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# Fracture effect on the hydro-mechanical behaviour of Callovo-Oxfordian claystone

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24 **ABSTRACT**

25 Excavation of the galleries for the geological disposal of radioactive waste can induce an  
26 excavation damaged zone (EDZ), which can have consequences on the long-term safety of the  
27 repository. In this study, intact Callovo-Oxfordian (COx) claystone taken from the  
28 Meuse/Haute-Marne Underground Research Laboratory in France was artificially fractured in  
29 different directions, and the hydro-mechanical behaviour was investigated by performing high  
30 pressure oedometer test and hydraulic conductivity test. Comparison between the fractured  
31 and intact COx samples allows identification of the effects of fracture in terms of swelling,  
32 compression, hydraulic conductivity and creep. It appears that the presence of fracture  
33 decreases the swelling strain and this phenomenon depends on the infiltration path and the  
34 orientation of fracture. In particular, the infiltration path affects the global swelling rate of  
35 fractured claystone. The self-sealing of fracture is mainly attributed to the swelling of COx  
36 claystone grains in the fracture zone. Lower compression coefficient  $\alpha$ , higher compression  
37 index  $C_c^*$  and higher secondary consolidation coefficient  $C_\alpha$  are observed for the fractured  
38 claystone, indicating a higher compressibility and creep than the intact one. The compression  
39 and creep behaviours depend on both the orientation of fracture and the stress level.  
40 Comparison of hydraulic conductivities between fractured and intact claystone indicates that  
41 the hydraulic conductivity can be partially recovered due to the collapse of macro-pores in the  
42 filled fracture zone. This is also confirmed by analysing the evolution of consolidation  
43 coefficients  $c_v$  with stress. Beyond a stress level about 16 MPa, the fracture effect can be  
44 neglected, but the compressibility increases further due to grain breakage. Interestingly, this  
45 stress is close to the in-situ stress before excavation.

46 **KEYWORDS:** COx claystone; fracture; swelling; compression; creep; hydraulic  
47 conductivity.

48

## 49 INTRODUCTION

50 The French National Radioactive Waste Management Agency (Andra) is in charge of  
51 studying the disposal of high-level and intermediate-level long-lived waste (HLW and ILW-  
52 LL) in a deep geological repository (Cigéo project) which will be located at the border of the  
53 Meuse and Haute-Marne departments, nearly 300 km East of Paris. The host formation is the  
54 Callovo-Oxfordian (COx) claystone layer with ~ 150 m of thickness and located about 500 m  
55 in depth. This argillaceous rocks exhibit very favourable conditions for a repository of  
56 radioactive waste, as they generally have a very low hydraulic conductivity, small molecular  
57 diffusion and significant retention capacity for radionuclide. Andra is conducting a scientific  
58 and technological program, including in-situ experiments at the Meuse/Haute-Marne  
59 Underground Research Laboratory (MHM URL), which aims to demonstrate the feasibility of  
60 constructing and operating the Cigéo project (ANDRA, 2005). Among the in-situ experiments  
61 at MHM URL, field observation about the excavation induced damage zone (EDZ) has been  
62 made with particular attention. Indeed, a major concern related to the long term safety of the  
63 geological radioactive waste disposal is that the fractures within EDZ could create preferential  
64 pathways to the radionuclide migration. A conceptual model of EDZ around drifts excavated  
65 at the main level of MHM URL was proposed by Armand et al. (2014). The in-situ  
66 measurements indicated that the hydraulic conductivity of damaged COx claystone in the  
67 vicinity of drift was significantly higher than that far from the wall, due to the fractures in the  
68 EDZ (de la Vaissière et al., 2015; Armand et al., 2014). Moreover, the convergence of  
69 excavated galleries might be intensified by the presence of fractures within the EDZ (Armand  
70 et al., 2013). In other words, the rock formation with EDZ will produce more significant time-  
71 dependent deformation, impacting the long-term evolution of nuclear waste repository. As  
72 shown by Alonso et al. (2021), the creep strain of COx claystone mainly controls the stress  
73 increase within the gallery concrete liner (i.e. the design of the gallery liner).

74 A large number of laboratory tests were conducted on COx claystone to clarify the  
75 evolution of fractures upon wetting (Pham et al., 2007; Wan et al., 2013; Menaceur et al.,  
76 2016). It appears that the pre-existing fractures in COx claystone can be closed due to the  
77 swelling of the clay minerals (interstratified illite /smectites, illite, and kaolinite, etc.) (Yven  
78 et al., 2007; Menaceur, 2014). This phenomenon strongly depends on the applied stress, the  
79 clay fraction and the hydration level (Zhang, 2011 and 2013; Giot et al., 2019; Di Donna et al.,  
80 2019). Zhang (2009, 2011, 2013) explored the effect of fracture aperture on the permeability  
81 of COx claystone through gas and water permeability tests, with artificially created fractures.  
82 It was observed that the swelling of the clay matrix due to wetting induced clogging of  
83 fractures, leading to a significant decrease of gas and water permeabilities by several orders of  
84 magnitude. This indicates that the self-sealing property of COx claystone can result in partial  
85 recovery of its permeability with clogging of fractures. However, under free swelling  
86 conditions, micro-cracks occur inside the intact COx claystone due to swelling (Bornert et al.  
87 2010; Wang et al. 2014; Menaceur et al. 2016). Besides, it is worth noting that the previous  
88 studies mainly focused on the swelling aspect of fractured COx claystone, less attention being  
89 paid to its compression behaviour.

90 Several studies were performed to investigate the volume change behaviour of intact COx  
91 claystone. Mohajerani et al. (2011) and Menaceur (2014) investigated the oedometer  
92 compression behaviour of intact COx claystone, showing that a high stress resulted in local  
93 pore collapse. Moreover, the damage-induced micro-cracks enhanced its swelling potential.  
94 Similar observations were observed on other swelling shales, which was interpreted by the  
95 damage of bonds by loading (Aversa et al., 1993; Carter et al., 2010). Besides, Chiarelli et al.  
96 (2003) investigated the isotropic compression behaviour of intact COx claystone at initially  
97 unsaturated state, and significant plastic volume change and anisotropic behaviour were  
98 observed, in agreement with the observations by Zhang et al. (2015, 2019). However, it

99 should be pointed out that previous studies only focused on the volume compression  
100 behaviour of intact claystone, few studies dealing with the volume change and creep  
101 behaviours of fractured COx claystone.

102 In this study, high pressure oedometer tests were carried out to investigate the effect of  
103 fracture on the hydro-mechanical behaviour of COx claystone. Two kinds of artificial  
104 fractured samples with different fracture directions (horizontal and vertical) were considered,  
105 together with an intact sample for the purpose of comparison. Besides, the hydraulic  
106 conductivity of COx claystone was measured in each loading step. The obtained results  
107 allowed the self-sealing characteristics and the effects of fracture on swelling, compression  
108 and creep behaviours of COx claystone to be clarified.

## 109 **MATERIALS AND METHODS**

### 110 **Materials**

111 The COx claystone used in this study was excavated at a depth of about -490 m, with a pore  
112 water pressure of 4.7 MPa and the in situ stresses of ~12.7 MPa in the vertical direction,  
113 ~12.7-14.8 MPa in the major horizontal stress direction, ~12.4 MPa in the minor horizontal  
114 stress direction (Wileveau et al., 2007). For the mineral composition, clay minerals account  
115 for 50-55%, including 30% illite, 15% kaolinite and chlorite and 55% interstratified  
116 illite\smectite. Besides, it also contains 3% pyrite, 20% iron oxides, 20%–25% tectosilicates  
117 of carbonates (Armand et al., 2013). The extracted COx claystone samples are preserved in  
118 T1 cell to keep the water content as in situ state and to minimize the decompression due to  
119 unloading from in situ stress (Conil et al., 2018). In this study, a COx core from T1 cell  
120 EST57180 was used. The physical parameters of this core were determined and presented in  
121 Table 1. Decagon WP4 dew point tensiometer was used to measure the initial total suction.  
122 Small pieces were cut to measure the water content by oven drying at 105 °C. The porosity

123 (void ratio) and degree of saturation were determined by measuring the volume (see  
124 Menaceur et al. (2016) for more details). Then, the dry density can be calculated.

### 125 **Sample preparation**

126 For the real fractures induced under the in situ conditions, they are quite complex (e.g.  
127 fracture size, number and direction), as reported by Armand et al. (2014). The fractures are  
128 classified into two types: shear fractures and unloading tensile fractures, based on the  
129 observations on drill cores. The shear fractures are generally oriented at an angle with respect  
130 to the drift wall, while most tensile fractures are perpendicular to the corresponding bedding  
131 plane in the vicinity of drift wall. In this context, it is very difficult to identify the effect of  
132 fractures on the hydro-mechanical behaviour of CO<sub>x</sub> claystone. To simplify the problem, only  
133 a well-defined single horizontal/vertical fracture with respect to the bedding direction is  
134 considered in this study. For the preparation of fractured CO<sub>x</sub> claystone samples, a CO<sub>x</sub>  
135 cylinder with diameter of 38 mm was first drilled along the direction perpendicular to the  
136 bedding plane. A diamond sawing machine was used to cut the cylinder to oedometer samples  
137 of 10 mm height. The preparation process is shown in Fig. 1. To acquire fractured samples,  
138 the intact sample was artificially cut into two parts in two directions - parallel (horizontal  
139 fracture) and perpendicular (vertical fracture) to the bedding plane as shown in Fig. 2. An  
140 intact sample was also used for comparison. For the horizontally fractured samples, the  
141 average width of a horizontal fracture depends on the roughness of the contact interface of the  
142 two disks after sand paper polishing. Each disk has a diameter of 38 mm and a height of 5 mm.  
143 The objective of polishing the interface was to well define the fracture width. The horizontal  
144 fracture thickness was determined as the difference between the total height of the two  
145 stacked disks after placed in the oedometer cell and the sum of the heights of the two separate  
146 disks. For the vertically fractured samples, the vertical fracture thickness was obtained by  
147 measuring the difference between the diameter in the direction perpendicular to the vertical

148 fracture and the initial one before cutting. For the control of vertical fracture size, a thin metal  
149 plate was used to separate the two parts after the sample was placed in the oedometer cell.

## 150 **Experimental methods**

151 High pressure oedometer was used and synthetic water was adopted with the same chemical  
152 composition as the site water, as shown in Table 2. The in situ COx claystone in the fractured  
153 zone is unsaturated due to the ventilation, but will be saturated after closure by the in situ  
154 water from the surrounding host formation. In order to simulate the swelling behaviour of  
155 fractured COx claystone in the fractured zones, two cases were considered: case 1 - the  
156 sample was wrapped with filter paper at the lateral surface to simulate the underground water  
157 directly flowing into the fractures (tests TH-1 and TV-1); case 2 - without filter paper at the  
158 lateral surface to simulate the underground water infiltrating into fracture through intact COx  
159 claystone (tests TH-2 and TV-2). Test TI was performed on the intact sample without filter  
160 paper at the lateral surface. The programs for the five tests are detailed in Table 3. It can be  
161 observed that different fracture openings were used for horizontal (0.1 mm) and vertical (0.3  
162 mm) fractures. This choice was made to ensure that all samples had the same initial global  
163 void ratio. Note that the initial global void ratio considered all the void including the fracture  
164 and the void inside the disks. In addition, based on the experimental evidence by Giot et al.  
165 (2019) and Di Donna et al. (2019), the selection of the fracture sizes in this study can ensure  
166 the fractures be totally closed by the swelling of clay minerals due to hydration.

167 After the sample was installed into the oedometer cell, synthetic water was injected from  
168 the bottom under a low vertical stress of 0.05 MPa to ensure the good contact. After the  
169 stabilization of vertical swelling strain according to ASTM-D4546 (2021), step loading up to  
170 64 MPa was applied. At each loading step, the hydraulic conductivity ( $k$ ) was measured in the  
171 vertical direction with a pressure-volume controller, as shown in Fig. 3.



172 Actually, considering the fracture effect, significantly large pores exist in the closed  
 173 fracture zone due to the swelling of clay minerals, as reported by Zhang (2011, 2013). Thus,  
 174 the samples cannot be regarded as homogeneous accounting for the presence of obvious dual  
 175 porosity (large pores in fractured zone and small pores in intact zone). Strictly speaking, it is  
 176 not suitable to analyze the consolidation behaviour of fractured COx claystone using the  
 177 Terzaghi consolidation theory due to the heterogeneity of samples. However, the direct  
 178 application of this theory seems to be the easiest way to evidence the effect of fractures on  
 179 permeability and compressibility. Therefore, in this study, the simplified one-dimensional  
 180 consolidation equation is still adopted to calculate the hydraulic conductivity and compression  
 181 coefficient, as shown in Eq. (1) (Terzaghi et al., 1996):

$$182 \quad c_v \frac{\partial^2 u_e}{\partial z^2} = \frac{\partial u_e}{\partial t} \quad (1)$$

183 where  $u_e$  is the excess pore water pressure,  $\sigma_z$  is the total vertical stress,  $t$  is the time, and  $c_v$   
 184 is the consolidation coefficient.

185  $c_v$  can be calculated with Eq. (2):

$$186 \quad c_v = \frac{k(1+e)}{\gamma_w a_v} \quad (2)$$

187 where  $k$  is the hydraulic conductivity,  $a_v$  is the compression coefficient,  $e$  is the  
 188 corresponded void ratio under each stress and  $\gamma_w$  is the water unit weight. The  
 189 compression coefficient  $a_v$  is the ratio between the decrement of  $e$  and the increment of  $\sigma_v$ .  
 190  $a_{v,n}$  at the loading step  $n$  can be calculated as following:

$$191 \quad a_{v,n} = \frac{e_n - e_{n-1}}{\sigma_{v,n} - \sigma_{v,n-1}} \quad (3)$$

192 where  $e_n$  and  $e_{n-1}$  are the void ratios at the loading step  $n$  and the last one, respectively;  $\sigma_{v,n}$   
 193 and  $\sigma_{v,n-1}$  are the corresponding vertical stresses.

194 In addition, based on the time-deformation curve under each vertical stress in oedometer  
195 test, the consolidation coefficient  $c_v$  can also be determined by Eq. (4) (ASTM-D2435, 2020).  
196 In this study, Eq. (4) is obtained with the Log of Time Method.

$$197 \quad c_v = \frac{T_{50}H_{D50}^2}{t_{50}} \quad (4)$$

198 where  $T_{50} = 0.197$ ,  $t_{50}$  is the time corresponding to 50 % of the primary consolidation,  $H_{D50}$   
199 is the length of the drainage path at 50 % of primary consolidation. Thus, the global vertical  
200 hydraulic conductivity ( $k$ ) can be calculated by combining Eqs. (2) and (4), as shown in Eq.  
201 (5).

$$202 \quad k = \frac{T_{50}H_{D50}^2}{t_{50}} \times \frac{\gamma_w a_v}{1+e} \quad (5)$$

203 Moreover, Considering the gradual yielding of COx claystone with stress, the step  
204 compression index  $C_c^*$  is determined to study the variation of compressibility with stress, as  
205 recommended by Deng et al. (2012) and Wang et al. (2021). Based on the time-void ratio  
206 curve, the secondary consolidation coefficient  $C_\alpha$  is determined to analyze the creep behavior  
207 (ASTM-D2435, 2020).

## 208 **RESULTS AND DISCUSSIONS**

### 209 **Swelling behaviour**

210 Upon hydration with synthetic water injection under the initial stress, the samples swelled in  
211 the two cases (with and without filter paper). Fig. 4 shows the evolution of vertical swelling  
212 strains with time. Three stages can be identified: initial swell, primary swell and secondary  
213 swell, as recommended by Rao et al. (2006) and ASTM-D4546 (2021). The vertical swelling  
214 strain increased slowly with time at the beginning, then increased quickly, finally increased  
215 progressively. At the end of the swelling process, test TH-1 exhibited a higher axial strain than  
216 test TV-1 (3.49 % against 3.06 %) in case 1, while the vertical strains of tests with fractures

217 (TH-2: 3.19 % and TV-2: 3.38 %) are closer in case 2. The vertical strains in both cases are  
218 smaller than that of test TI (3.54 %).

219 Fig. 5 shows the evolution of vertical swelling strain rate with time, which is defined as the  
220 difference of swelling strain at time interval in log scale. It is found that the vertical swelling  
221 strain rates of all tests increased with time at the beginning, then reached the maximum,  
222 finally decreased steadily. As presented in Fig. 5a, the vertical swelling strain rates of test TH-  
223 1 in the initial swell and secondary swell stages were slightly lower than that of test TV-1,  
224 while much larger in the primary swell stage. However, in the case without filter paper (case 2,  
225 tests TH-2, TV-2 and TI), a similar vertical swelling strain rate was observed in the primary  
226 swell stage (Fig. 5b). In the initial swell stage, TV-2 has a larger swelling rate than TH-2 and  
227 TI. Nevertheless, test TI has a larger swelling rate than tests TH-2 and TV-2 in the secondary  
228 swell stage.

229 Fig. 6 can be used to explain the observed swelling phenomena. As the injection direction  
230 was vertical synthetic water went into the vertical fracture more easily even in the case with  
231 filter paper. Thus, the samples with vertical fracture swelled more quickly in the initial swell  
232 stage, as shown in Fig. 5. In case 1 with filter paper, after water entered the horizontal fracture  
233 via the filter paper, the hydration rate of test TH-1 speeded up because of the shorter  
234 infiltration path compared to test TV-1, resulting in a higher vertical swelling strain rate in the  
235 primary swell stage (Fig. 5a). In addition, at the end of the tests, the higher final swelling  
236 strain and lower strain rate of test TH-1 lead to a swelling strain closer to that of test TV-1.  
237 This can be explained by their similar global initial void ratios or dry densities. By contrast, in  
238 case 2 without filter paper, as tests TH-2 and TI have the same infiltration path, similar  
239 vertical swelling strains (Fig. 4b) and strain rates (Fig. 5b) were observed in the initial and  
240 primary swelling stages. It can thus be inferred that the swelling of fractured claystone  
241 depends on the infiltration path and the direction of the initial fracture.

242 Due to the effect of swelling, the fractures can be closed. This corresponds to the self-  
243 sealing property as reported by Zhang (2011, 2013). The self-sealing in COx claystone is  
244 mainly induced by the swollen clay minerals, as demonstrated by Giot et al. (2019) and Di  
245 Donna et al. (2019) through 3D tomography observations. Due to self-sealing, the hydraulic  
246 conductivity decreases gradually, as observed by Giot et al. (2019). From a hydro-mechanical  
247 point of view, it appears that the self-sealing process can be divided into three stages (van  
248 Geet et al., 2008; Zhang, 2011; de la Vaissière et al., 2015): (i) fracture closure - the swelling  
249 of claystone near the fracture surface induces fracture closure with the expansion of clay  
250 minerals; (ii) fracture clogging - the claystone grains disaggregate and clog the fracture zone;  
251 (iii) homogenization - the macro-pores between the disaggregated claystone grains collapse  
252 by the further swelling of claystone farther from the fracture zone.

### 253 **Compression, hydraulic conductivity and creep**

254 All compression curves are reported in Fig. 7 and Fig. 8a for case 1 and case 2, respectively,  
255 in terms of global void ratio (including the filled fracture). Fig. 7 shows that with increasing  
256 vertical stress, the void ratios of test TH-1 become smaller than that of test TV-1, indicating  
257 that the compressibility of the sample with a horizontal fracture is higher than that with  
258 vertical fracture. This confirms the dependency of the compression behaviour on the fracture  
259 orientation. A similar phenomenon is observed in Fig. 8a. The yield stress (0.45 MPa) of test  
260 TH-1 is smaller than that of test TV-1 (0.65 MPa). The similar phenomenon is observed while  
261 comparing TH-2 and TV-2: the yield stress of test TH-2 (0.48 MPa) is smaller than that of  
262 TV-2 (0.71 MPa). By contrast, test TI exhibits a significantly higher yield stress (1.08 MPa).  
263 Besides, the curve of test TI becomes closer to that of test TH-2 in the high stress range, as  
264 shown in Fig. 8a. It appears from these results that: (i) the filled fracture zone due to swelling  
265 is a weak zone, resulting in a higher compressibility of the fractured sample; (ii) the increase  
266 of stress can induce the collapse of the macro-pores in the filled fracture zone, enabling the

267 compression curve to gradually approach the intact one. Note that this macro-pore collapse  
268 effect was also reported by Zhang (2011, 2013). In addition, an increase of the slopes of  
269 compression curves is observed after 16 MPa (Fig. 7 and Fig. 8a), indicating an increase in  
270 compressibility. Interestingly, the oedometer tests conducted by Mohajerani, et al. (2011) and  
271 Menaceur (2014) on intact COx claystone also showed a similar compression phenomenon -  
272 with the increase of vertical stress, the slope of the compression curve increases continuously  
273 even under higher stress, up to 100 MPa. This is different from the observations on common  
274 clays - the slope first increases, then decreases (Mesri and Godlewski, 1977). Wang et al.  
275 (2021) reported that this increase in compressibility is due to the breakage of calcite and  
276 quartz in claystone. As mentioned before, calcite and quartz grains account for around 50% of  
277 the mineral composition of COx claystone. Wang (2012) observed that the calcite and quartz  
278 grains in COx claystone can be crushed under uniaxial compression.

279 The measured vertical hydraulic conductivity ( $k$ ) is shown in Fig. 8b. By referring to the  
280 compression curves shown in Fig. 8a, it is found that the  $k$  of test TV-2 slightly decreases with  
281 loading before the yield stress, then decreases significantly. This is closely related to the  
282 volume change of the sample. A similar phenomenon was observed by Zhang (2011, 2013).  
283 Blackwell et al. (1990) highlighted that the hydraulic conductivity of clayey soils is  
284 significantly related to the macro-porosity. In this sense, it can be inferred that the measured  $k$   
285 of test TV-2 is controlled by the large pores in the filled fracture zone. For test TH-2, the  
286 measured  $k$  is governed by the small pores in the intact part, which can be deduced from the  
287 comparison between tests TH-2 and TI in Fig. 8b. This is correlated to the direction of the  
288 measured  $k$  (vertical) with respect to the direction of fracture (horizontal). Note that intact part  
289 means the zone without fracture inside the sample before the test. The stress 0.25 MPa (Fig.  
290 8b) can be regarded as the yield point of intact part in test TV-2. Interestingly, this stress  
291 corresponds to the yield stress identified in Fig. 8a. After around 16 MPa, the  $k$  of TV-2

292 decreases steadily and is comparable with that of test TI, indicating that the hydraulic  
293 conductivity of the fractured sample is “recovered” to the intact one (Fig. 8b). By contrast,  
294 due to the steady decrease of the porosity of the intact part, test TH-2 displays a gradual  
295 decrease of  $k$ , as test TI.

296 To further estimate the hydraulic conductivity of COx claystone, the hydraulic conductivity  
297 was also determined by back-analyzing the oedometer test results based on the consolidation  
298 theory (ASTM-D2435, 2020). All values obtained ( $k$ -calculation) are summarized and  
299 presented against vertical effective stress and void ratio in Fig. 9. With the increase of vertical  
300 effective stress, all hydraulic conductivities exhibit a similar decreasing tendency (Fig. 9a).  
301 Fig. 9b shows that small changes of void ratio can lead to a significant reduction of hydraulic  
302 conductivity, indicating the strong dependencies on volume change. For test TI, the measured  
303  $k$  is similar to the calculated one at a low vertical stress or a large void ratio, while  
304 significantly larger than the latter at a high vertical stress or a small void ratio. This is  
305 attributed to the effect of physico-chemical interaction between bound water and clay particle  
306 in the low-compressibility zone of soils, as reported by Mesri et al. (1994a) and Su et al.  
307 (2020). The similar phenomenon is observed on test TH-2. However, the measured  $k$  in test  
308 TV-2 is obviously larger than the calculated one at a low vertical stress or a large void ratio,  
309 showing the effect of infiltration path (infiltration direction parallel to the fracture), as shown  
310 in Fig. 6. Besides, at a same vertical stress or void ratio, the measured and calculated  $k$  in test  
311 TV-2 both are larger than those of the other two tests even after the closure of fracture under  
312 high stress, which indicates that the large pores in the filled fracture zone indeed intensify the  
313 hydraulic conductivity. Favero et al. (2016) and Crisci et al. (2019) made the similar  
314 observations on Opalinus clay shale, pointing out that the hydraulic conductivity is  
315 significantly affected by the larger pores and can be enhanced by the presence of fractures.

316 Fig. 10 depicts the evolutions of compression coefficient  $a_v$  and consolidation coefficient  
317  $c_v$ , which are determined by Eqs. (3) and (4), respectively.  $a_v$  and  $c_v$  both decrease rapidly in  
318 low stress range with the increase of vertical stress for tests TH-2, TV-2 and TI. Beyond  
319 16 MPa, the compression coefficients  $a_v$  of three tests change little and exhibit the same  
320 decreasing tendency (Fig. 10a). This further confirms that the fracture effect on  
321 compressibility is negligible. Besides, the values of consolidation coefficient  $c_v$  also tend to  
322 stabilize (Fig. 10b). Because the void ratios change little ( $\Delta e$  less than 0.1) in Fig. 8a, while  
323 the hydraulic conductivities change by several orders of magnitude in Fig. 9b, it can be  
324 inferred that  $c_v$  is rather governed by the variation of hydraulic conductivity. Thus, the higher  
325  $c_v$  of test TV-2 as compared to those of tests TH-2 and TI (Fig. 10b) also verifies the  
326 observations from Fig. 9. Compared to test TI, test TV-2 has a hydraulic conductivity indeed  
327 intensified by the macro-pores in the filled fracture zone, while TH-2 shows the negligible  
328 effect of the filled fracture zone. This confirms the dependency of hydraulic conductivity on  
329 the orientation of fractures.

330 To further analyse the effect of fracture on compression and creep, two parameters  $C_c^*$  and  
331  $C_\alpha$  are calculated. The calculation method is shown in Fig. 11. Fig. 12 shows that with the  
332 increase of stress in case 1, both  $C_c^*$  and  $C_\alpha$  increase first, then change little, finally increase  
333 significantly. The  $C_\alpha$  and  $C_c^*$  of test TH-1 are slightly higher than those of test TV-1, showing  
334 the effect of fracture orientation. This also suggests that although the fracture was healed up  
335 by swelling, the filled fracture zone is mechanically still a weak zone, characterised by higher  
336 compressibility and a larger creep. The  $C_c^*$  and  $C_\alpha$  in Fig. 12 are replotted with respect to the  
337 fracture orientation in Fig. 13. It is observed that both  $C_\alpha$  and  $C_c^*$  show a three-stage  
338 relationship.  $C_\alpha$  and  $C_c^*$  almost increase linearly with stress in the lower (zone I) and higher  
339 stress (zone III) ranges, but change little in the mid-range (zone II). The stress (1 MPa) for  
340 TH-1 corresponding to the dividing point between zone I and zone II is lower than that (4

341 MPa) for TV-1. The stresses (around 16 MPa) corresponding to the dividing point between  
342 zone II and zone III are almost the same, which is consistent with the observations made on  
343 the compression curves in Fig. 7 and Fig. 8a.

344 Fig. 14 depicts the evolutions of  $C_c^*$  and  $C_\alpha$  of tests TH-2 and TV-2 in case 2, together with  
345 that of TI. A negligible effect of infiltration paths is observed – the evolutions are similar for  
346 tests TH-2 and TV-2. It is worth noting that before 16 MPa, the  $C_\alpha$  and  $C_c^*$  of tests TH-2 and  
347 TV-2 are significantly higher than those of test TI, showing a higher compressibility and a  
348 higher creep. This is consistent with the compression curves shown in Fig. 8a. Besides, for  
349 test TI,  $C_c^*$  and  $C_\alpha$  exhibit a continuously increasing tendency, suggesting that the  
350 compressibility and creep of COx claystone are stress-dependent. This phenomenon is quite  
351 uncommon because  $C_c^*$  and  $C_\alpha$  increase generally with the increase of stress in the low stress  
352 range, while keeping almost constant in the high stress range (Mesri and Godlewski, 1977;  
353 Lambe and Whitman, 1979; Favero et al., 2016). This is to be attributed to the breakage of  
354 calcite and quartz grains, as mentioned previously (Wang et al., 2021).

355 A conceptual model can be proposed to describe the evolutions of  $C_c^*$  and  $C_\alpha$  with stress  
356 (Fig. 15). Two key points, transitional and threshold points, are defined. There are significant  
357 differences ( $\Delta C_c^*$  and  $\Delta C_\alpha$ ) between the fractured sample and the intact sample before the  
358 threshold point. Before the transitional point,  $\Delta C_c^*$  and  $\Delta C_\alpha$  increase with increasing stress,  
359 then reach the maximum values at the transitional stress, suggesting that the effect of weak  
360 fracture zone to the compressibility and creep reach the maximum. The corresponding  
361 transitional stress depends on the fracture orientation, as observed in Fig. 13. After the  
362 transitional point,  $\Delta C_c^*$  and  $\Delta C_\alpha$  decrease with increasing stress. At the threshold point  
363 (around 16 MPa),  $\Delta C_c^*$  and  $\Delta C_\alpha$  are close to zero, suggesting that the influence of fracture  
364 becomes negligible. After that, the fractured and intact samples exhibit similar  $C_c^*$  and  $C_\alpha$ ,  
365 suggesting that the compression and creep properties of fractured claystone are almost



366 recovered. Note that the threshold stress 16 MPa is close to the in situ stresses (12 - 16 MPa)  
367 (Wileveau et al., 2007). Beyond this stress, the stable structure formed by the grain inclusions  
368 (quartz and calcite, etc.) under the in situ stress state was significantly disturbed, giving rise to  
369 a drastic change of compressibility. This indicates the effect of stress history on the  
370 compression behaviour of COx claystone.

371 Fig. 16 shows the relationship between  $C_\alpha$  and  $C_c^*$  for all the tests. It is almost linear for the  
372 intact claystone with a slope of 0.0358. This is consistent with the observations ( $C_\alpha / C_c^* =$   
373  $0.03 \pm 0.01$ ) on shale and mudstone (Mitchell and Soga, 2005; Deng et al., 2012).  
374 Interestingly, for the fractured claystone,  $C_\alpha$  is significantly larger than that predicted by a  
375 linear relationship before  $C_c^* = 0.045$  which corresponds to 16 MPa of stress (i.e. threshold  
376 point) in Fig. 15. After that, the fractured and intact samples show similar  $C_\alpha / C_c^*$  values,  
377 indicating a negligible effect of fracture in the high stress range. Mesri et al. (1994b) reported  
378 that softer soils have a larger  $C_\alpha / C_c^*$  value. It can be thus inferred that the larger  $C_\alpha$  results  
379 from the weaker mechanical property of the filled fracture zone.

## 380 CONCLUSIONS

381 In this study, oedometer tests were conducted on fractured and intact COx claystone samples,  
382 aiming at investigating the effects of fracture on its hydro-mechanical behaviour in terms of  
383 swelling, compression, creep and hydraulic conductivity. The obtained results allow the  
384 following conclusions to be drawn:

385 The presence of fracture decreases the swelling strain of the claystone sample and this  
386 phenomenon depends on the infiltration path and the orientation of fracture. In particular, the  
387 infiltration path affects the global swelling rate of fractured claystone. The self-sealing of  
388 fracture is mainly attributed to the swelling and clogging of COx claystone grains in the  
389 fracture zone.

390 Due to the weaker mechanical properties of the filled fracture zone, lower compression  
391 coefficient  $a_v$ , higher compression index  $C_c^*$  and higher secondary consolidation coefficient  
392  $C_\alpha$  are observed for the fractured claystone, defining higher compressibility and more  
393 significant creep than the intact one. Besides, comparing the results of tests on fractured  
394 samples with different fracture directions, it is found that the test on vertically fractured  
395 sample presents a larger yield stress and consolidation coefficient, as well as a smaller  
396 compression index and secondary consolidation coefficient. This indicates the compression  
397 and creep behaviours depend on the orientation of fracture and the stress level. Comparison of  
398 hydraulic conductivities between the fractured and intact claystone samples indicates that the  
399 hydraulic conductivity can be partially recovered due to the collapse of macro-pores in the  
400 filled fracture zone. This is also confirmed by analysing the evolution of consolidation  
401 coefficients  $c_v$  with stress.

402 These findings clearly show the effect of fracture on the swelling, compression, creep and  
403 hydraulic conductivity of COx claystone. An interesting behaviour has been highlighted  
404 concerning the stress level. Beyond 16 MPa, the fracture effect can be neglected, but the  
405 compressibility increases further due to grain breakage. Fracture accelerate the creep strain,  
406 confirming the field measurement in the MHM URL. This fracture-dependent creep  
407 behaviour is a key issue in the design of the gallery concrete liner to ensure its stability during  
408 the operational phase of the geological disposal.

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411 National Radioactive Waste Management Agency (Andra) are gratefully acknowledged.

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542 stress.

543 Fig. 16.  $C_c^*$  versus  $C_\alpha$ .



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Table 1. Initial characteristics of COx claystone core

Core ID	Density (Mg/m <sup>3</sup> )	Dry density (Mg/m <sup>3</sup> )	Porosity (%)	Water content (%)	Initial suction (MPa)	Degree of saturation (%)
EST57180	2.4	2.2	17.8	7.8	20.0	97.7

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Table 2. Chemical composition of the synthetic water

Components	NaCl	NaHCO <sub>3</sub>	KCl	CaSO <sub>4</sub> ·2H <sub>2</sub> O	MgSO <sub>4</sub> ·7H <sub>2</sub> O	CaCl <sub>2</sub> ·2H <sub>2</sub> O	Na <sub>2</sub> SO <sub>4</sub>
Mass (g/L)	0.130	2.216	1.950	0.035	1.082	1.356	0.053

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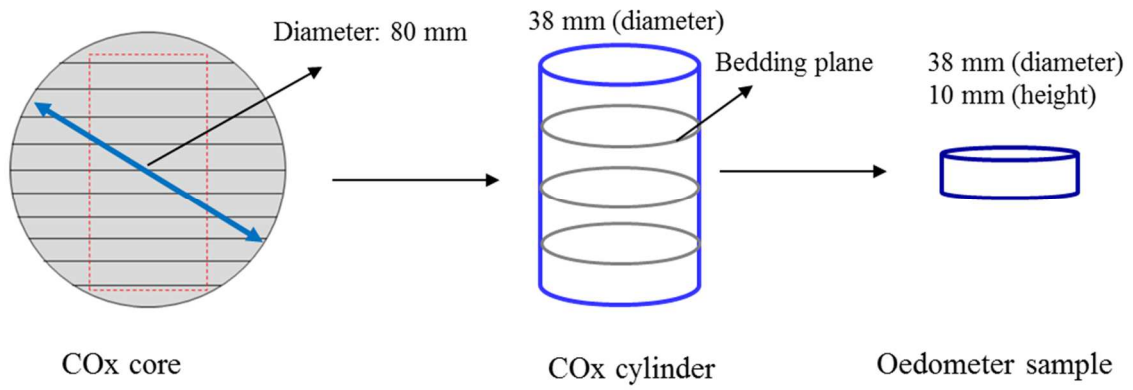
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Table 3. Test programme

Test No.	Initial suction (MPa)	Direction of fracture	Thickness of fracture	Core ID	Filter paper	Hydraulic conductivity
TH-1	22.2	Horizontal	0.1 mm	EST57180	yes	no
TV-1	22.6	Vertical	0.3 mm	EST57180	yes	no
TH-2	23.7	Horizontal	0.1 mm	EST57180	no	yes
TV-2	23.3	Vertical	0.3 mm	EST57180	no	yes
TI	22.9	/	/	EST57180	no	yes

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Fig. 1. Schematic representation of the preparation of intact oedometer samples.

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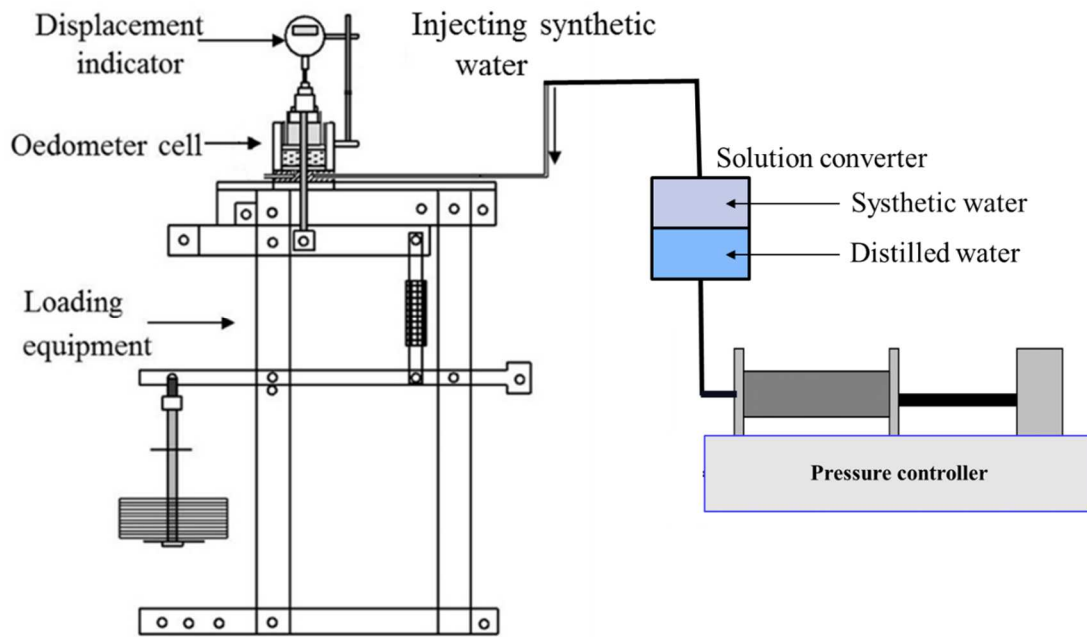
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559 fractured directions and intact sample (TI) (dotted line: fracture).

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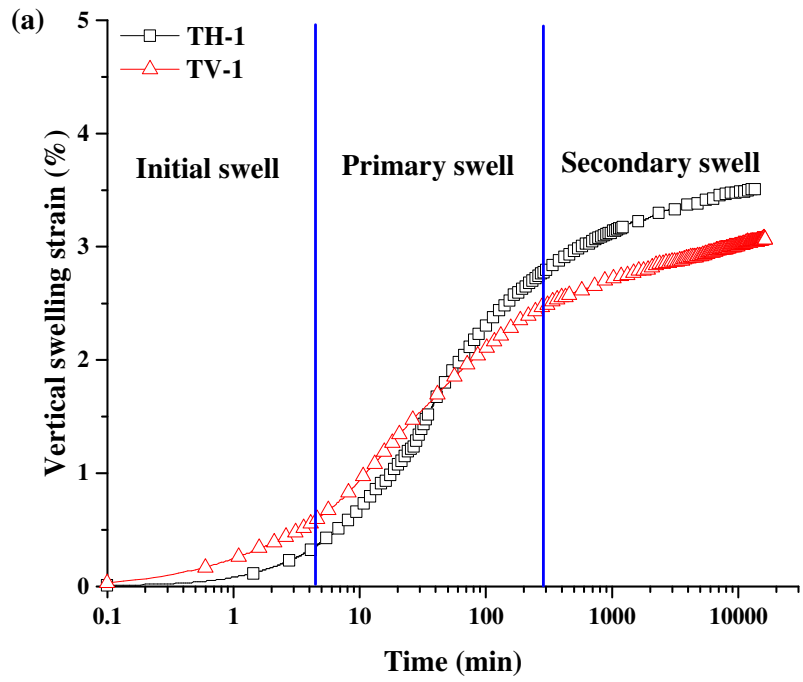
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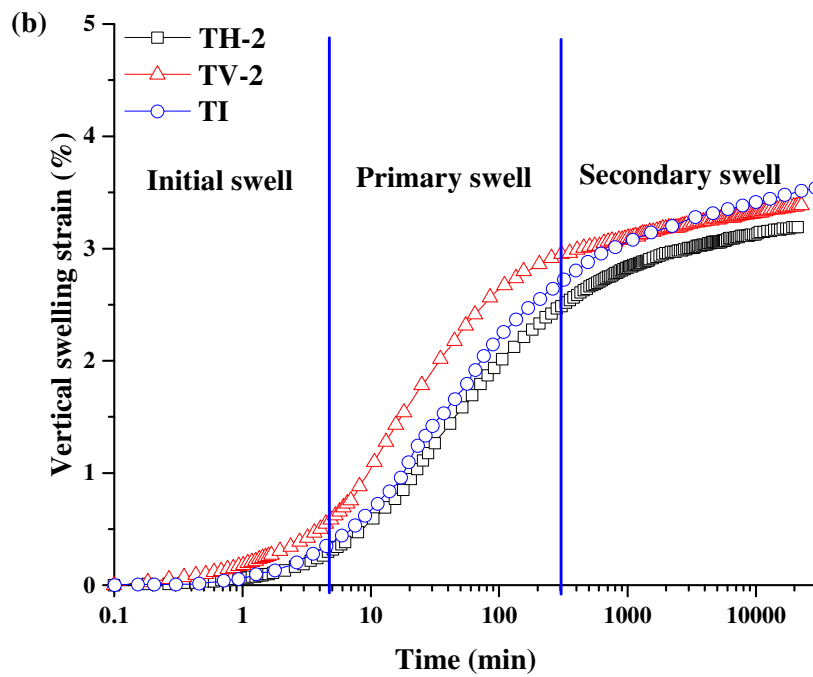
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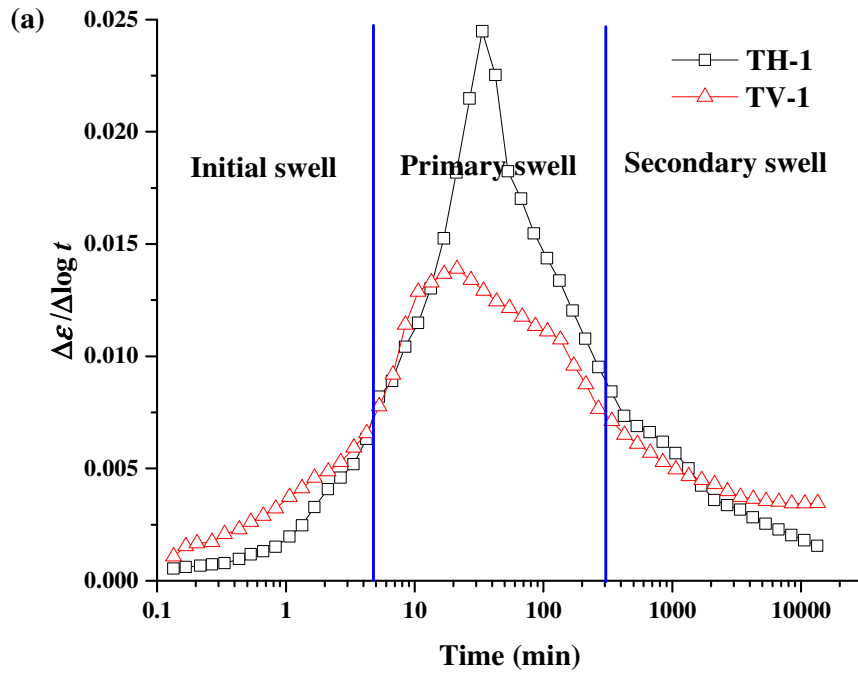
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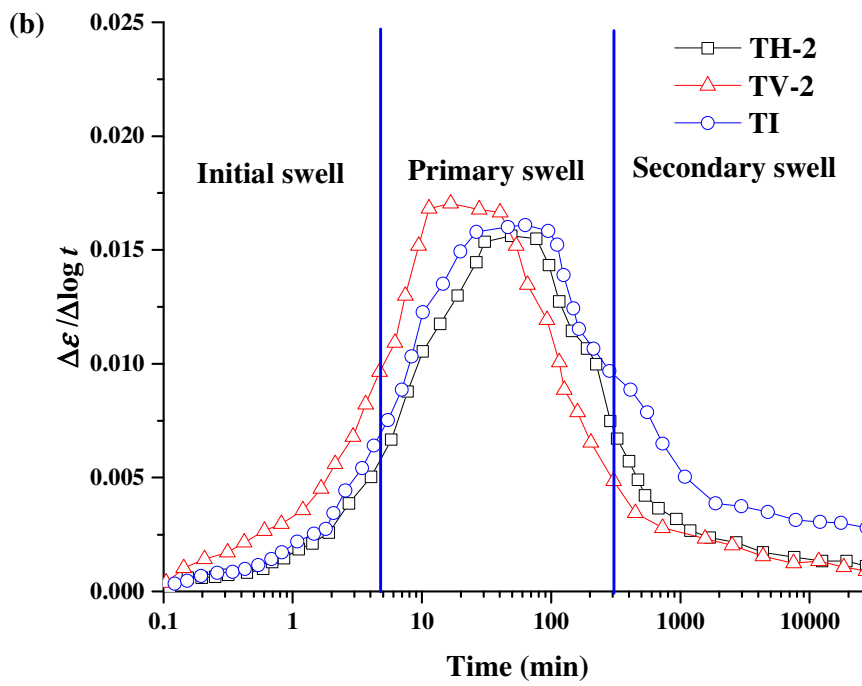
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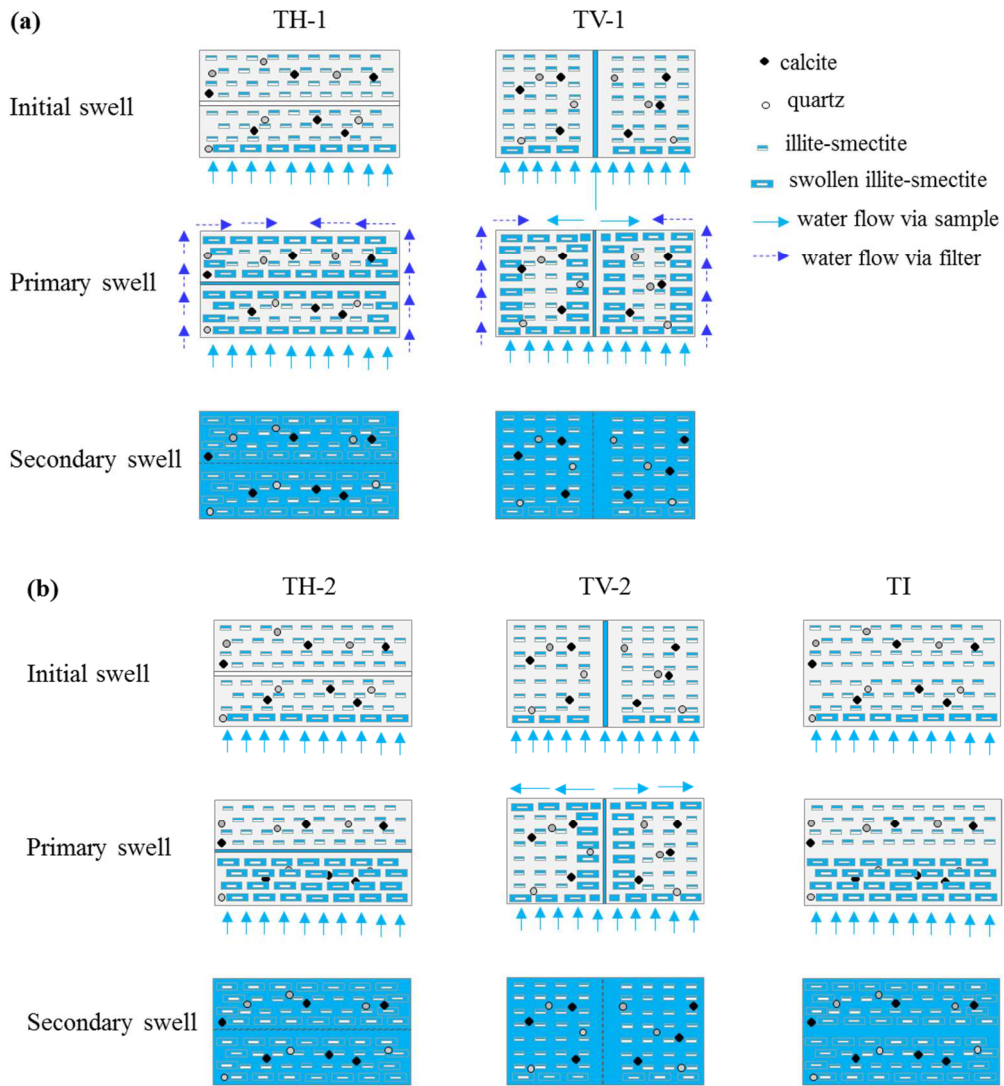
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573 Fig. 5. Vertical swelling strain rate ( $\Delta\varepsilon/\Delta\log t$ ) versus time: (a) case 1; (b) case 2 and test TI.

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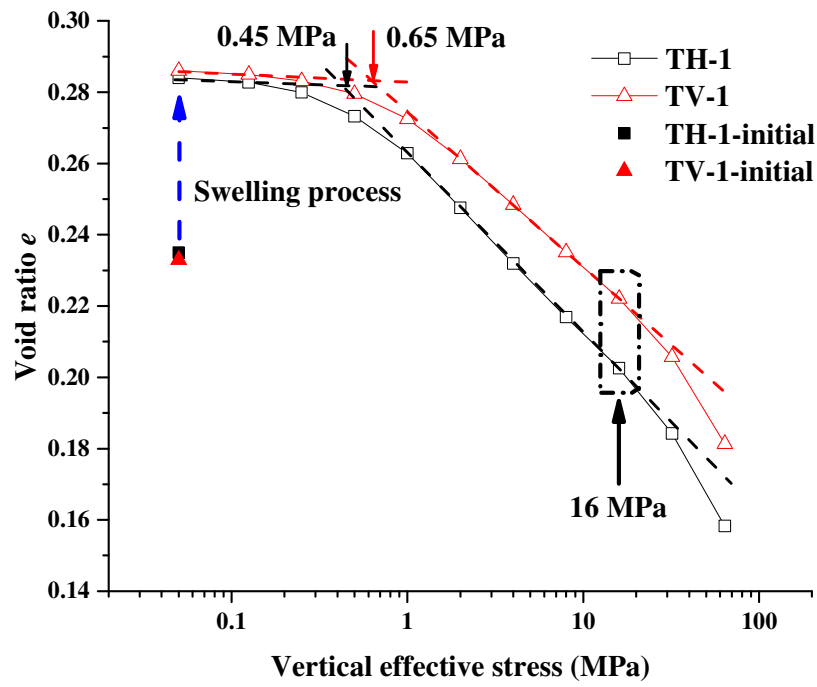
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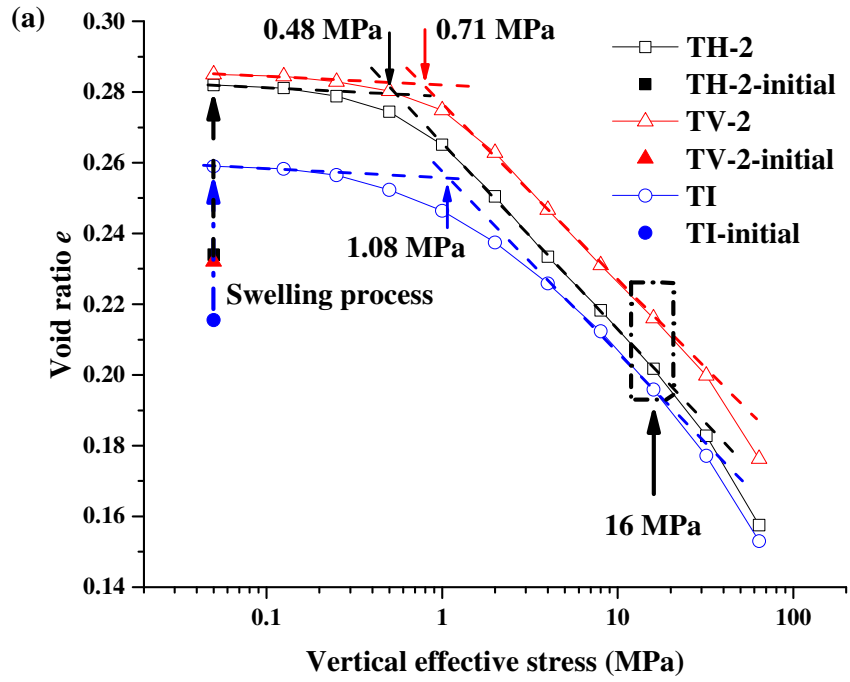
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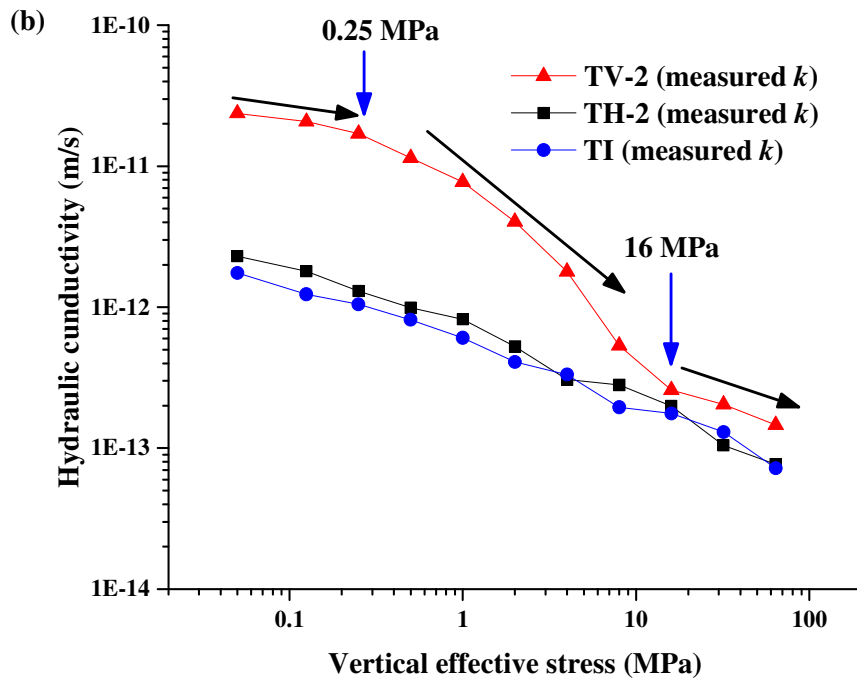
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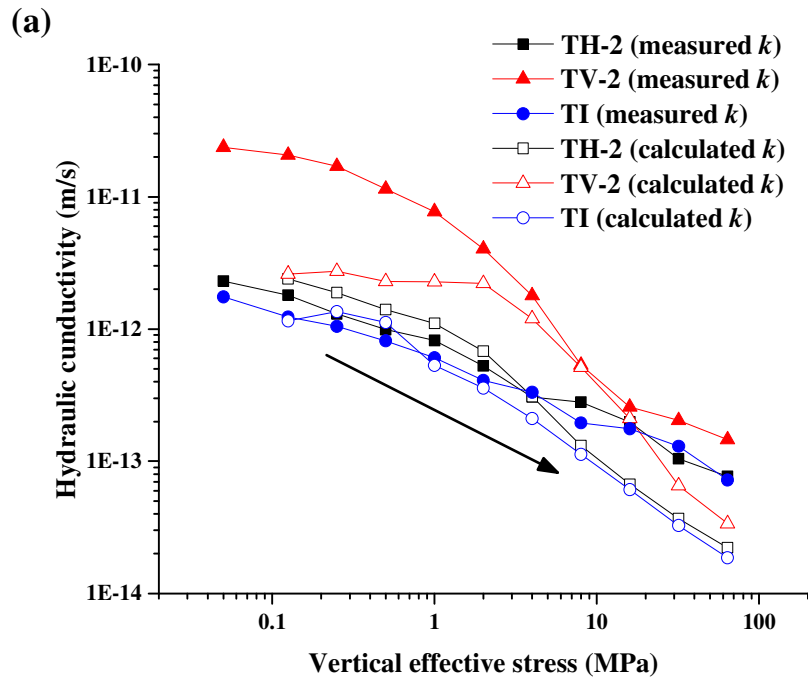


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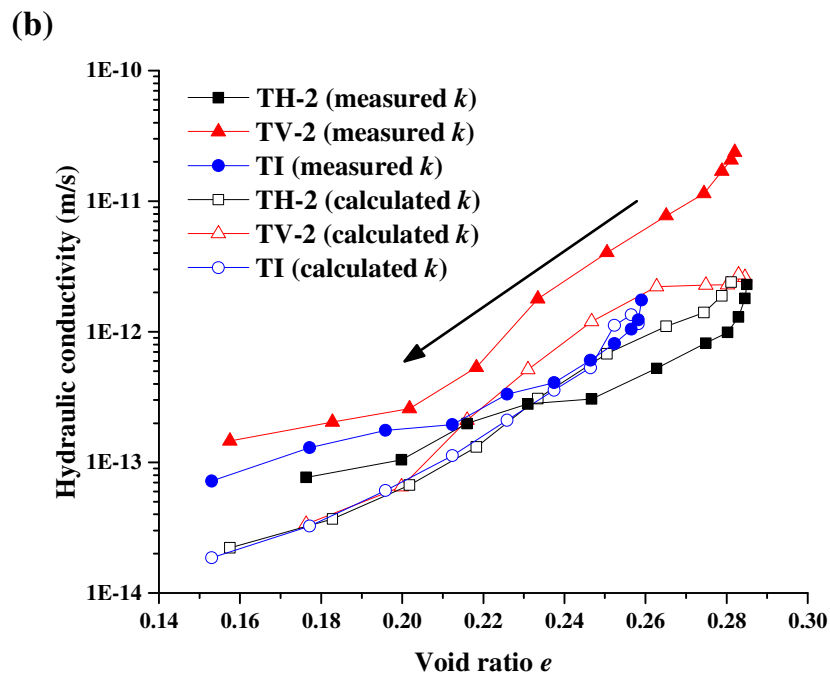
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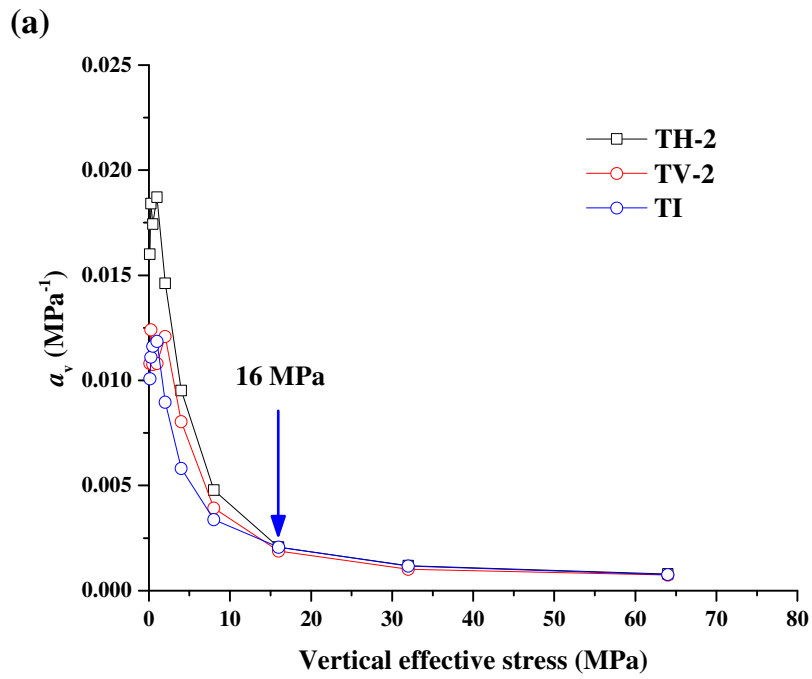
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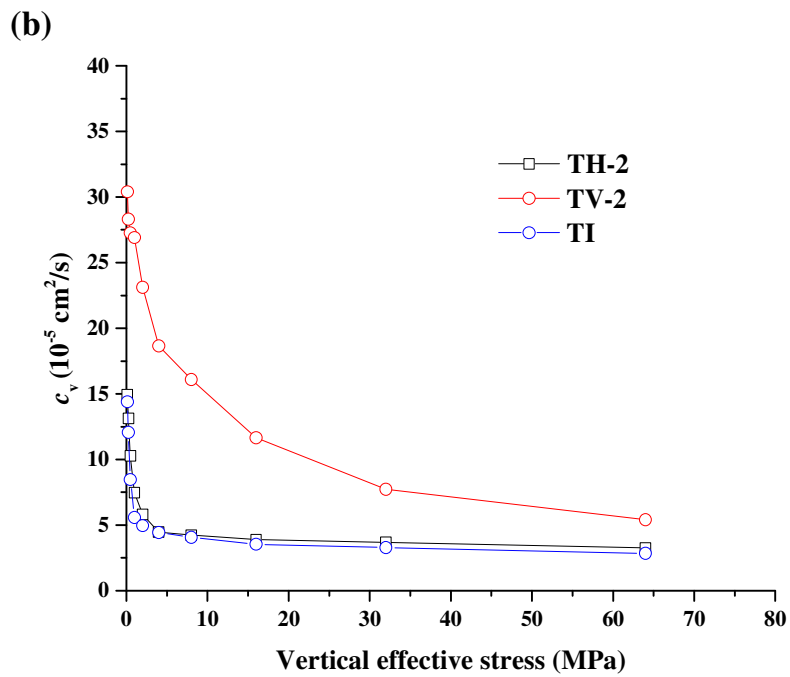
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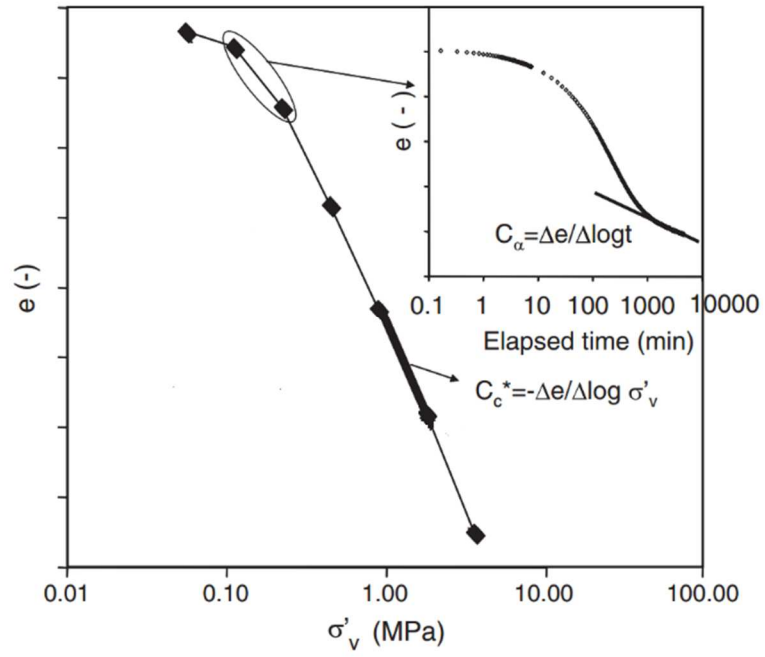
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601 (b) consolidation coefficient versus vertical effective stress.

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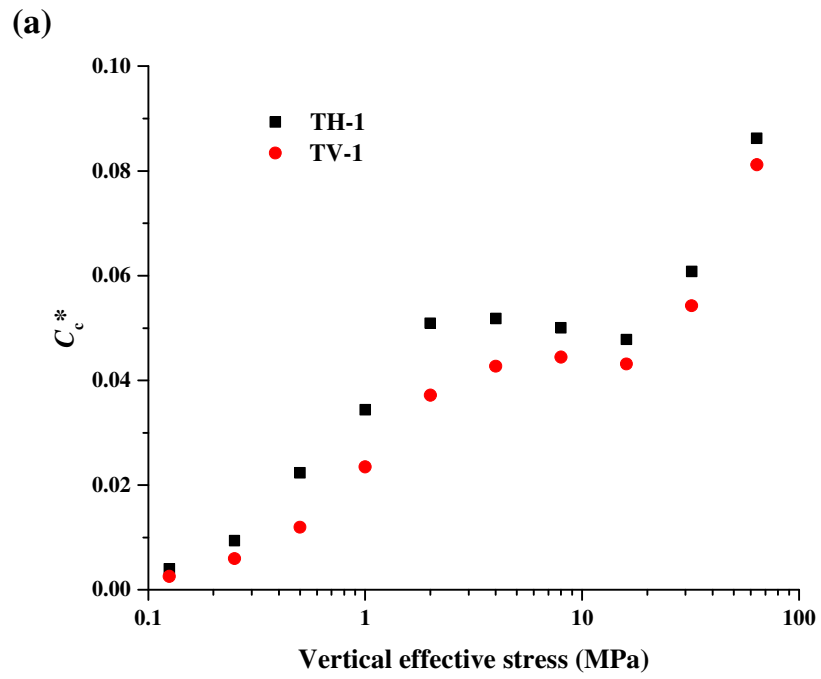
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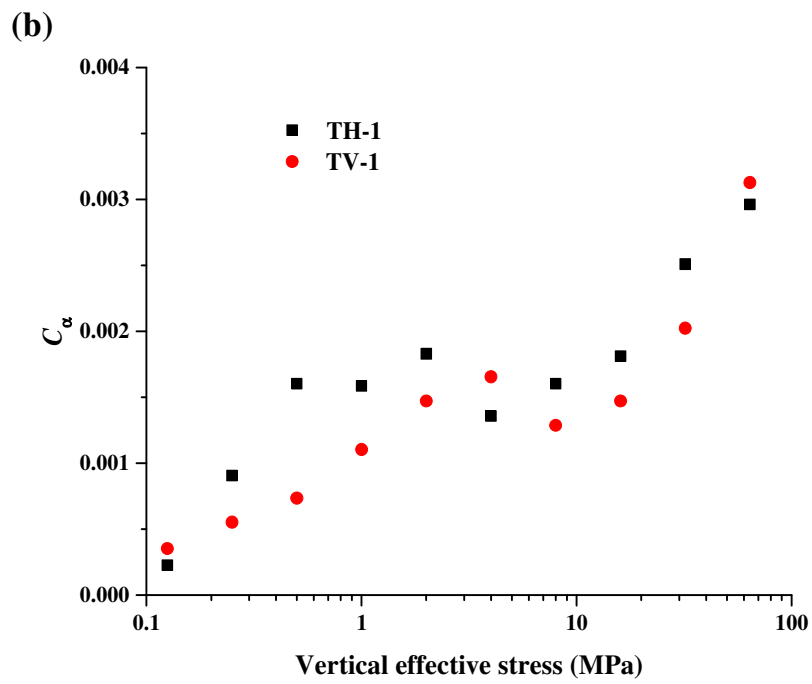
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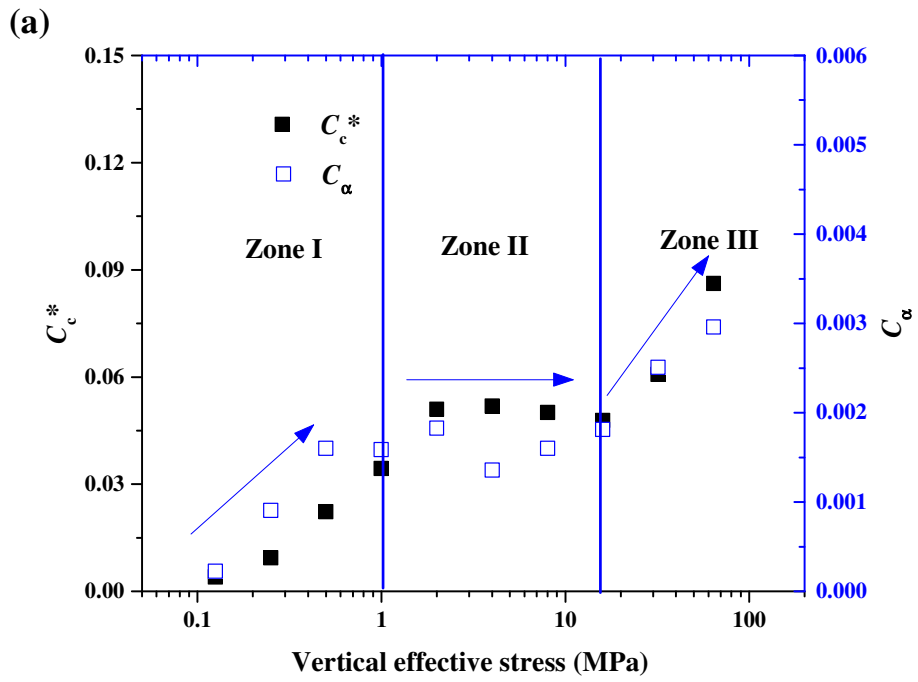


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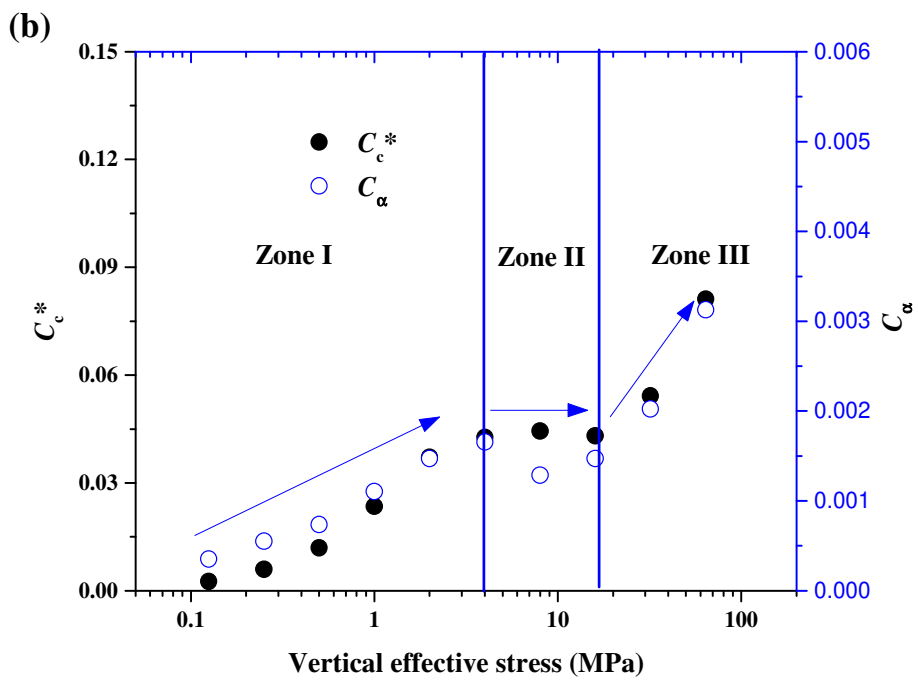
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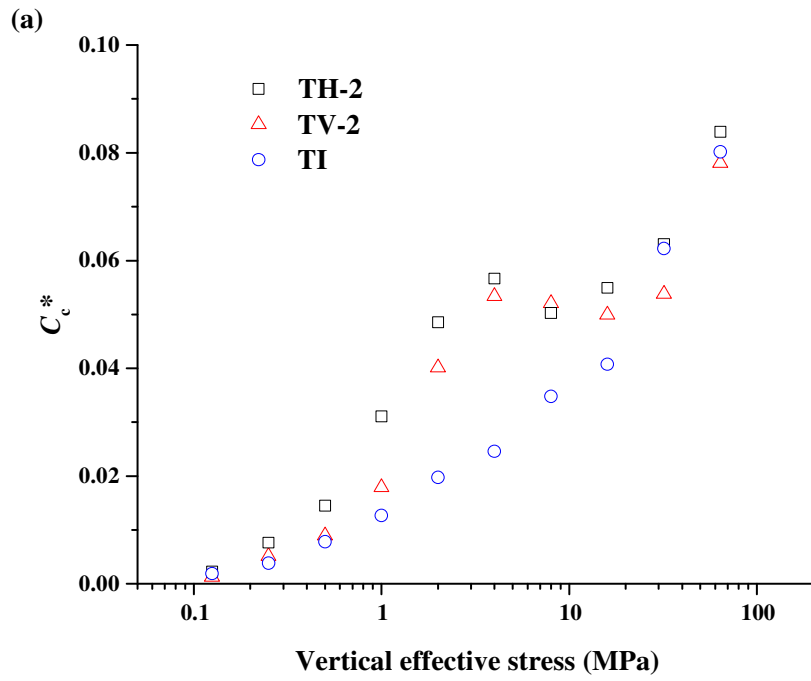
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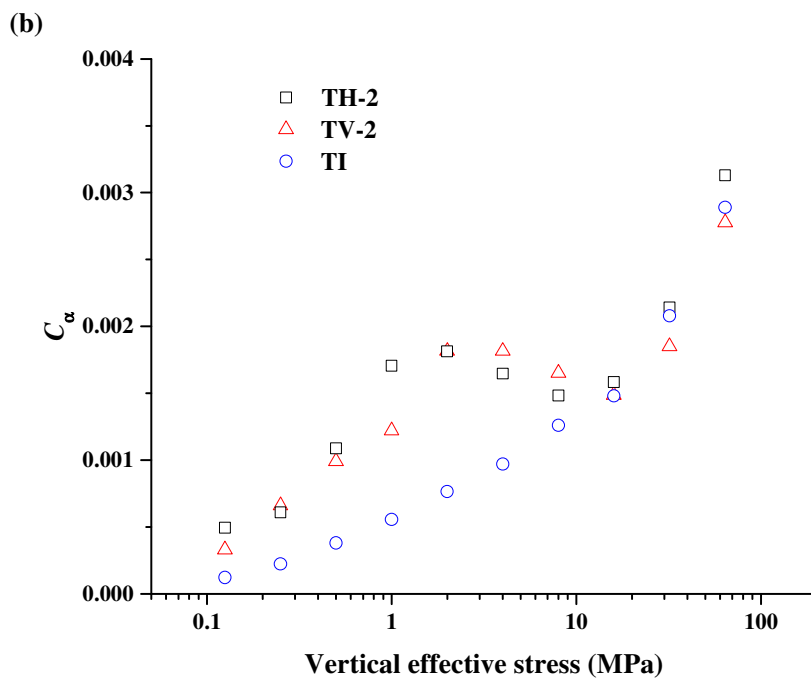
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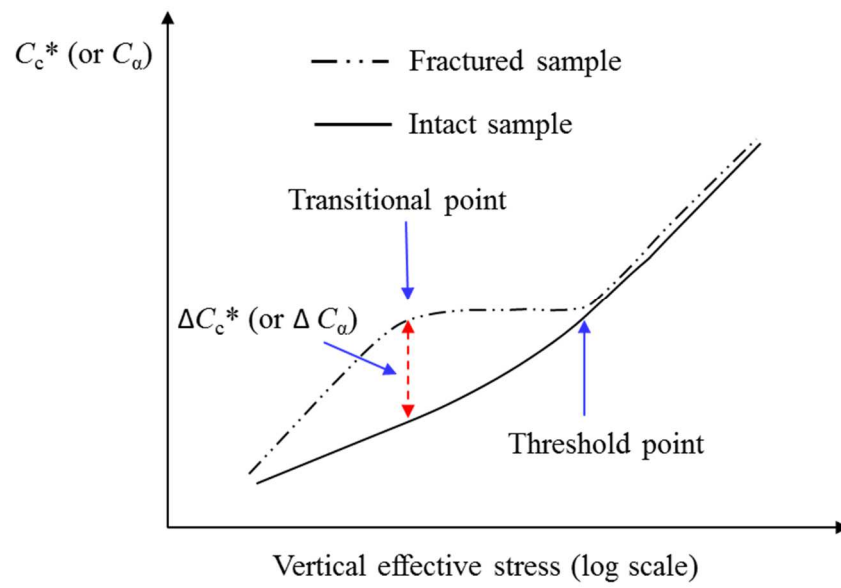
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vertical effective stress.

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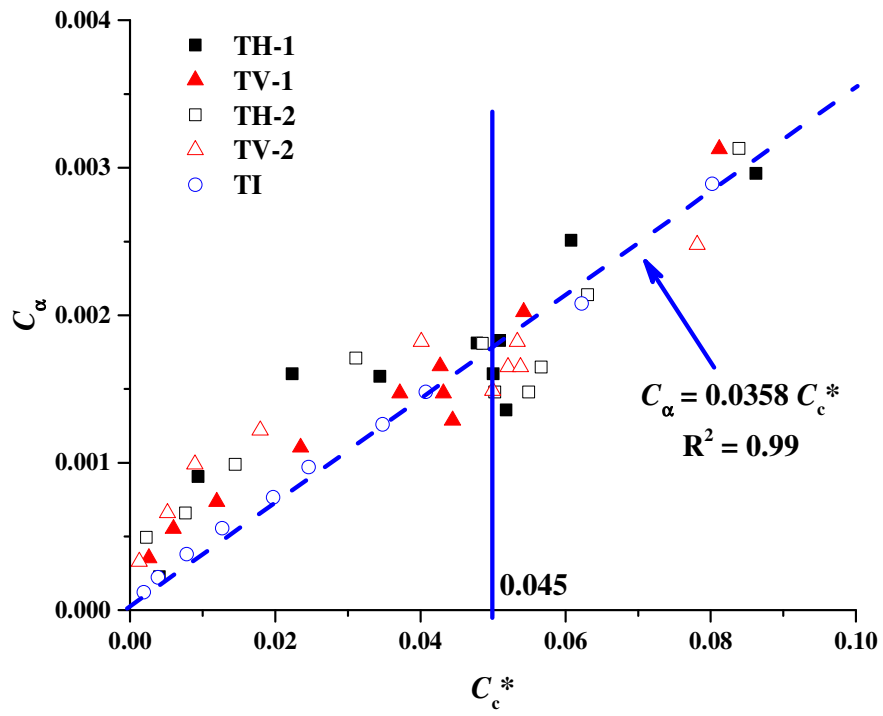
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Fig. 16.  $C_c^*$  versus  $C_\alpha$ .

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