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1           **Experimental study on the aeolotropic swelling behaviour of compacted**  
2           **bentonite/claystone mixture with axial/radial technological voids**

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24 **Abstract:** Pre-compacted blocks of MX80 bentonite/Callovo-Oxfordian (COx) claystone  
25 mixture are chosen as sealing/backfilling materials in the French concept of deep geological  
26 disposal for radioactive waste. Creating technological voids is normally unavoidable during  
27 installation in the disposal galleries, in the form of axial voids between compacted blocks and  
28 radial voids between the compacted blocks and the host rock. In this work, the aeolotropic  
29 swelling behaviour of compacted mixture with axial/radial technological voids was  
30 experimentally investigated. Results showed that the aeolotropy coefficient (ratio of radial to  
31 axial pressures) of samples without voids increased from 0.46 to 0.88 with the increasing dry  
32 density from 1.6 to 2.0 Mg/m<sup>3</sup> due to the relatively concentrated macro-pores which defined a  
33 relatively lower local dry density in the side part. For the samples with axial/radial voids, their  
34 final axial swelling pressures were in agreement with the unique correlation with final dry  
35 density, regardless of the soil density heterogeneity. Samples with axial voids had a larger  
36 aeolotropy coefficient than samples without voids, due to the reduction of the orientation of clay  
37 particles upon hydration, while samples with radial voids had a smaller aeolotropy coefficient, due  
38 to the relatively lower dry density near the cell wall.

39 **Keywords:** bentonite/claystone mixture; axial/radial technological voids; swelling pressure;  
40 aeolotropy coefficient

## 41 **1. Introduction**

42 In many countries, deep geological disposal has been considered as a possible solution to store  
43 high-level radioactive wastes. (Pusch 1982; Sellin and Leupin 2013). In a promising concept, waste  
44 canisters are emplaced within galleries excavated in a low-permeability formation a few hundred  
45 metres below the surface. Bentonite-based materials are used to construct the sealing/backfilling  
46 elements thanks to their favourable swelling characteristic, low permeability and good radionuclides  
47 retention capacity (Dixon et al. 1985). A typical approach is to emplace bentonite-based materials in  
48 the form of pre-compacted blocks between the host rock and waste canisters. Creating axial  
49 technological voids between the compacted blocks, and radial technological voids between the  
50 compacted blocks and the host rock is normally unavoidable during such installation operation.  
51 After the disposal galleries are closed, the groundwater from the host rock will fill the technological  
52 voids and progressively infiltrate into the bentonite-based materials. They swell and form a gel,  
53 filling up the technological voids. Afterwards, swelling pressure develops progressively under  
54 constrained volume condition. This swelling pressure must be high enough to limit the convergence  
55 of the galleries in case of concrete lining failure (Cuisinier et al. 2008), but lower than the yield  
56 stress supported by the sealing plugs (Saba et al. 2014a). It is therefore crucial to investigate the  
57 swelling behaviour of compacted bentonite-based materials to achieve a reliable design of the  
58 repository.

59 Numerous investigations have been carried out on the swelling behaviour of compacted  
60 bentonite-based materials in the context of radioactive waste disposal (e.g. Komine and Ogata 1994,  
61 1999; Cho et al. 2000; Lee et al. 1999; Saba et al. 2014a). It was well documented that the final  
62 swelling pressure is dominated by bentonite dry density (Dixon et al. 1985; Lee et al. 1999; Wang et

63 [al. 2012](#)). However, the laboratory measurement of swelling pressure was generally carried out only  
64 in the axial direction and the swelling pressures in different directions were considered as the same  
65 in many cases. Recently, some researchers attempted to determine the difference between the  
66 swelling pressures in different directions ([Lee et al. 2001, 2012](#); [Saba et al. 2014a](#); [Jia et al. 2019](#)).  
67 [Lee et al. \(2012\)](#) measured both the axial and radial swelling pressures of compacted Korean  
68 bentonite with a dry density of 1.5-1.7 Mg/m<sup>3</sup> and observed a larger difference between the axial  
69 and radial swelling pressures at a higher dry density. They attributed this phenomenon to the  
70 fabrication process of compacted block, in which bentonite powders were uniaxially compacted. To  
71 address this point, [Saba et al. \(2014a\)](#) defined an anisotropy coefficient as the ratio of radial to axial  
72 swelling pressures. For compacted GMZ bentonite, [Jia et al. \(2019\)](#) found that the anisotropy  
73 coefficient decreased from 1.0 to 0.76 owing to the increasingly oriented arrangement of bentonite  
74 grains when the dry density increased from 1.46 to 1.71 Mg/m<sup>3</sup>. [Saba et al. \(2014a\)](#) studied the axial  
75 and radial swelling pressures of compacted MX80 bentonite/sand mixture with a wide range of  
76 bentonite dry density. They indicated that the anisotropy coefficient was mainly related to the  
77 bentonite dry density: at low bentonite dry densities (lower than 1.16 Mg/m<sup>3</sup>), the anisotropy  
78 decreased with increasing bentonite dry density; at medium dry densities (from 1.16 to 1.3 Mg/m<sup>3</sup>),  
79 the coefficient was near 1.0; at high bentonite dry densities (larger than 1.3 Mg/m<sup>3</sup>), anisotropy  
80 increased with increasing bentonite dry density. They explained this phenomenon by the swelling  
81 and splitting of bentonite upon hydration, which could lead to microstructure collapse and thus  
82 reduce the initial anisotropy induced by uniaxial compaction. At medium bentonite dry densities,  
83 the microstructure collapse eliminated the initial anisotropy, developing an isotropic microstructure.  
84 At high bentonite dry densities, the initial anisotropy would remain because the smaller macro-pore

85 space prevented the microstructure collapse. At very low dry densities, the macro-pores were not  
86 fully filled by the swollen bentonite and the oriented microstructure was also preserved.

87 In the real deep geological repository, filling of technological voids will lead to a decrease in  
88 the dry density of compacted blocks and the swelling behaviour can change upon hydration.  
89 Moreover, the dry density distribution is not heterogeneous due to the presence of technological  
90 voids in short term, influencing the swelling pressures in various directions. Many studies on the  
91 swelling behaviour of compacted bentonite-based materials with technological voids were reported  
92 (Villar et al. 2005; Saba et al. 2014a; Bian et al. 2019a, 2019b, 2020; Jia et al. 2019; Zeng et al.  
93 2020a, 2020b, 2020c). Wang et al. (2013) and Saba et al. (2014a) pointed out that the unique  
94 relationship between axial swelling pressure and final bentonite dry density could be extended to  
95 compacted MX80 bentonite/sand mixture (70% bentonite-30% sand in dry mass) with 14% radial  
96 technological voids. Moreover, Saba et al. (2014a) suggested that 14% radial technological voids  
97 had a negligible effect on the anisotropy coefficient. Jia et al. (2019) performed several swelling  
98 pressure tests on compacted GMZ bentonite with 13.3-26.7% axial voids. They concluded that a  
99 void of more than 16.7% could induce a lower axial swelling pressure without significant change of  
100 radial swelling pressure, resulting in an anisotropy coefficient higher than that without voids even  
101 though the global dry density was the same. Their works were however limited to the voids between  
102 compacted samples and the rigid cell wall, which simulated the host rock. The effect of axial  
103 technological voids between the blocks was not studied. Moreover, the mechanism of swelling  
104 behaviour of compacted blocks with axial/radial technological voids was not investigated.

105 This study investigated the aeolotropic swelling behaviour of compacted MX80  
106 bentonite/Callovo-Oxfordian (COx) claystone mixture with technological voids. Unlike in Saba et

107 [al. \(2014a\)](#), the term of “aeolotropy” was adopted to distinguish from the common term of  
108 “anisotropy”, which physically represents the intrinsic material property. To this end, the swelling  
109 pressure of the samples was measured in both axial and radial directions by the constant-volume  
110 method. Three set of experiments were performed to examine the effects of dry bulk density and  
111 voids: (i) initial dry density varied without voids; (ii) final dry density varied using different initial  
112 axial technological voids; (iii) final dry density varied using different initial radial technological  
113 voids. After the swelling pressure tests, the water content and dry density at various positions were  
114 determined to interpret the aeolotropic swelling mechanism of the compacted mixture with different  
115 technological voids.

## 116 **2. Materials and methods**

### 117 *2.1. Materials*

118 The soil used in this study was a mixture of MX80 bentonite and crushed CO<sub>x</sub> claystone (30/70 in  
119 dry mass), which was selected as a candidate buffer/backfill material for the Cigéo project by the  
120 French National Agency for Nuclear Waste Management (ANDRA). The MX80 bentonite was  
121 extracted from Wyoming, USA. Its physical and mineralogical properties are presented in [Table 1](#).  
122 The MX80 bentonite is of light gray colour, dominated by montmorillonite (86% in dry mass). The  
123 liquid limit is 494%, the plastic limit is 46% and the unit mass is 2.76 Mg/m<sup>3</sup>, which are consistent  
124 with the results of [Karnland et al. \(2008\)](#), [Tang et al. \(2008\)](#), [Seiphoori et al. \(2014\)](#) and [Saba et al.](#)  
125 [\(2014\)](#). The crushed CO<sub>x</sub> claystone used in this study was sampled from the ANDRA Underground  
126 Research Laboratory (URL) in Bure. The CO<sub>x</sub> claystone has an interstratified illite-smectite content  
127 of 40-45% ([Fouché et al. 2004](#)) and a unit mass of 2.70 Mg/m<sup>3</sup>. The grain size distributions of the  
128 bentonite and claystone powders determined by dry sieving and sedimentation ([ASTM D422, 2007](#))

129 are presented in Fig. 1. The  $D_{50}$  values of the dry bentonite and claystone powders are 0.55 and 0.58  
130 mm, respectively. After saturation, the clay-size fractions of the bentonite and claystone are 86%  
131 and 26%, respectively.

132 The saturation water used in this study was synthetic water prepared according to the methods  
133 of Zeng et al. (2019).

## 134 2.2. Experimental technique and procedure

135 Fig. 2 depicts the experimental set-up used in this study. The test sample was installed in a stainless  
136 cell (50 mm in diameter) and placed between two porous stones (hydraulic conductivity is about  
137  $1.0 \times 10^{-5}$  m/s) and filter papers (hydraulic conductivity is about 0.15 m/s). It was saturated from the  
138 bottom of the cell at a constant water pressure of 9.8 kPa and the expelled air/water flowed through  
139 the air/water outlets at the top. The confined saturation conditions for the sample were guaranteed  
140 by the cell wall and a metallic cap that was locked using a screw. A force transducer was mounted  
141 under the cell base. A total pressure sensor (6 mm in diameter) was installed through a port on the  
142 side of the cell and its measuring surface was flush with the cell wall to ensure satisfactory pressure  
143 measurement. Based on the cell design, the axial force at the top of samples was transmitted to the  
144 piston and then the force transducer while the total pressure sensor directly measured the radial  
145 pressure at one location around the perimeter of the sample. All data were automatically collected  
146 by a data logger. The whole set-up was placed in a constant temperature room (controlled at  $20 \pm$   
147  $1$  °C).

148 The soil was prepared by mixing the bentonite powder with claystone powder using a stirrer  
149 for more than 10 min. The initial gravimetric water contents of the bentonite and claystone powders  
150 were 11.4 and 6.1%, respectively. The water content of the obtained mixture was 7.7%. A

151 pre-determined amount of mixture was weighed and poured into a cylindrical mould. The samples  
152 were prepared by compaction in the mould. Five disks (50 mm in diameter and 10 mm in height)  
153 were compacted to the dry densities of 1.6, 1.7, 1.8, 1.9 and 2.0 Mg/m<sup>3</sup>, respectively, in order to  
154 investigate the effect of dry density on the aeolotropic swelling behaviour (Table 2). Additionally,  
155 another four disks at the same dimensions were compacted to a dry density of 2.0 Mg/m<sup>3</sup> to study  
156 the effect of radial voids. In the case of axial voids, twelve disks (49.80 mm in diameter and 5 mm  
157 in height) with a dry density of 2.0 Mg/m<sup>3</sup> were prepared.

158 For the tests without voids (T01 to 05), the samples were directly transferred into the test cell  
159 by connecting the ends of the two cells (the compaction mould and test cell). For tests T06 to 09,  
160 axial voids between the 5-mm disks were simulated by a pre-defined space between disks using  
161 bentonite grains (Fig. 3a). For each test, three identical disks were used. After the installation of the  
162 first disk, 0.10 g of bentonite grains of pre-defined sizes were scattered on the top of the disk. Then,  
163 the second disk, the second layer of bentonite grains and the third disk were emplaced in sequence.  
164 As a result, two identical layers of bentonite grains were sandwiched among three disks and two  
165 gaps were created between disks. In this study, four samples with different gaps of 0.60, 0.80, 1.20  
166 and 1.70 mm (corresponding to the technological voids of 7.4%, 9.6%, 13.8% and 18.5%,  
167 respectively) were prepared using four groups of bentonite grains (0.25-0.40, 0.63-0.80, 1.00-1.25  
168 and 1.60-2.00 mm). Note that the total mass of bentonite grains was smaller than 0.5% of all disks'  
169 mass and thereby, their influence could be ignored. To facilitate the synthetic water to go into the  
170 technological voids at the beginning of hydration, the lateral surfaces of all the disks were covered  
171 by filter papers (about 0.10 mm thick), in addition to the filter papers at the top and bottom of  
172 samples (Fig. 3a). For tests T10 to 13 (Fig. 3b), four compacted disks with a dry density of 2.0

173  $\text{Mg/m}^3$  were extracted from the compaction mould and trimmed into smaller disks with the same  
174 height of 10 mm but with different diameters of 48.73, 47.43, 46.10 and 44.72 mm. The trimmed  
175 disks were positioned at the centre of test cell, keeping the initial gaps of 5, 10, 15 and 20% of the  
176 total volume respectively between the samples and cell wall. For all the tests (T01 to 13), the  
177 pressure sensor corresponded to the middle position of samples by changing the thickness of the  
178 porous stone at the bottom of samples. Note that for the tests with axial technological voids (T06 to  
179 09), the testing surface of pressure sensor (6 mm in diameter) was in contact with the central disk (5  
180 mm in thickness) and initial technological voids on the two sides of the central disk. Then, the  
181 synthetic water was injected from the bottom of the cell and the axial and radial pressures were  
182 measured during the hydration.

183 After the infiltration tests, the samples without voids (T01 to 05) and with radial voids (T10 to  
184 13) were extracted from the cell by pushing the sample from the bottom. By contrast, for the tests  
185 with axial voids (T06 to 09), the samples were carefully trimmed from the cell by cutting the edge  
186 of sample, because the common extruding method may cause significant sample compaction and  
187 lead to misjudgment on the soil density distribution in the vertical direction. The samples with  
188 initial axial voids (T06 to 09) were divided into five parts termed part I, part II, part III, part IV and  
189 part V, numbered sequentially from the top. As shown in [Fig. 4a](#), parts II and IV corresponded to  
190 initial voids and a 1-mm thick surface disk from the two sides, while parts I, III and V were the  
191 three disks. The sample T01 and those with initial radial voids (T10 to 13) were divided into parts I,  
192 II and III. As shown in [Fig. 4b](#), part I is a ring having inner and outer diameters of 40 and 50 mm,  
193 which included initial voids; part II is a ring with inner and outer diameters of 20 and 40 mm; part  
194 III is the rest of the cylinder within a diameter of 20 mm. Each part was cut into two pieces. One

195 piece was oven-dried at 105 °C for a period of 24 h to determine the water content; the other piece  
196 was immersed into non-aromatic hydrocarbon fluid (Kerdane) to determine the dry density.

### 197 **3. Experimental results**

#### 198 *3.1. Swelling behaviour of samples without technological voids*

199 The evolutions of axial and radial swelling pressures with respect to elapsed time for the samples  
200 without voids (T01 to 05) are shown in Fig. 5. Both axial and radial swelling pressures started with  
201 a quick increase. For the samples with high dry densities (larger than 1.8 Mg/m<sup>3</sup>), the axial swelling  
202 pressure increased and then reached stabilization at 5.18, 2.81 and 1.60 MPa after about 2600, 1860  
203 and 1710 min for tests T01 to 03, respectively. For the samples with low dry densities (smaller than  
204 1.7 Mg/m<sup>3</sup>), it increased until reaching peak values, then decreased and finally reached stabilization  
205 at 0.83 and 0.46 MPa at about 1580 and 1060 min for T04 and T05, respectively. The times needed  
206 to reach stabilization were comparable for the axial and radial swelling pressures. The final values  
207 of swelling pressures are summarized in Table 2. The larger the dry density, the larger the final axial  
208 and radial swelling pressures, in agreement with the observation by Zeng et al. (2019). Moreover,  
209 the difference between them increased with the increase of dry density.

#### 210 *3.2 Swelling behaviour of samples with axial technological voids*

211 The evolutions of axial and radial swelling pressures of samples T06 to 09 with different axial  
212 technological voids are illustrated in Fig. 6. At the beginning of hydration, the axial swelling  
213 pressure kept zero. After 5.4, 6.6, 12.0 and 28.8 min for tests T06 to 09, respectively, the axial  
214 swelling pressure became measurable (Fig. 6a). With further hydration, the axial swelling pressure  
215 increased and then tended to stabilize at 2.30, 1.59, 1.00 and 0.53 MPa after 2940, 2720, 2250 and  
216 2120 min for tests T06 to 09, respectively. Overall, the larger the axial technological voids, the

217 lower the increasing rate. Unlike the axial swelling pressure, the radial swelling pressure started  
218 with a quick increase at almost the same rate for tests T06 to 09. Subsequently, the radial swelling  
219 pressure reached a peak value and then decreased. After about 390-min hydration, the radial  
220 swelling pressures increased again and then reached stabilization values of 2.19, 1.53, 0.98 and 0.53  
221 MPa after 2920, 2720, 2290 and 2060 min for tests T06 to 09, respectively. The final axial and  
222 radial swelling pressures and the difference between them decreased with the increasing  
223 technological voids.

224 At the end of tests, the samples were extracted from the cell and the dry density and water  
225 content of different parts were determined. [Fig. 7](#) shows the distributions of dry density and water  
226 content of samples. It appeared that the distributions of dry density and water content were  
227 heterogeneous. Moreover, the larger the technological voids, the more heterogeneous the dry  
228 density and water content distributions. Parts II and IV which included initial voids had a lower dry  
229 density than the global one, whereas parts I, III and V had a higher dry density. The denser zone  
230 (parts I, III and V) could undergo further swelling, while the looser zone (parts II and IV) would be  
231 subjected to compression by the swelling pressure ([Bian et al. 2019a](#)). According to the measured  
232 dry density and water content, the saturation degree of each part was calculated to be 98.6-104.4%  
233 and the samples were almost saturated, confirming that no air was entrapped within the samples  
234 after 10-day hydration.

### 235 *3.3. Swelling behaviour of samples with radial technological voids*

236 The evolutions of axial and radial swelling pressures of samples T10 to 13 with different radial  
237 voids are depicted in [Fig. 8](#). The axial swelling pressure increased rapidly upon hydration. For tests  
238 T10 and T11 (with less than 10% radial voids), the axial swelling pressure reached stabilization at

239 2.86 and 1.62 MPa after 500 and 440 min. For tests T12 and T13 (with more than 15% radial voids),  
240 the axial swelling pressure increased and then reached the peak values of 0.97 and 0.80 MPa at 99  
241 and 41 min, respectively. Afterwards, the axial swelling pressure tended to be stable at about 0.86  
242 and 0.52 MPa after 410 and 400 min, respectively. Regarding the radial pressure, it kept zero during  
243 the first 1.8, 4.8, 8.4 and 10.8 min of hydration for samples T10 to 13, respectively. After that, the  
244 radial swelling pressure started to increase and then reached stabilization at 2.33, 1.14, 0.47 and  
245 0.20 MPa after 480, 470, 460 and 400 min, respectively. On the whole, the increasing rate decreased  
246 with the increasing technological voids. As the technological voids increased, the axial and radial  
247 swelling pressures decreased, while the difference between them increased.

248 The dry density and water content profiles of samples T10 to 13 after infiltration tests are  
249 depicted in Fig. 9. Heterogeneous distributions of dry density and water content were observed for  
250 all the samples, with a lower dry density and higher water content in part I (looser) while a higher  
251 dry density and lower water content in parts II and III (denser zone). This heterogeneity increased  
252 with the increasing technological voids. According to the measured dry density and water content,  
253 the saturation degree of each part was calculated and the calculated results varied from 98.4 to  
254 101.5%, indicating that the samples were almost saturated even though the dry density distribution  
255 was still heterogeneous.

## 256 **4. Interpretation and discussion**

### 257 *4.1. Swelling pressure kinetics*

258 As mentioned above, the swelling pressure kinetics of samples were highly dependent on the mode  
259 and amount of technological voids. For the samples with axial technological voids (T06 to 09), the  
260 axial voids were rapidly filled up by water with the help of lateral filter paper once the hydration

261 started. Then, the compacted disks swelled under free-swell condition in the axial direction and  
262 under confined condition in the radial direction. The samples with different amount of axial voids  
263 (T06 to 09) were under the same condition. Therefore, the axial pressure kept zero while the radial  
264 one started with a quick increase at the same increasing rate until the adjacent disks came into  
265 contact (Fig. 6a). Subsequently, the axial swelling pressure started to increase. However, the axial  
266 swelling of the central disk (corresponding to the radial pressure sensor) simultaneously led to a  
267 decrease in dry density in the vicinity of radial pressure sensor, resulting in a reduction of the radial  
268 pressure. When this reduction induced by the axial swelling of the central disk was larger than the  
269 increase of the radial swelling, peaks occurred on the radial swelling pressure curves (Fig. 6b). After  
270 the axial voids were filled up by the swollen soils, the radial swelling pressure increased again and  
271 then tended to stabilization. For the samples with radial technological voids (T10 to 13), the water  
272 rapidly filled up the radial technological voids upon hydration, allowing the trimmed disk to imbibe  
273 water from all the directions. In the axial direction, the axial swelling pressure increased quickly  
274 while the soils swelled in the radial direction, filling the radial technological voids. Owing to the  
275 significant radial swelling, a peak occurrence was identified on the axial swelling pressure curve of  
276 samples with large radial technological voids (T12 and T13) (Fig. 8a). Once the radial technological  
277 voids were filled by the swollen soils, the radial swelling pressure became measurable (Fig. 8b).  
278 Afterwards, the samples imbibed water from the top and bottom, and tended to homogeneity.

279 To clarify the effect of technological voids on the swelling pressure kinetics of samples, the  
280 evolutions of axial and radial swelling pressures of samples with the same initial dry density of 2.0  
281 Mg/m<sup>3</sup> (T01 and T06 to 13) are shown in Figs. 6 and 8. Additionally, the evolutions of axial and  
282 radial swelling pressures of samples at a given global dry density (as an example, samples T03, T07

283 and T11 are selected and their global dry densities are 1.80, 1.81 and 1.80 Mg/m<sup>3</sup>, respectively) are  
284 compared in Fig. 10. Compared to the samples without voids, a larger increasing rate of axial  
285 swelling pressure was observed for the samples with radial voids at the beginning of hydration  
286 while the samples with axial voids exhibited a lower one (Fig. 8a). This phenomenon could be  
287 explained as follows. At the beginning of hydration, the samples with radial technological voids  
288 were wetted from all the direction while the samples without voids were wetted only from the  
289 bottom. As a result, the samples (T01 and T10 to T13) exhibited a similar increasing rate, regardless  
290 of the radial technological voids. With further hydration, the radial voids would be filled by the  
291 swollen soils, with a decrease of the dry density of compacted disk (T10 to T13) while the upper  
292 layers of samples without voids (T01) were gradually hydrated by the synthetic water and swelled.  
293 Hence, the increasing rate of axial swelling pressure for the sample without voids T01 became  
294 larger than that of the samples with radial voids. For the samples with axial voids, the soils swelled  
295 axially in volume at the beginning of hydration due to the presence of axial voids. Upon the filling  
296 of axial voids, the samples absorbed water from the lateral sides, in addition to the top and bottom.  
297 Therefore, a larger increasing rate was identified for the samples with axial voids compared to the  
298 samples with radial voids at the same global dry density (water imbibition from the top and bottom),  
299 as shown in Fig. 10a. As regards the radial pressure, even though the middle part of the sample  
300 without voids could not significantly imbibe water from the bottom at a short time owing to the low  
301 permeability of compacted disk, the middle part would be subjected to axial compression by the  
302 lower layers through the  $K_0$  effect (Saba et al. 2014c). This explained the rapid increase of radial  
303 pressure (Figs. 6b and 8b), which accompanied the increasing axial swelling pressure. Owing to the  
304 smaller distance to the water inlet, the radial pressure even exhibited a larger increasing rate than

305 the axial one, which was determined at the top of the samples (Fig. 2). For the samples with axial  
306 voids, the pressure sensor was in contact with the central disk. Upon hydration, the central disk  
307 swelled axially, filling the technological voids with a decreasing dry density of the compacted disk.  
308 Thereby, a lower increasing rate of radial swelling pressure was observed, compared to the samples  
309 without voids (Fig. 6b). For the samples with radial voids, the radial swelling pressure would be  
310 measureable only after the filling of radial voids. This was why the samples with radial voids  
311 exhibited the lowest increasing rate of radial swelling pressure (Fig. 10b).

## 312 4.2. Final axial and radial swelling pressures

### 313 4.2.1. Aeolotropic swelling pressure of samples without voids

314 In addition to the swelling pressure kinetics, the final swelling pressures of samples are of equal  
315 importance. Fig. 11 shows the relationships between the final axial and radial swelling pressures  
316 and the global dry density for the samples without voids. The logarithm of axial and radial swelling  
317 pressures increased linearly with the increasing dry density. The relationships between the final  
318 axial swelling pressure ( $P_{s\text{-axial}}$  in MPa), the final radial swelling pressure ( $P_{s\text{-radial}}$  in MPa) and the  
319 dry density ( $\rho_d$  in  $\text{Mg/m}^3$ ) for the samples without voids could be described by unique correlations  
320 with squared correlation coefficients of 0.999:

$$321 \quad P_{s\text{-axial}} = 2.030 \times 10^{-3} \rho_d^{11.313} \quad (1)$$

$$322 \quad P_{s\text{-radial}} = 5.112 \times 10^{-4} \rho_d^{13.122} \quad (2)$$

323 From Fig. 11, it could also be observed that the axial swelling pressure was larger than the radial  
324 one. To further analyse this aeolotropic behaviour, the ratio of measured radial to axial swelling  
325 pressures, which was termed as aeolotropy coefficient, for all the samples was calculated. The  
326 relationship between the aeolotropy coefficient and global dry density for the samples without voids

327 is shown in Fig. 12. It appears that the aeolotropy coefficient increased from 0.46 to 0.88 as the dry  
328 density increased from 1.6 to 2.0 Mg/m<sup>3</sup>. Similar experimental studies were conducted on  
329 compacted pure Korean bentonite with dry densities ranging from 1.5 to 1.7 Mg/m<sup>3</sup> by Lee et al.  
330 (2012) and on compacted MX80 bentonite/sand mixture (70/30 in dry mass) with bentonite dry  
331 densities from 0.94 to 1.45 Mg/m<sup>3</sup> by Saba et al. (2014a). With the increase of dry density, the  
332 aeolotropy coefficient increased until reaching a peak value at the turning point and then decreased  
333 (Fig. 13). This phenomenon could be due to the combined effects of the heterogeneous distribution  
334 of macro-pores in the radial direction and the oriented arrangement of grains (Fig. 14). When grains  
335 with a dimension significantly larger than others were poured in the compaction mould, they would  
336 favour an oriented arrangement with a larger face side in the horizontal direction, as shown by Saba  
337 (2013) in a quantitative study. Additionally, more macro-pores could exist in the side part of  
338 samples due to the friction between grains and the mould wall, which was verified by Saba et al.  
339 (2014b) and Than et al. (2016) through X-ray computed tomography ( $\mu$ CT). Both of them would  
340 lead to an aeolotropic swelling behaviour upon hydration. During the subsequent compaction  
341 process, the oriented arrangement of grains increased with the increasing dry density while the  
342 heterogeneity of macro-pores would be reduced because of the squeeze of small grains into the side  
343 part (Than et al. 2016). Fig. 15 shows a sketch of compacted bentonite (various dry densities)  
344 before and after saturation. For the samples at low dry densities, the bentonite grains swelled and  
345 split up, but they could not fill up the macro-pores, especially at the side part. As shown in Fig. 2,  
346 the pressure sensor in contact with the side part of samples measured a lower radial swelling  
347 pressure when there were more macro-pores present in this zone (Fig. 15a), giving rise to a lower  
348 aeolotropy coefficient. For the samples at high dry densities, the grains could not fully swell due to

349 the limited macro-pores between grains (Fig. 15c). Thus, the initial orientation would be preserved.

350 For the samples at medium dry densities, the bentonite grains could swell and well fill the

351 macro-pores (Fig. 15b), resulting in a relatively isotropic behaviour. Summarizing, the aeolotropic

352 swelling behaviour for the samples at low dry densities could be mainly attributed to the

353 heterogeneous distribution of macro-pores in the radial direction while the influence of grain

354 orientation became dominant when the dry density of samples was larger than the turning point.

355 Obviously, the swelling capacity of bentonite governed the filling process of macro-pores,

356 influencing the turning point. Because of the lower montmorillonite content of Korean bentonite

357 (70%) as compared with that of MX80 bentonite (86%), a larger turning point was observed for the

358 Korean bentonite (Fig. 13). Furthermore, this turning point was also dependent on the property of

359 studied material such as grain size and water content. For the sample with a larger size and lower

360 water content, more macro-pores could be present in the side part owing to the larger friction with

361 the mould wall. In that case, a larger turning point could be expected. In this work, the used material

362 was a MX80 bentonite/COx claystone mixture with a claystone fraction as large as 70%. As the

363 grain size of COx claystone was larger than that of MX80 bentonite while its water content was

364 lower than that of MX80 bentonite, a higher concentration of macro-pores in the side parts could be

365 expected in this bentonite/claystone mixture. Additionally, the swelling capacity of this mixture was

366 quite low because the swelling capacity of major claystone is lower than 1% of that of bentonite

367 (Zeng et al. 2019). Therefore, the heterogeneity of macro-pores in the radial direction was difficult

368 to eliminate after hydration and a large turning point was obtained for this mixture. For the samples

369 with dry densities ranging from 1.6 to 2.0 Mg/m<sup>3</sup>, their aeolotropic swelling behaviour would be

370 mainly influenced by the heterogeneity of macro-pores and only the increasing trend of aeolotropy

371 coefficient with the increasing dry density was observed.

#### 372 4.2.2. Aeolotropic swelling pressure of samples with axial/radial voids

373 As far as the effect of technological voids was concerned, their presence led to the decreases of  
374 axial and radial swelling pressures (Table 2). The variations of the axial swelling pressure with the  
375 global dry density for the samples with axial/radial voids are also presented in Fig. 11. It could be  
376 observed that the axial swelling pressure for samples with axial/radial voids were in satisfactory  
377 agreement with that of samples without voids. This good agreement indicted that the final axial  
378 swelling pressure of compacted disks were mainly dependent on the global dry density, irrespective  
379 of the heterogeneity due to the presence of technological voids and the mode of voids (axial/radial  
380 voids). The variation in the radial swelling pressure with dry density for the samples with radial  
381 voids and without voids is also illustrated in Fig. 11. For samples with axial voids, since the dry  
382 density distribution was heterogeneous along the sample height at the end of infiltration tests, the  
383 distribution of radial swelling pressure was expected to be non-uniform. As the pressure sensor was  
384 located at the middle of the samples and in contact with parts II, III and IV, and the areas of contact  
385 between the pressure sensor and parts II, III and IV ( $A_2$ ,  $A_3$  and  $A_4$ ) were 5.23, 17.22 and 5.23 mm<sup>2</sup>,  
386 the average dry density of soils ( $\rho_{d\text{-sensor}}$  in Mg/m<sup>3</sup>) in contact with the pressure sensor could be  
387 calculated using Eq. (3):

$$388 \quad \rho_{d\text{-sensor}} = (\rho_{d\text{-II}} \times A_2 + \rho_{d\text{-III}} \times A_3 + \rho_{d\text{-IV}} \times A_4) / (A_2 + A_3 + A_4) \quad (3)$$

389 where  $\rho_{d\text{-II}}$ ,  $\rho_{d\text{-III}}$ ,  $\rho_{d\text{-IV}}$  are the dry density of parts II, III and IV, respectively. The values of average  
390 dry density were calculated to be 1.87, 1.81, 1.74 and 1.64 Mg/m<sup>3</sup>, for tests T06-09, respectively.  
391 Thereby, the radial swelling pressure versus the average soil dry density near the pressure sensor is  
392 shown in Fig. 11. It appears that the samples with axial voids exhibited a larger radial swelling

393 pressure than those without voids at the same dry density, while the samples with radial voids  
394 showed a lower one, especially for those with more than 15% radial voids. The aeolotropy  
395 coefficients of the samples with axial/radial voids are also summarized in Fig. 12. Note that the  
396 aeolotropy coefficient for the samples with axial voids was determined according to the axial and  
397 radial swelling pressures of soils in the vicinity of the pressure sensor. The axial swelling pressures  
398 of soils in contact with the pressure sensor were estimated using Eq. (1). From Fig. 12, the samples  
399 with axial voids exhibited a larger aeolotropy coefficient than those without voids, whereas the  
400 samples with radial voids showed a lower one, albeit at the same dry density. The aeolotropic  
401 swelling mechanism of the compacted bentonite/claystone mixture with axial/radial voids is shown  
402 in Fig. 16. Upon hydration, the clay particles of the samples with axial voids swelled and split up,  
403 filling up the initial axial voids. This process allowed the rearrangement of clay particles and  
404 reduced the initial orientation of clay particles (Fig. 16a). Consequently, a less aeolotropic  
405 behaviour was observed for the samples with axial voids. Furthermore, larger axial voids would  
406 provide more spaces for the swelling of clay particles, leading to more pronounced reductions in the  
407 orientation of clay particles. This explained why the aeolotropy coefficient increased with the  
408 increasing axial technological voids (decreasing dry density). When the radial technological voids  
409 were considered, the radial sensor was in contact with the soils in the side part (part I) where the dry  
410 density was lower than the global one (Fig. 16b) and the measured radial swelling pressure was  
411 lower than that of samples without voids, especially for the samples with more than 15% voids (Fig.  
412 11). As shown in Fig. 10a, the larger initial voids, the more heterogeneous the dry density  
413 distribution. Hence, a larger reduction in the aeolotropy coefficient was observed for the samples  
414 with larger initial radial voids. In other words, radial voids would increase the heterogeneity of dry

415 density in the radial direction, giving rise to a more pronounced aeolotropic behaviour; by contrast,  
416 the axial voids could decrease the initial orientation of clay particles, leading to a less pronounced  
417 aeolotropic behaviour.

418 As remarked above, the dry density distributions of samples with axial/radial voids were  
419 non-uniform at the end of infiltration tests. Over time, the soils in the looser zone would be  
420 compressed by swelling pressure with an increase in dry density, whereas the soils in the denser  
421 zone underwent further swelling with a decrease in dry density, resulting in a relatively  
422 homogenous distribution. For the samples with axial technological voids, the swollen clay particles  
423 would become more oriented under the swelling pressure, leading to a decrease of aeolotropy  
424 coefficient. For the samples with radial voids, this homogenization process would reduce the  
425 concentration of macro-pores in the side part, resulting in an increase of aeolotropy coefficient.  
426 However, the dry density gradient could remain for longtime because of the friction between the  
427 samples and cell wall. To this end, the samples with axial voids would present a relatively higher  
428 aeolotropy coefficient in long term than those without voids whereas the samples with radial voids  
429 would show a lower one.

## 430 **5. Conclusions**

431 Constant-volume swelling pressure tests were performed on compacted MX80 bentonite/COx  
432 claystone mixture at different dry densities and the swelling pressures in both axial and radial  
433 directions were obtained, allowing the effect of dry density on the aeolotropic swelling behaviour to  
434 be determined. To study the effects of axial/radial voids on the aeolotropic swelling behaviour,  
435 swelling pressures of the samples with different axial/radial technological voids were measured,  
436 together with the determination of dry density and water content at different positions. From the

437 experimental results, the following conclusions can be drawn.

438         The axial swelling pressure was dominated by global dry density, regardless of the presence of  
439 technological voids and the mode of technological voids (axial or radial voids). At the same dry  
440 density, the samples with axial technological voids had a larger radial swelling pressure than those  
441 without voids while the samples with radial voids exhibited a smaller one, especially for the  
442 samples with larger voids.

443         For the samples without voids, the aeolotropy coefficient (ratio of radial to axial swelling  
444 pressures) increased and then decreased with the increasing dry density due to the combined effects  
445 of the concentration of macro-pores in the border of samples and the orientation of clay particles. At  
446 low dry densities, the swelling aeolotropy was mainly conditioned by the former. As the dry density  
447 decreased, the heterogeneous distribution of macro-pores decreased while grain orientation  
448 increased. Therefore, the swelling aeolotropy was dominated by the latter, in case of high dry  
449 densities.

450         At the same dry density, the samples with axial voids exhibited a larger aeolotropy coefficient  
451 than those without voids, thanks to the reductions of the orientation of clay particles. On the  
452 contrary, the samples with radial voids presented a lower one because of the lower dry density in the  
453 side part. Furthermore, the larger the technological voids, the more significant the influence of  
454 axial/radial voids on the aeolotropic swelling behaviour.

455

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531 **List of Tables**

532 Table 1 Physical and mineralogical properties of MX80 bentonite

533 Table 2 Experimental program and main results

534 **List of Figures**

535 Fig. 1 Grain size distribution of MX80 bentonite and crushed COx claystone

536 Fig. 2 Layout of the constant-volume cell

537 Fig. 3 Different technological voids considered: (a) axial voids and (b) radial voids

538 Fig. 4 Schematic view of sample cutting: (a) axial voids and (b) radial voids

539 Fig. 5 Evolutions of axial and radial swelling pressures of samples without voids: (a) axial swelling  
540 pressure and (b) radial swelling pressure

541 Fig. 6 Evolutions of axial and radial swelling pressures of samples with axial voids: (a) axial  
542 swelling pressure and (b) radial swelling pressure

543 Fig. 7 Dry density and water content profiles for the samples with axial voids: (a) dry density and (b)  
544 water content. Note: the dash lines in the left graph represent the global dry density calculated using  
545 the total volume after filling technological voids instead of initial state while the dash lines in the  
546 right graph refer to the global water content corresponding to the global dry density and a 100%  
547 degree of saturation

548 Fig. 8 Evolutions of axial and radial swelling pressures of samples with radial voids: (a) axial  
549 swelling pressure and (b) radial swelling pressure

550 Fig. 9 Dry density and water content profiles for sample T01 and those with radial voids (T10 to13):  
551 (a) dry density and (b) water content. Note: the dash lines in the left graph represent the global dry  
552 density calculated using the total volume after filling technological voids instead of initial state  
553 while the dash lines in the right graph refer to the global water content corresponding to the global  
554 dry density and a 100% degree of saturation

555 Fig. 10 Comparison of the swelling pressure kinetics of samples in different cases: (a) axial  
556 swelling pressure and (b) radial swelling pressure

557 Fig. 11 Relationship between axial and radial swelling pressures and dry density

558 Fig. 12 Relationship between aeolotropy coefficient and dry density of bentonite/claystone mixture.  
559 Note: the aeolotropy coefficient of the samples with axial voids was determined according to the  
560 axial and radial swelling pressures of the soils in contact with the pressure sensor

561 Fig. 13 Aeolotropy coefficient changes with bentonite dry density for different bentonites (data  
562 from Lee et al. (2012) and Saba et al. (2014a))

563 Fig. 14 Representation of the effects of grain orientation and concentrated macro-pores in the side  
564 part. Note: the curves in the figure are schematically drawn and do not represent measured values

565 Fig. 15 Schematic view of aeolotropic swelling mechanism in compacted bentonite at: (a) low dry

566 densities; (b) medium dry densities; (c) high dry densities

567 Fig. 16 Schematic view of aeolotropic swelling mechanism in compacted bentonite/claystone

568 mixture with: (a) axial voids; (b) radial voids

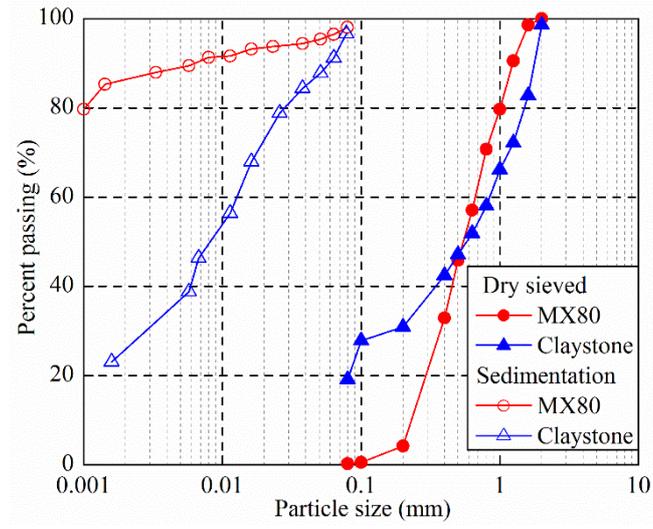
**Table 1** Physical and mineralogical properties of MX80 bentonite

Soil property	This work	Tang et al. (2008)	Seiphoori et al. (2014)	Saba et al. (2014)	Karland et al. (2008)
Specific gravity	2.76	2.76	2.74	2.77	-
Consistency limit					
Liquid limit (%)	494	520	420	575	-
Plastic limit (%)	46	42	65	53	-
Plasticity index (%)	448	478	355	522	-
Main minerals					
Montmorillonite (%)	86	92	85	-	80
Quartz (%)	7	3	-	-	2-3

**Table 2** Experimental program and main results

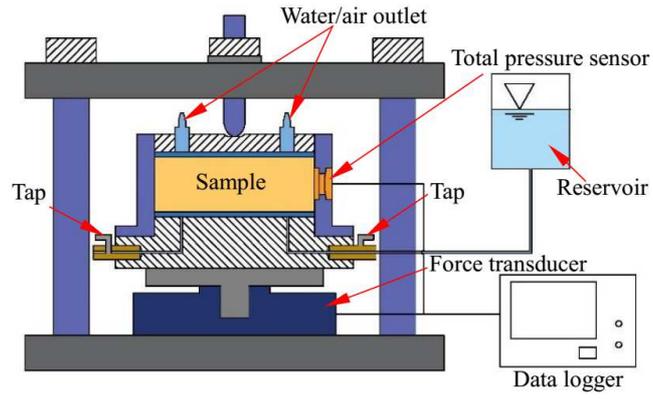
Test No.	Technological voids		Global dry density (Mg/m <sup>3</sup> )	Final axial swelling pressure (MPa)	Final lateral swelling pressure (MPa)
	Mode	Amount (%)			
T01	Without	0	2.0	5.18	4.55
T02	voids	0	1.90	2.81	2.35
T03		0	1.80	1.60	1.14
T04		0	1.70	0.83	0.53
T05		0	1.60	0.46	0.21
T06		Axial	7.4	1.85	2.30
T07	voids	9.6	1.81	1.59	1.53
T08		13.8	1.72	1.00	0.98
T09		18.5	1.63	0.53	0.53
T10	Radial	5	1.90	2.86	2.33
T11	voids	10	1.80	1.62	1.14
T12		15	1.70	0.86	0.47
T13		20	1.60	0.52	0.20

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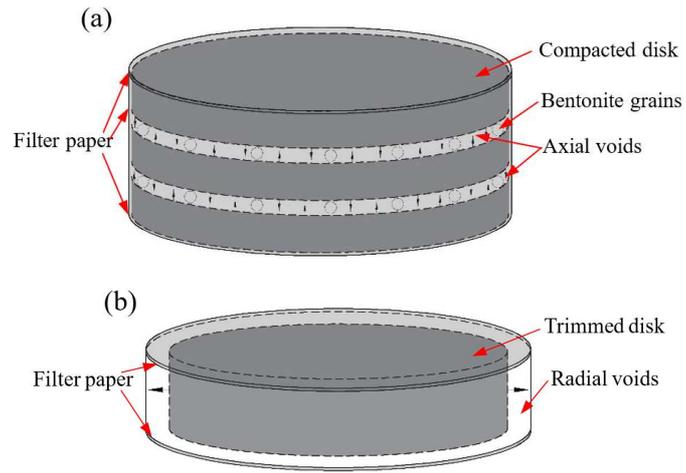


**Fig. 1** Grain size distributions of MX80 bentonite and crushed COx claystone

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**Fig. 2** Layout of the constant-volume cell



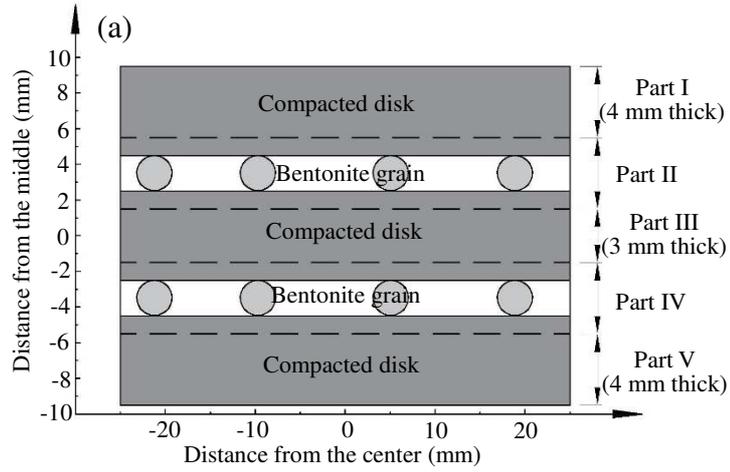
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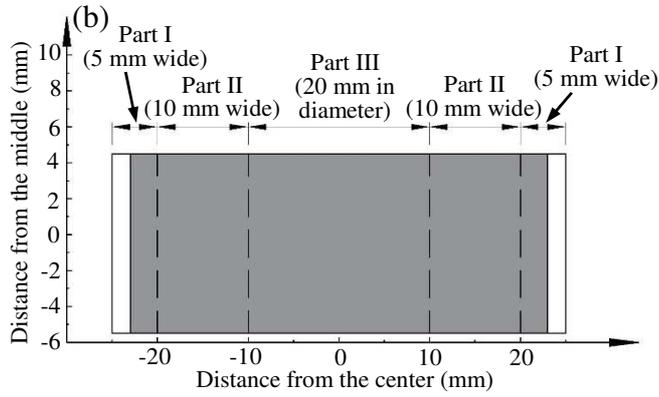
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**Fig. 3** Different technological voids considered: (a) axial voids and (b) radial voids

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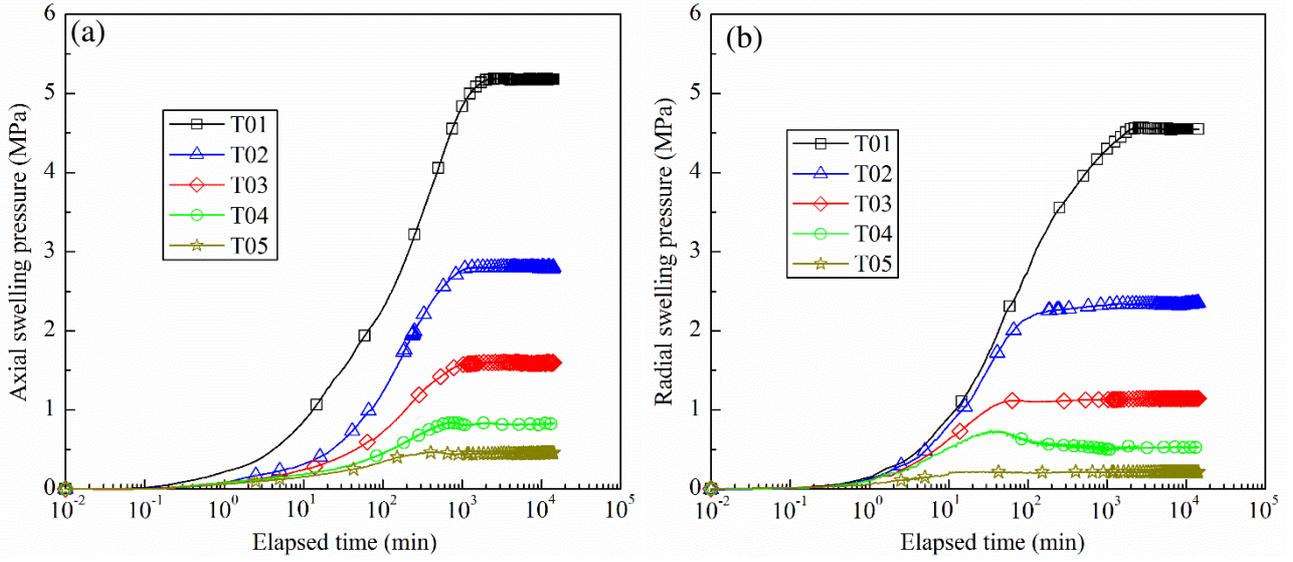


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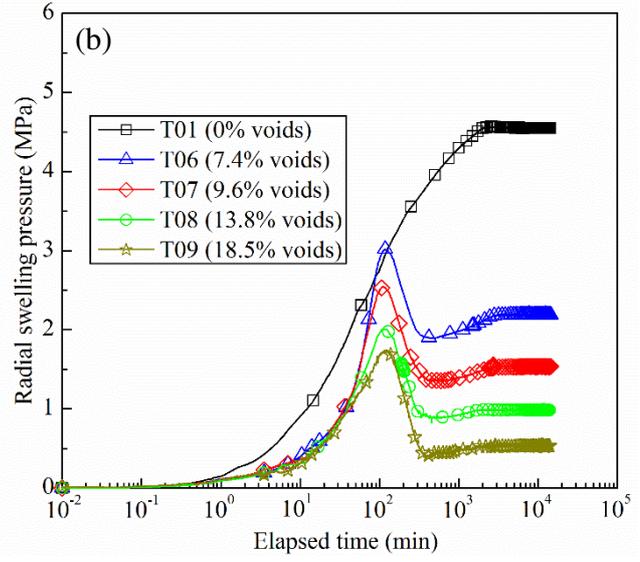
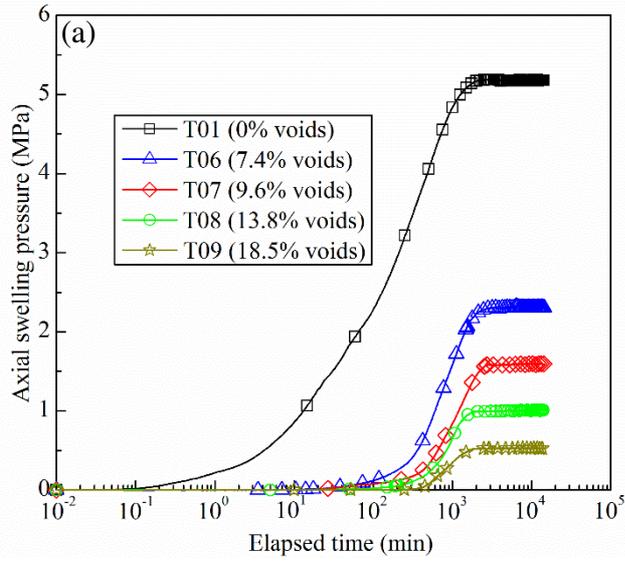
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Fig. 4 Schematic view of sample cutting: (a) axial voids and (b) radial voids



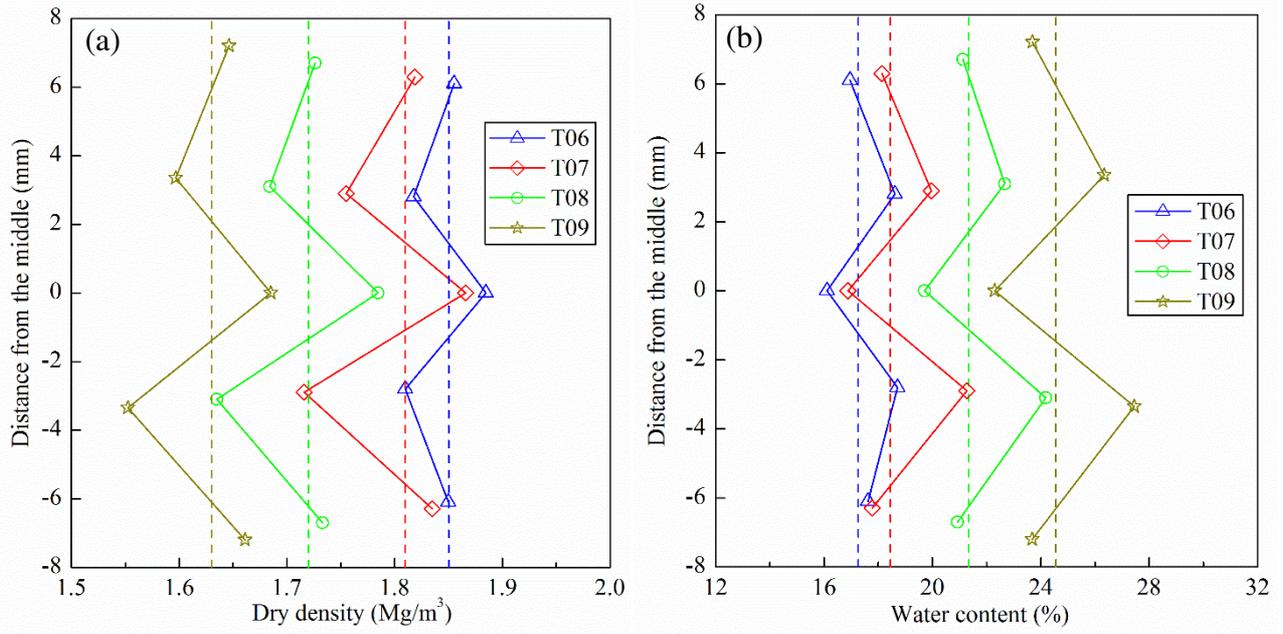
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**Fig. 5** Evolutions of axial and radial swelling pressures of samples without voids: (a) axial swelling pressure and (b) radial swelling pressure

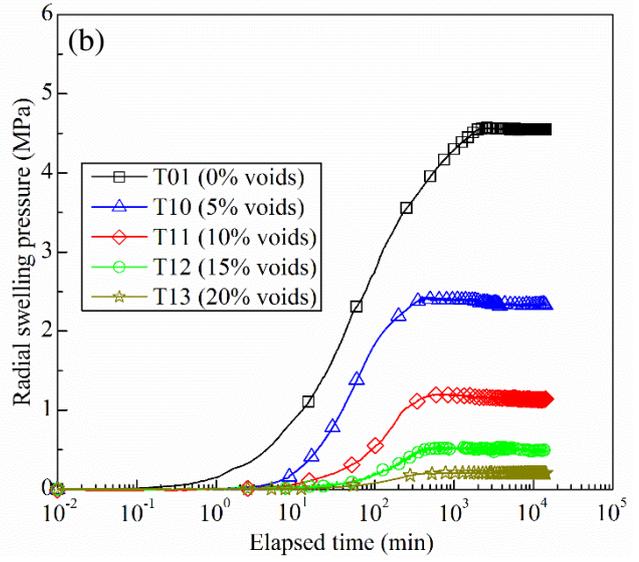
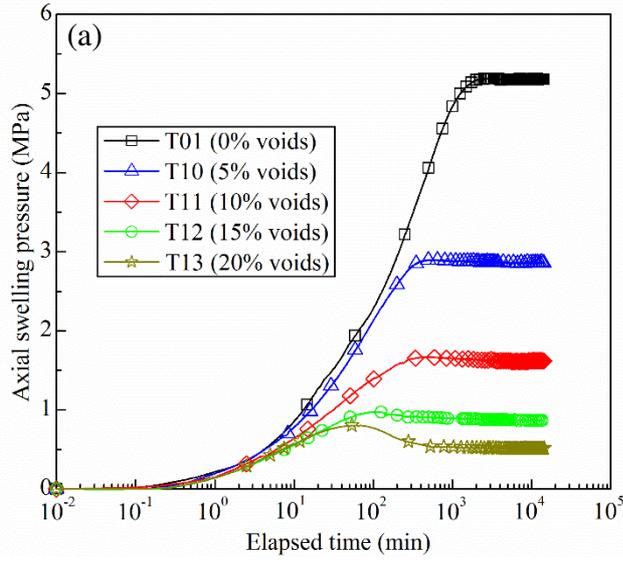


**Fig. 6** Evolutions of axial and radial swelling pressures of samples with axial voids: (a) axial swelling pressure and (b) radial swelling pressure

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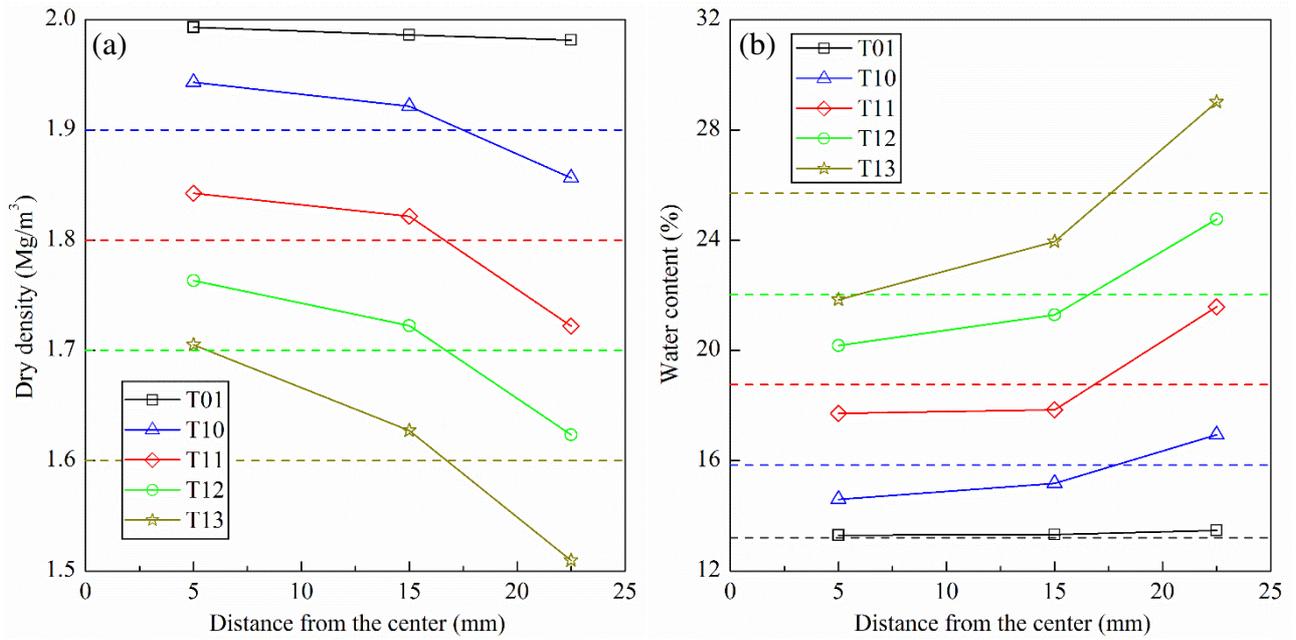


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 590 **Fig. 7** Dry density and water content profiles for the samples with axial voids: (a) dry density and (b) water content. Note: the dash  
 591 lines in the left graph represent the global dry density calculated using the total volume after filling technological voids instead of  
 592 initial state while the dash lines in the right graph refer to the global water content corresponding to the global dry density and a 100%  
 593 degree of saturation



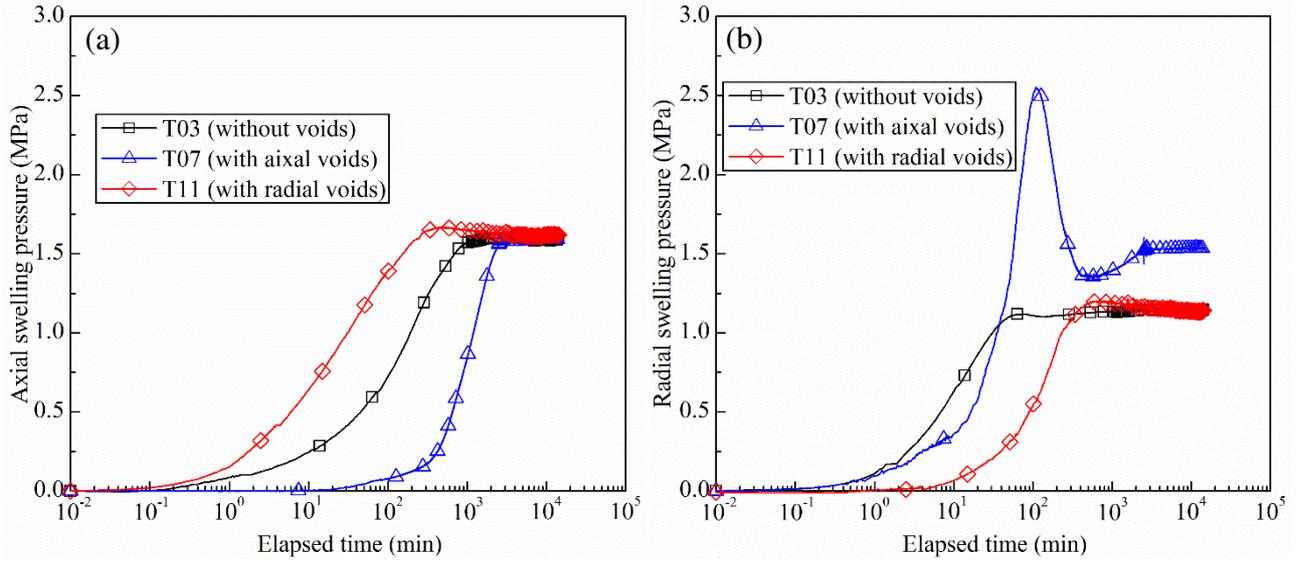
**Fig. 8** Evolutions of axial and radial swelling pressures of samples with radial voids: (a) axial swelling pressure and (b) radial swelling pressure

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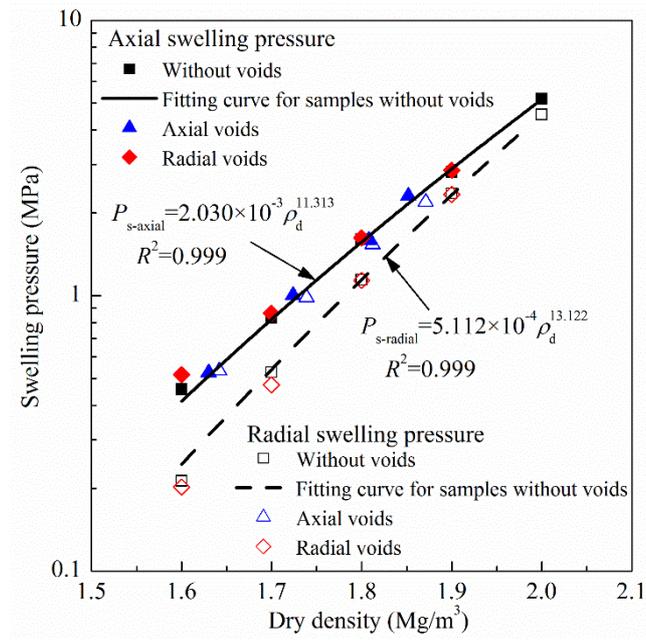
**Fig. 9** Dry density and water content profiles for sample T01 and those with radial voids (T10 to T13): (a) dry density and (b) water content. Note: the dash lines in the left graph represent the global dry density calculated using the total volume after filling technological voids instead of initial state while the dash lines in the right graph refer to the global water content corresponding to the global dry density and a 100% degree of saturation



**Fig. 10** Comparison of the swelling pressure kinetics of samples in different cases: (a) axial swelling pressure and (b) radial swelling pressure

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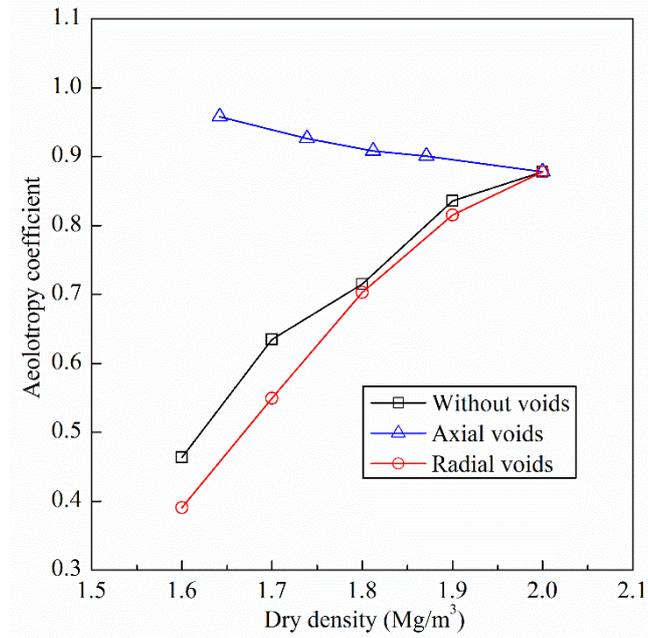
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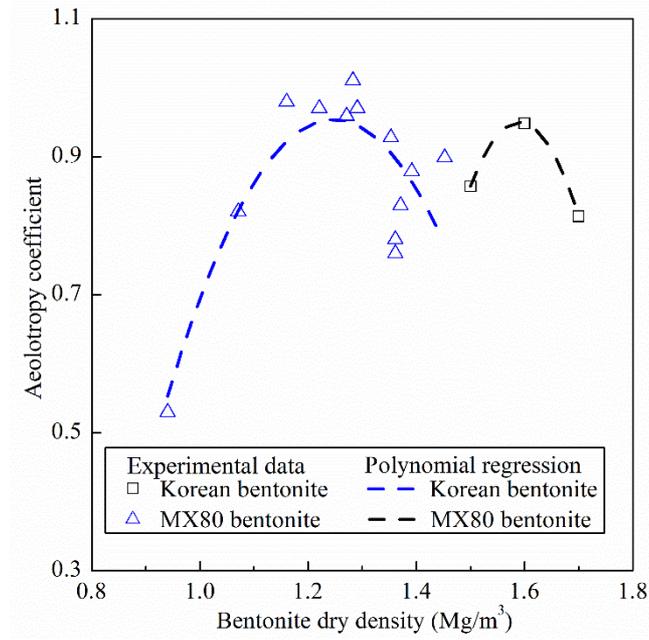
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**Fig. 11** Relationship between axial and radial swelling pressures and dry density



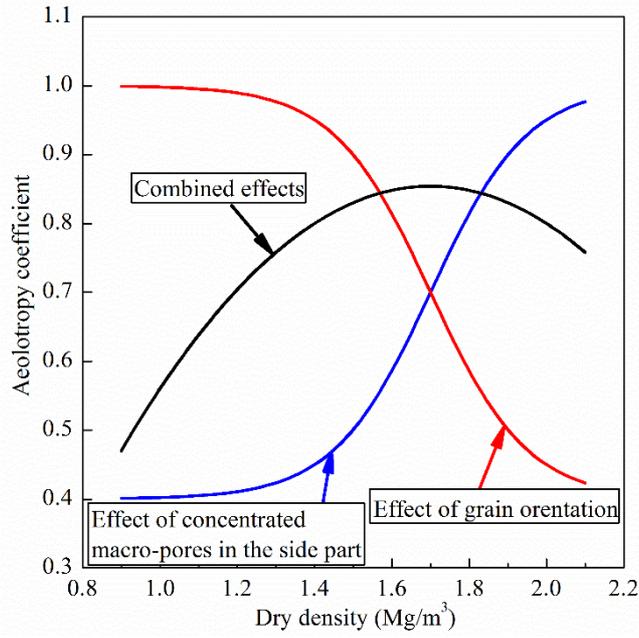
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**Fig. 12** Relationship between aelotropy coefficient and dry density of bentonite/claystone mixture. Note: the aelotropy coefficient of the samples with axial voids was determined according to the axial and radial swelling pressures of the soils in contact with the pressure sensor



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**Fig. 13** Aeolotropy coefficient changes with bentonite dry density for different bentonites (data from [Lee et al. \(2012\)](#) and [Saba et al. \(2014a\)](#))

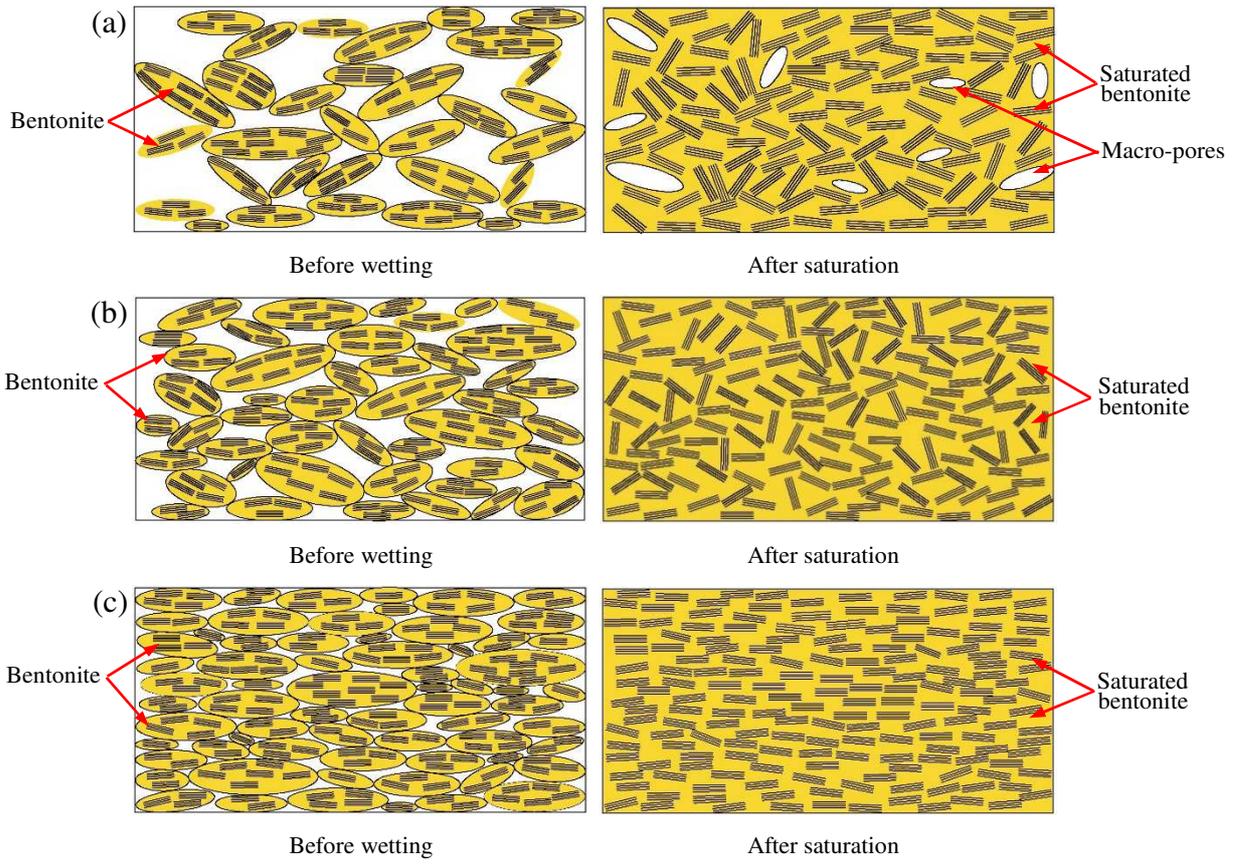


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**Fig. 14** Representation of the effects of grain orientation and concentrated macro-pores in the side part. Note: the curves in the figure are schematically drawn and do not represent measured values



**Fig. 15** Schematic view of aeolotropic swelling mechanism in compacted bentonite at: (a) low dry densities; (b) medium dry densities; (c) high dry densities

