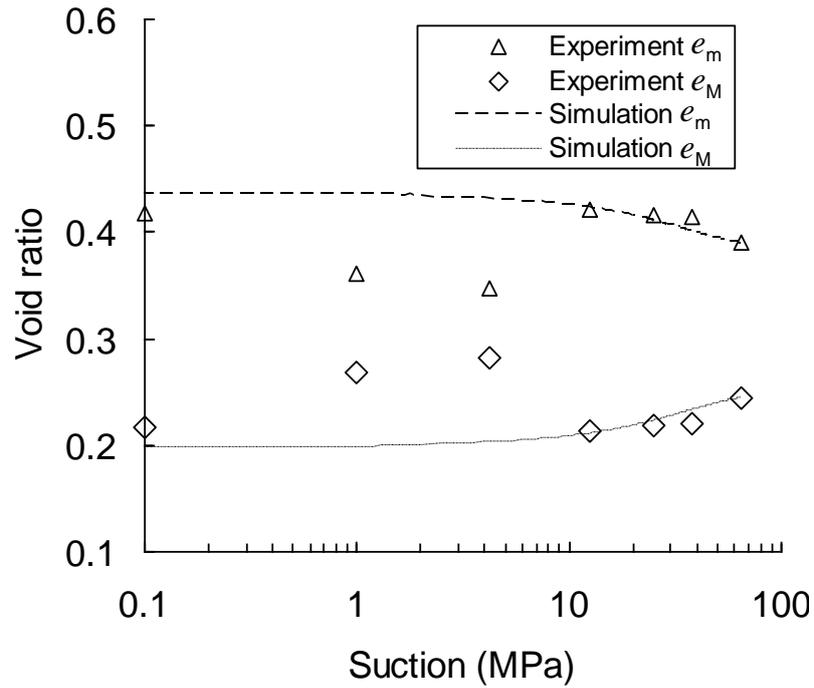
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475 Figure 7. Stress path followed during the swelling pressure simulation



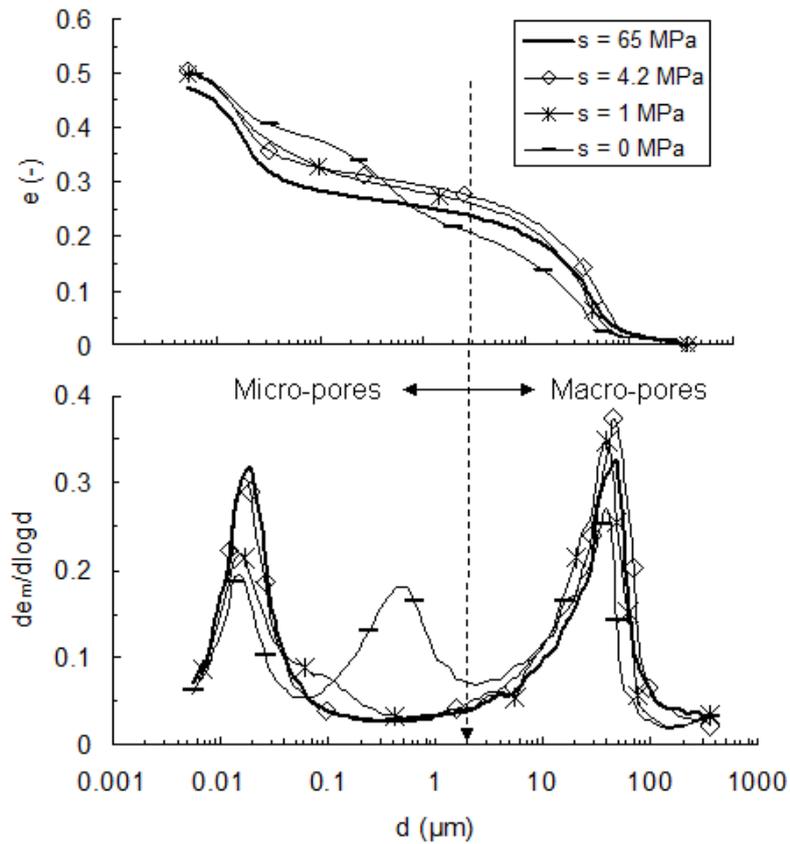
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477 Figure 8. Changes of swelling pressure during suction decrease under constant volume
478 condition



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480 Figure 9. Changes in the e_m and e_M during suction decrease under constant volume condition



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Figure 10 Pore size distribution changes

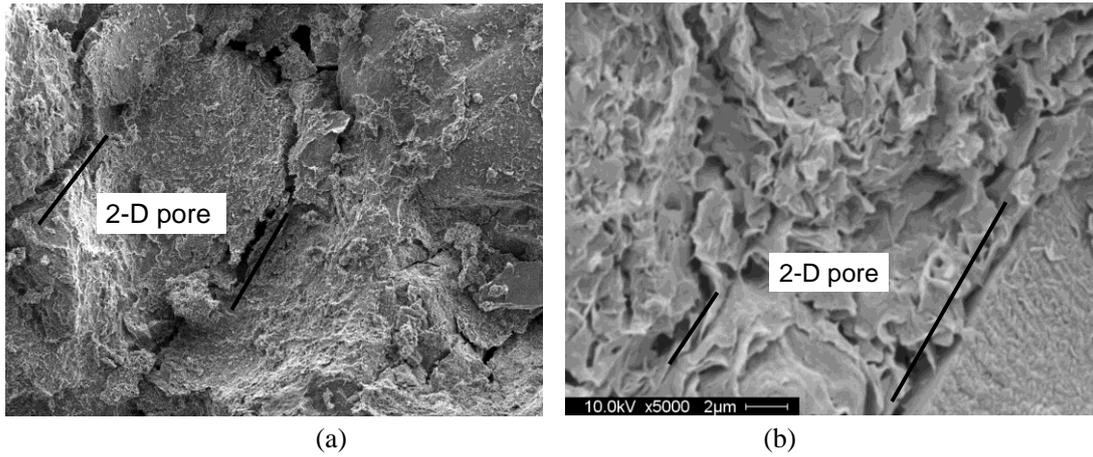


Figure 11 2-D pores with diameter of 50µm (a) and 1µm (b)

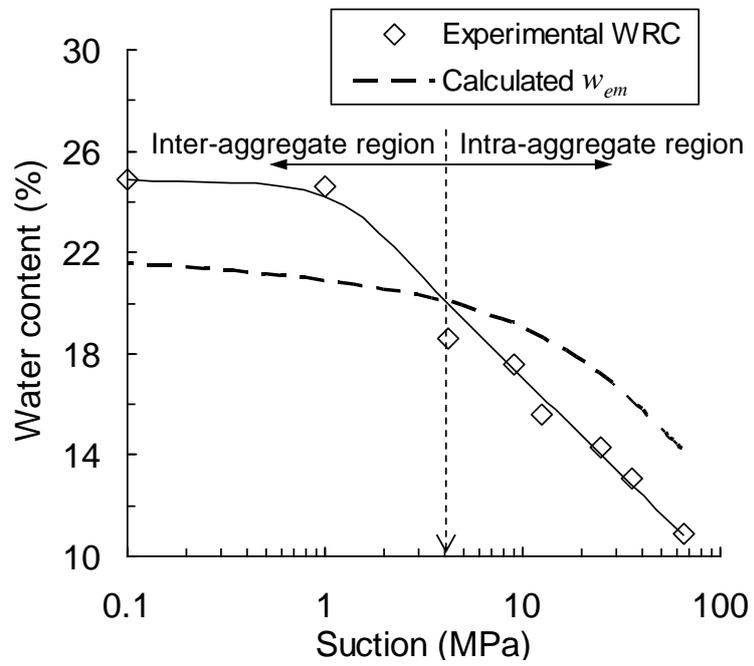


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