

1 **Desiccation Crack Formation Beneath the Surface**

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4

5 **Abstract.** Desiccation cracks affect all mechanical and conduction properties. Previous studies  
6 have investigated the formation of surface desiccation cracks in fine-grained sediments in relation  
7 to their compressibility and suction potential. This study explores the formation of internal  
8 desiccation cracks in saturated kaolinite specimens consolidated inside self-reactive oedometer  
9 cells to reproduce the initial effective stress in buried sediments. We use X-ray tomography to  
10 monitor internal processes during consolidation and drying. Images capture the evolution of a  
11 perimetric fracture, transverse contraction, volumetric changes in entrained gas bubbles, and the  
12 development of internal desiccation cracks. Entrained gas bubbles act as nucleation sites. They  
13 shrink during loading and early stages of desiccation. Eventually, the gas-water interface  
14 penetrates the soil at the bubble surface, pushes particles away, enlarges local pores and facilitates  
15 further growth of the internal desiccation crack. While air entry is grain-displacive in soft fine-  
16 grained sediments, it becomes pore-invasive in stiff coarse-grained sediments and internal  
17 desiccation cracks are not expected in silts or sands.

18

19 **Keywords:** Clays, Compaction, Laboratory tests, Partial saturation, Suction

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## 22 1. Introduction

23 Fine-grained sediments are susceptible to desiccation crack formation because of their high  
24 compressibility and suction potential. Desiccation cracks nucleate at large surface pores where air  
25 invades the water-saturated sediment (Scherer, 1990; Shin & Santamarina, 2011a; Cordero et al.,  
26 2017). Restrained lateral shrinkage hinders horizontal contraction, facilitates air invasion and leads  
27 to the extensive fracture patterns observed in drying thin mud layers.

28 Can desiccation cracks nucleate and grow within the sediment, beneath the surface?  
29 Subsurface syneresis cracks can develop due to changes in pore fluid salinity (Plummer & Gostin,  
30 1981) or earthquake-induced dewatering (Pratt, 1998). Internal cracks have been reported in  
31 laboratory desiccation tests where cracks nucleated at the centre or at the bottom boundary of  
32 specimens (Corte & Higashi, 1960; Lakshmikantha et al., 2018). Internal fracture formation would  
33 be relevant to many engineering applications, such as nuclear buffers, compacted liners (Yesiller  
34 et al., 2000), embankment dams (Sherard, 1986; Dyer et al., 2009), seal layers for CO<sub>2</sub> storage  
35 (Espinoza & Santamarina, 2012), and giant desiccation cracks (Harris, 2004). This study focuses  
36 on desiccation cracks that nucleate around internal gas bubbles. Possible formation mechanisms  
37 for gas bubbles include entrapment during sedimentation, bioactivity, anaerobic oxidation, and gas  
38 exsolution during suction-driven depressurization.

39 There are no published studies on the evolution of internal gas bubbles during desiccation  
40 and their role in internal crack nucleation. This experimental study investigates the desiccation of  
41 kaolinite specimens under confinement to reproduce various burial depths. We keep entrapped air  
42 bubbles as potential nucleation sites and use X-ray tomography to see inside the confining vessel  
43 and monitor internal processes during drying.

## 44 2. Experimental Study

### 45 2.1. Materials

46 The kaolinite used in this study has liquid limits  $LL_{\text{water}}= 48\%$ ,  $LL_{\text{brine}}= 55\%$ , and  $LL_{\text{ker}}=$   
47  $74\%$ , and is classified as a fine sediment of low plasticity and intermediate electrical sensitivity  
48 LP/IS in the Revised Soil Classification System (Jang & Santamarina, 2015; CL in USCS). We  
49 use a dewpoint hygrometer to determine the soil water retention curve (WP4C PotentialMeter;  
50 Campbell et al., 2007). The test starts with a paste prepared at  $w \approx 1.2$  LL; it dries at room  
51 temperature and homogenizes overnight between each recording of suction  $\psi$  and water content  
52  $w$ . The specimen contracts during desiccation, therefore, the measured soil water characteristic  
53 curve reflects the evolving pore size distribution (Khalili et al., 2008). Air entry takes place at a  
54 suction  $\psi_{\text{AE}} \approx 2.0$  MPa (Fig. 1).

### 55 2.2. X-ray Tomographer

56 The custom-built X-ray tomographer can scan large and heavy specimens (max weight~  
57 300 N). The system consists of (1) a high power cone-beam source to see through specimens within  
58 vessels (Comet, MXR-225HP, 225 kV), (2) a high-resolution flat panel detector (Varian, PaxScan  
59 1313Dx, size= 130×130 mm, 1024×1024 pixels), and (3) a precision rotation base for heavy  
60 specimens (Parker SM162BE-N10M motor and Parker R200M rotary stage; microstep  $\delta= 0.005^\circ$ ).  
61 Pixel resolution ranges from 40  $\mu\text{m}$  for 40 mm specimens, to 100  $\mu\text{m}$  for 100 mm specimens.

### 62 2.3. Self-reacting Oedometer Cells

63 Three identical oedometer cells are made of aluminum to minimize X-ray attenuation (Fig.  
64 2 – OD= 75 mm,  $H_0 \sim 100$  mm, wall thickness  $t= 5$  mm). Perforated plates and porous stones allow

65 water evaporation from both the upper and lower ends. The cell body includes a pneumatic cylinder  
66 to apply the vertical load during specimen compaction and drying, and an LVDT to measure the  
67 vertical displacement of the sediment. This self-reacting cell design allows moving the oedometer  
68 between the environmental chamber and the tomographer without perturbing on-going processes.  
69 The air pressure hose disconnects from the cell at the isolation valve for scanning (Fig. 2). The air  
70 pressure remains almost constant in the pneumatic cylinder, and specimens are stable during  
71 tomographic scans.

#### 72 *2.4. Test Sequence*

73 Small air bubbles remain entrapped in the otherwise water-saturated kaolinite pastes  
74 (mixed at  $w= 50\%$ ). We fill three chambers and consolidate specimens to different vertical stress  
75 levels to reproduce various burial depths:  $\sigma'_{z0}= 10$  kPa, 20 kPa, and 50 kPa. Then, let specimens  
76 dry at room temperature ( $T= 25^\circ\text{C}$ ) for  $\sim 40$  days. The second drying phase takes place in an  
77 environmental chamber at  $T= 60^\circ\text{C}$  (Fig. 3). We measure the specimen weights throughout the  
78 drying process, and collect X-ray tomographic images at specific drying states.

#### 79 *2.5. Image Processing*

80 The analysis of tomographic images involves three steps. First, we distinguish soil voxels  
81 from air, aluminum, and porous stones with threshold values that maximize the variance of voxel  
82 intensities between classes (Otsu method, Liao et al., 2001). We identify and label air bubbles to  
83 track their development. Finally, we measure the volume of the soil matrix and individual air  
84 bubbles. Calibration tests show that specimen volumes measured from X-ray tomograms deviate  
85 by less than 1% from physically measured volumes, however the error on single small bubbles can  
86 be higher than 1%.

## 87 3. Experimental Results

### 88 3.1. Vertical Strain and Water Content

89 Figure 3 shows the evolution of water content and vertical strain measured for the three  
90 specimens during the three experimental stages. Experimental results show:

- 91 • Loading stage: higher vertical strains and lower final water contents correlate with higher  
92 effective stress, in agreement with the consolidation response of this kaolinite.
- 93 • Drying at room temperature ( $\sim 40$  days,  $38 \pm 2\% < w < 50\%$ ): there is a limited decrease in water  
94 content and a minor vertical strain in all specimens. Suction remains low during this phase ( $\psi$   
95  $< 100$  kPa, inferred from water contents and the soil water retention curve in Fig. 1).
- 96 • Drying in the environmental chamber at  $60$  °C (additional 40 days): the response becomes  
97 suction-controlled and the three specimens experience a similar vertical strain of  
98 approximately 5.2%. The water content decreases below the water content at air entry ( $w_{AE} \approx$   
99 24%). Finally, the vertical strains stabilize while the soil specimens finish drying.

100

### 101 3.2. Tomograms

102 We obtain high-resolution tomograms ( $95$   $\mu\text{m}$  voxel size) throughout the loading-  
103 desiccation history. Points shown on the vertical strain curves in Fig. 3 identify scanning events.  
104 Figure 4 presents two cross sections at different depths obtained at three different stages of drying.  
105 These images capture the evolution of the perimetric fracture and transverse contraction, changes  
106 in bubble geometry (slices across the equatorial plane of large bubbles), and the development of  
107 internal desiccation cracks. Internal cracks nucleate at gas bubbles (see arrows) at a water content  
108 similar to or lower than the water content at the air entry value AEV ( $w_{AE} \approx 24\%$ , Fig. 1); a slice-  
109 by-slice examination confirms that these internal cracks are isolated and do not reach the external

110 soil boundaries. Bubbles near the perimeter are weak zones and alter the path of the perimetric  
111 fracture. Detailed analyses based on tomographic images follow.

### 112 3.3. *Sediment Volume*

113 Vertical strains are not sufficient to quantify the sediment volume contraction when  
114 desiccation cracks form. Therefore, we use the X-ray tomograms to track the sediment volume  
115 response. Fig. 5 plots the void ratio computed with the sediment volume from image analysis,  
116 against the Bishop stress computed for  $\chi = 1.0$ , where suction values are estimated from the  
117 measured water contents and the soil water retention curve (Fig. 1). The void ratio vs. Bishop stress  
118 trend tracks the 1D consolidation response of water saturated kaolinite ( $e_{1\text{kPa}} = 1.38$ ,  $C_c = 0.18$ ).  
119 Suction prevails over the initial vertical stress  $\sigma'_{z0}$  throughout the desiccation phase (Fig. 5). The  
120 consolidation trend breaks at the AEV, and a further increase in suction has a diminishing effect  
121 on the void ratio, i.e., Bishop's effective stress parameter  $\chi \rightarrow 0$ . These results suggest that soil  
122 blocks between desiccation cracks remain saturated even after fracture formation.

### 123 3.4. *Perimetric Desiccation Crack*

124 Tomograms show the formation of a fracture around the perimeter at relatively low suction  
125  $\psi < 100$  kPa, possibly due to a combination of a higher contact angle against the aluminum wall  
126 and larger pore sizes between the clay particles and the cell wall (Fig. 3). Eventually, the specimen  
127 separates completely from the lateral cell walls, i.e., lateral shrinkage and radial strain  $\varepsilon_r$ . We  
128 obtain the vertical strain  $\varepsilon_z$  from LVDT measurements and the volumetric strain  $\varepsilon_v$  from  
129 tomograms. Then, the radial strain is  $\varepsilon_r = (\varepsilon_v - \varepsilon_z)/2$ . Fig. 6 shows the radial strain plotted against  
130 the vertical strain. The initial 1D consolidation (Phase I) shows the increase in vertical strain  $\varepsilon_z$   
131 proportional to the vertical stress  $\sigma'_z$  while the radial strain is  $\varepsilon_r = 0$ . The formation of the

132 perimetric fracture along the cell wall corresponds to the radial contraction with almost no vertical  
133 strain (Phase II). During the second drying stage  $\psi > 100$  kPa, the sediment separated from the cell  
134 wall experiences no side friction, and the vertical strain increases proportionally to the radial strain  
135 (Phase III). The biasing vertical load affects the strain ratio  $\varepsilon_z/\varepsilon_r$ :  $\varepsilon_z/\varepsilon_r = 1.02$  for  $\sigma'_{z0} = 10$  kPa,  
136  $\varepsilon_z/\varepsilon_r = 1.11$  for  $\sigma'_{z0} = 20$  kPa, and  $\varepsilon_z/\varepsilon_r = 1.30$  for  $\sigma'_{z0} = 50$  kPa.

### 137 3.5. Gas Bubbles

138 We label individual air bubbles and track their evolution during loading and desiccation  
139 (Fig. 7a – tracked bubbles range from 1 mm<sup>3</sup> to 10 mm<sup>3</sup>, i.e., the number of voxels per bubble >  
140 1200). Fig. 7b shows the total volume of gas bubbles in the three specimens plotted versus water  
141 content. Air bubbles shrink during both loading and early stages of desiccation: the total volume  
142 of bubbles reduces by approximately 40% before the water content at the AEV (Fig. 7b). There is  
143 a small volume increase after the AEV, however, changes are within the measurement precision.

### 144 3.6. Internal Desiccation Cracks

145 Internal desiccation cracks form in the three specimens at a suction near the air entry value  
146 AEV (see sequences in Fig. 4 and detailed cross sections in Fig. 8). Typical internal desiccation  
147 cracks are 5 mm to 15 mm long with an aperture of  $\sim 0.3$  mm (resolution limited). The spacing  
148 between these cracks is larger than their length (Fig. 8a). Cracks have a planar or curved surface  
149 and irregular 3D morphology (Fig. 8b). All cracks are associated with one or more air bubbles that  
150 served as nucleation sites (Fig. 8c). The nucleation of 2 or 3 cracks at 120° are common (Fig. 8d).  
151 We also observe multiple cases of dual-parallel cracks that cannot be justified as imaging artifacts.  
152 Large vertical cracks (length up to 30 mm) develop from the interface with porous stone in spite

153 of the high frictional confinement. While suction controls the effective stress, the applied vertical  
154 stress biases crack growth and favors vertical alignment as observed in tomograms.

#### 155 4. Analyses of Gas Bubbles and Internal Cracks

156 The volume of a cavity contracts when the host medium experiences isotropic confining  
157 stress (Fig. 7b inset – Timoshenko & Goodier, 1951); this mechanical analogy explains the  
158 observed bubble contraction during early desiccation and shrinkage (Fig. 7b). Contraction leads to  
159 the increase in gas pressure  $u_b$  inside the bubble (if the gas does not dissolve), which becomes  
160 higher than the air pressure  $u_{air}$  outside the specimen. Yet, the water pressure  $u_w$  is quasi-constant  
161 throughout the specimen during slow drying. Then, the Kirsch solution for a circular hole in a 2D  
162 infinite plate predicts that the tangential stress on the bubble wall would become tensile when  $(u_b -$   
163  $u_w) \geq 2(u_{air} - u_w)$  (Jaeger et al., 2009).

164 Increased gas pressure eventually leads to gas invasion at a large pore along the bubble  
165 surface; this is the initiation of an internal crack. The sequence of particle-scale events resembles  
166 the formation of desiccation cracks at the free surface (Fig. 9 – Shin & Santamarina, 2011a): (a)  
167 capillary forces at the air-water interface on the bubble surface convert into skeletal interparticle  
168 forces within the sediment, (b) the soil contracts and the granular skeleton stiffens, (c) suction  
169 continuous increasing and the air-water interface invades the soil at the largest pores around the  
170 bubble surface, (d) membrane invasion alters particle forces and causes grain displacement,  
171 enlarges local pores and facilitates further membrane invasion leading to crack growth.

172 Note that air entry does not alter the fabric in stiff, coarse-grained sediments, however, air  
173 entry is grain-displacive in soft, fine-grained sediments. Force equilibrium between grain-scale  
174 capillary forces and effective stress-dependent skeletal forces defines the transition from grain-

175 displacement to pore-invasion, as captured in the dimensionless ratio  $\Pi_{inv}=10 \cdot T_s / (\sigma' \cdot d_{grain})$  where  
176  $T_s$  is the surface tension,  $d_{grain}$  is the particle size,  $\sigma'$  is the effective stress (Shin & Santamarina,  
177 2011b).

178 We recognize that the complexity of natural processes exceeds the plain macro- and  
179 particle-scale analyses proposed above. In fact, we do not address differences in volume  
180 contraction between bubbles and the sediment, and also disregard time dependent water pressure  
181 diffusion throughout the medium. Internal desiccation cracks are open-mode discontinuities; their  
182 initiation and growth reflect hydro-mechanical coupling and depend on many factors such as  
183 mechanical boundary conditions and principal stress directions, bubble size and shape, and bubble-  
184 bubble interactions. However, these analyses are an attempt to elucidate the essential processes  
185 behind internal desiccation crack formation.

## 186 **5. Conclusions**

187 This study explored the possibility of internal desiccation crack formation in soils. We  
188 tested water-saturated kaolinite specimens (with a few entrapped gas bubbles for potential  
189 nucleation sites), and used X-ray tomography to observe the evolution of consolidation and  
190 desiccation in self-reacting oedometer cells that reproduce various burial depths.

191 Air enters along the cell wall first due to higher contact angle and larger pore sizes. The  
192 perimetric crack detaches the specimen from cell walls; thereafter, the vertical strain increases  
193 proportional to the horizontal strain as suction increases.

194           Entrained gas bubbles shrink together with the specimen during early stages of desiccation,  
195 as theoretically predicted for a cavity inside a host medium subjected to isotropic confinement.  
196 The gas pressure inside bubbles increases during contraction. Eventually, the gas-water interface  
197 penetrates the soil at the largest pores around the bubble surface. Capillary forces at the air-water  
198 (soil) interface convert into skeletal interparticle forces within the sediment. Then, invasion of the  
199 interfacial membrane pushes particles away from the crack tip, enlarges local pores and facilitates  
200 further growth of the internal desiccation crack.

201           While air entry is grain-displacive in soft fine-grained sediments, it becomes pore-invasive  
202 in stiff coarse-grained sediments. Thus, internal desiccation cracks are not expected in silts or  
203 sands.

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207

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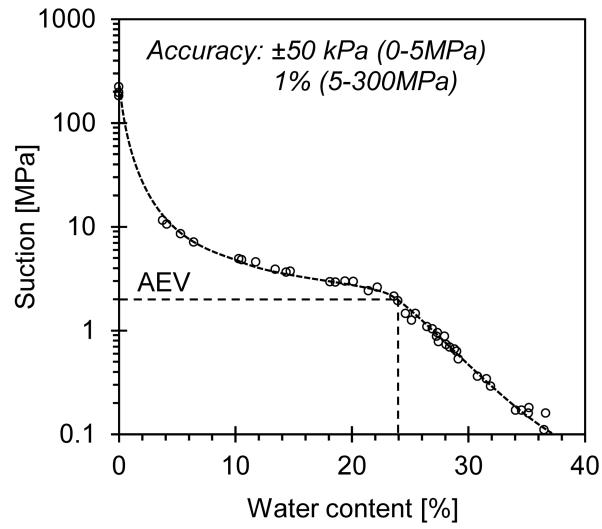
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- 263

264 **Figures**

265 Fig. 1. Soil water retention curve for the kaolinite used in this study. Suction values measured  
266 using a chilled-mirror hydrometer.

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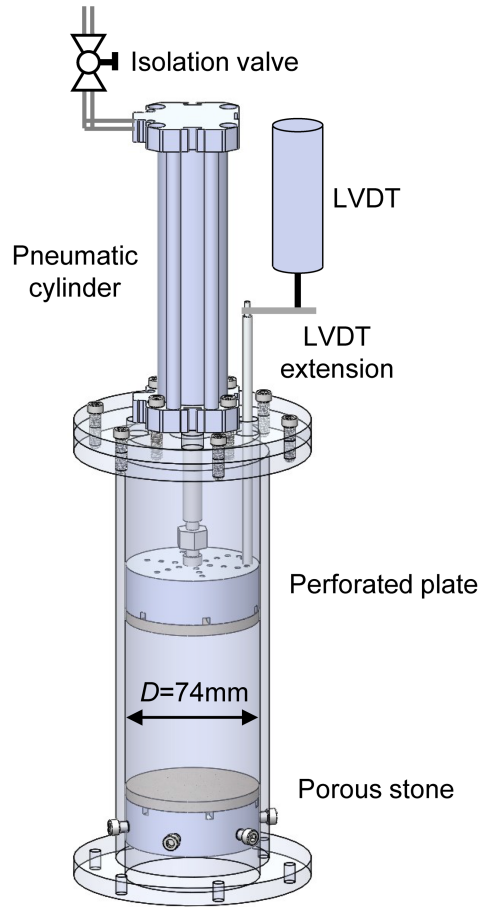


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270 Fig. 2. Self-reactive, X-ray transparent oedometer cell.

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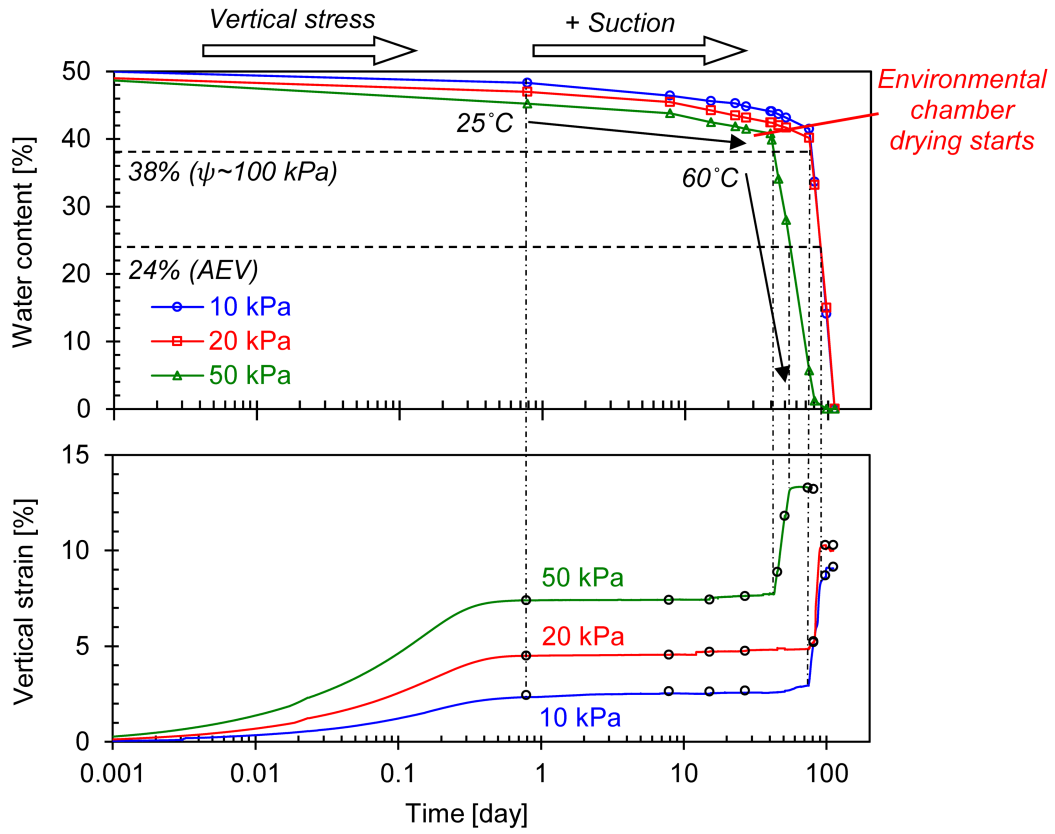


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274 Fig. 3. Water content and vertical strain evolution during consolidation and drying. The open  
275 circles shown on the vertical strain curves identify scanning events.

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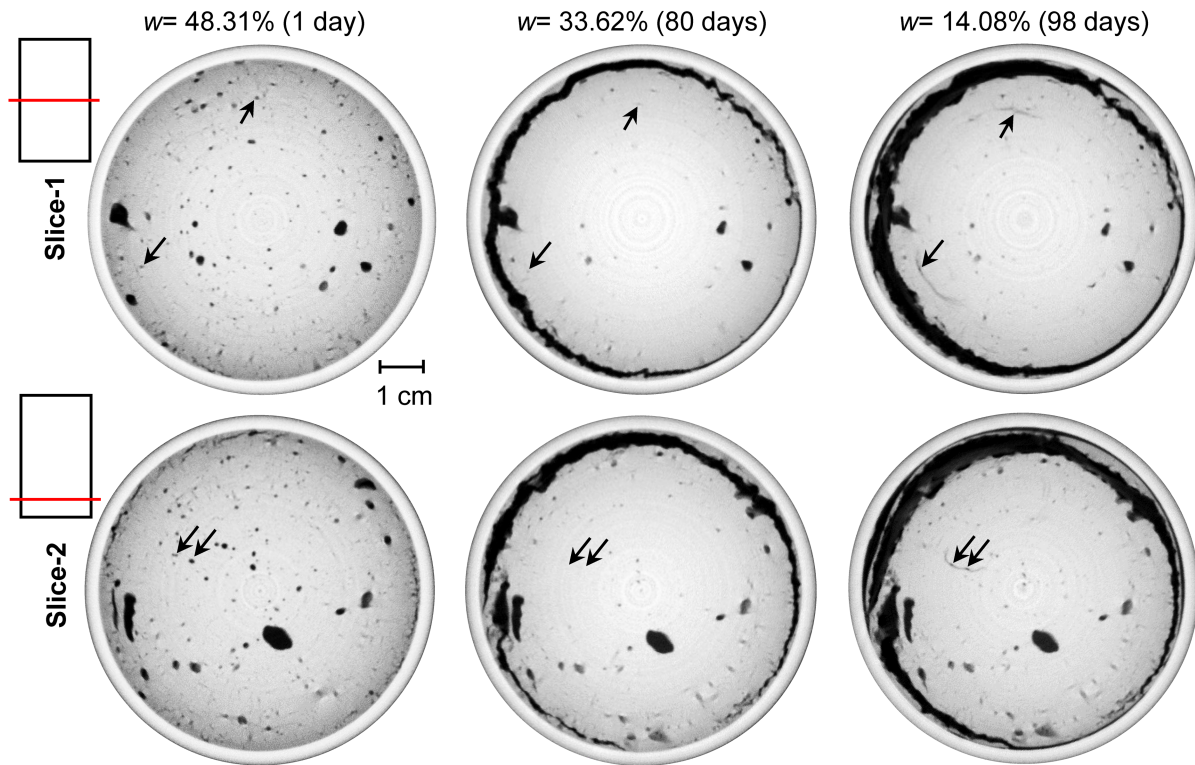


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279 Fig. 4. Two slices of the 3D tomogram gathered at different depths. Evolution during drying.  
 280 Specimen subjected to  $\sigma'_{z0} = 10$  kPa. Arrows mark internal cracks and their origin at gas bubbles.  
 281 Note: light grey= aluminum cylinder; grey= kaolinite pastes; black= air voids.

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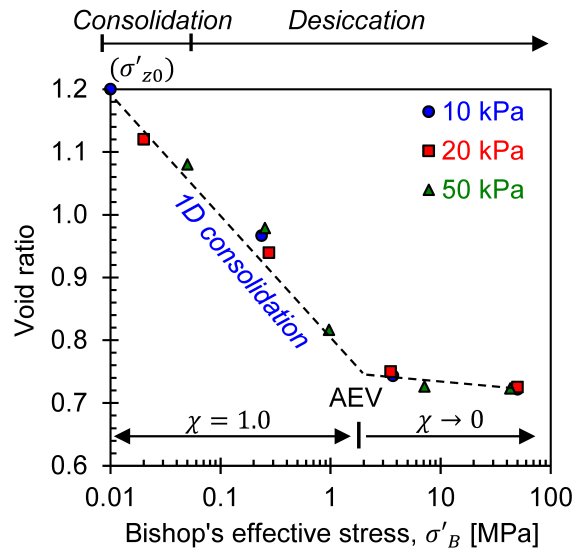


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285 Fig. 5. Volume contraction during loading and desiccation. Void ratio versus Bishop's effective  
 286 stress  $\sigma'_B = (\sigma - u_a) + \chi(u_a - u_w)$  computed assuming  $\chi = 1.0$ .

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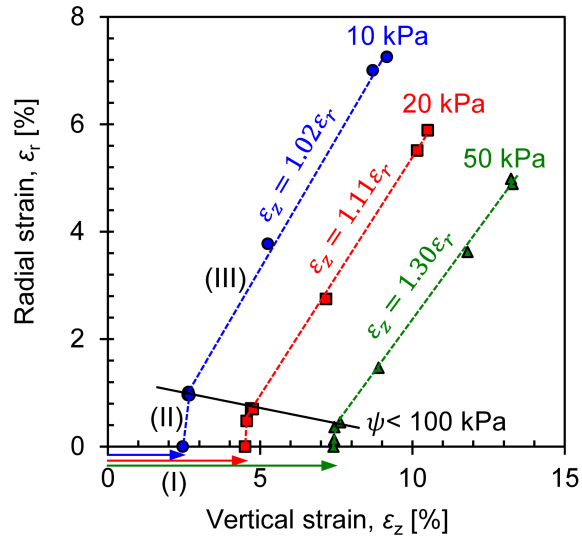


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290 Fig. 6. Vertical and radial strains. Evolution during (I) stress-controlled consolidation, (II)  
291 formation of perimetric fracture, (III) further contraction during desiccation.

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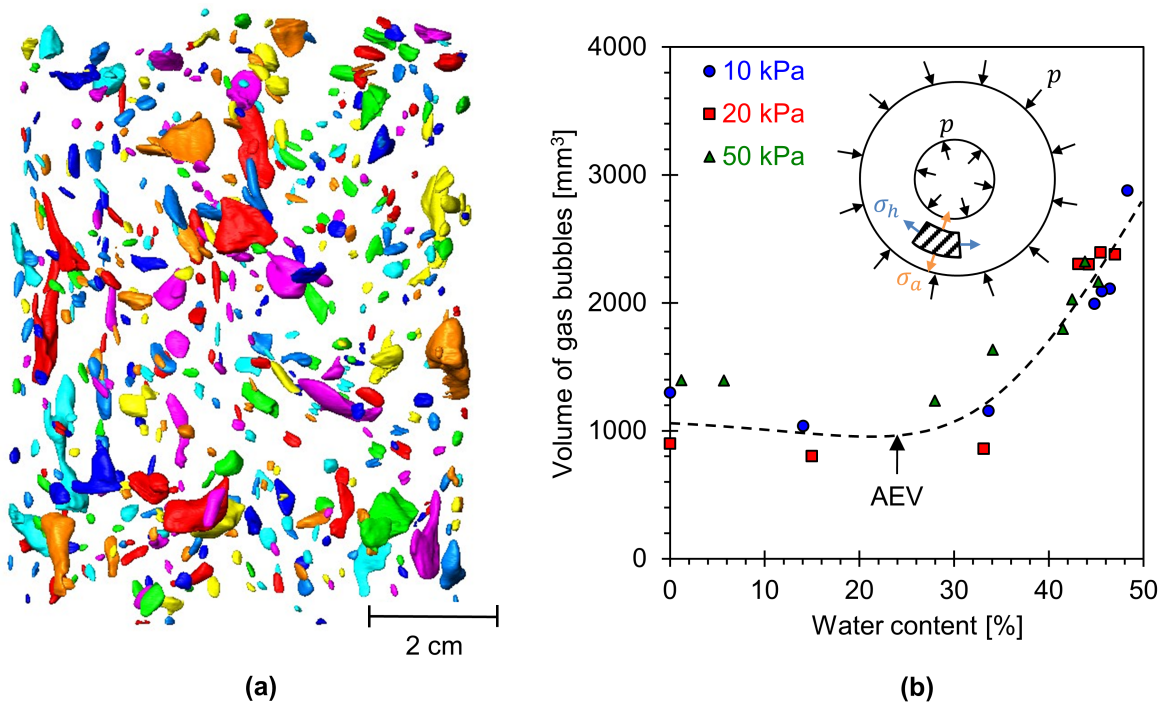


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295 Fig. 7. Evolution of gas bubbles. (a) Identified and labelled gas bubbles ( $V \geq 1 \text{ mm}^3$ ) for the  
 296 specimen subjected to  $\sigma'_{z0} = 20 \text{ kPa}$ ; tomographic image gathered at  $w = 47\%$ . (b) Evolution of the  
 297 total volume of gas bubbles during drying for the three specimens. (b-inset) Radial stress  $\sigma_a$  and  
 298 hoop stress  $\sigma_h$  in a spherical thick-wall volume under the same external and internal pressure  $p$   
 299 (Timoshenko & Goodier, 1951).

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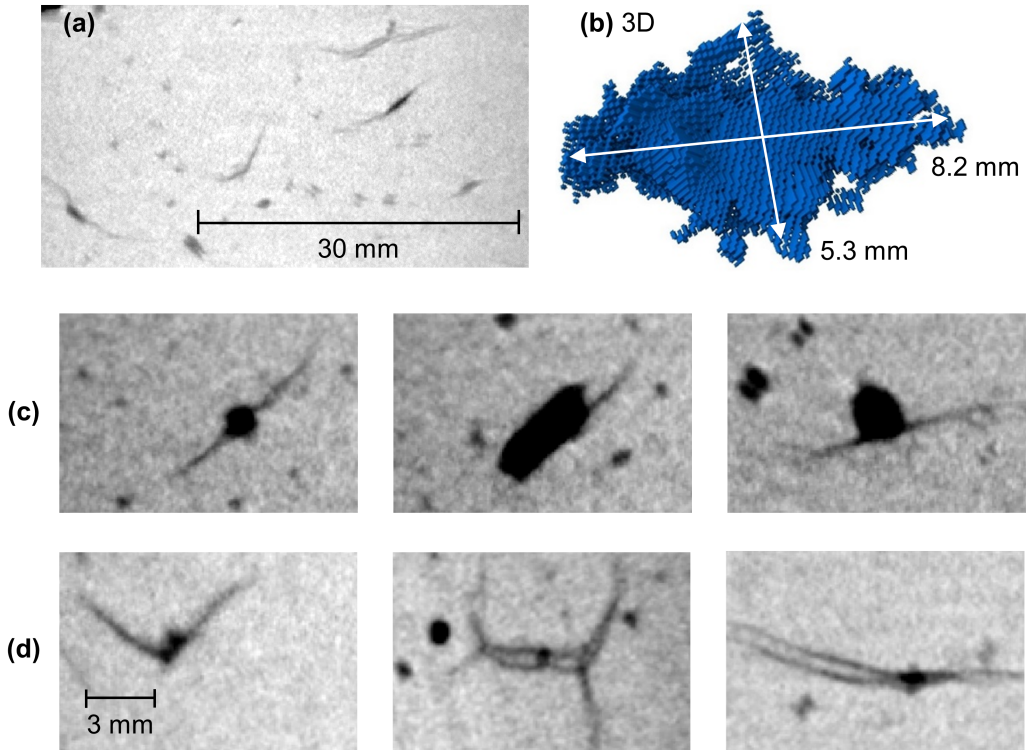


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303 Fig. 8. Internal desiccation cracks. Images obtained at an estimated suction of 3.5 MPa (for  
304 reference, the suction value at air entry is  $\psi_{AE} = 2$  MPa). (a) Internal cracks. (b) 3D morphology.  
305 (c) Gas bubbles as nucleation sites. (d) Nucleation at  $120^\circ$  and dual-parallel cracks.

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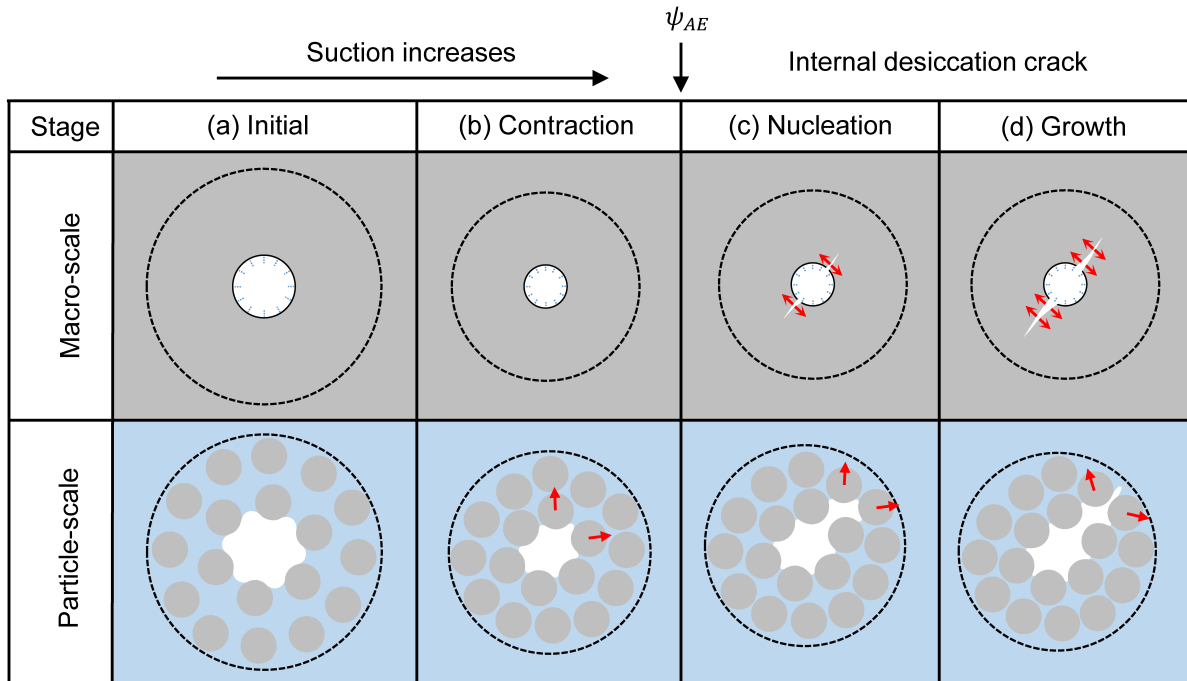
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310 Fig. 9. Macro-scale and particle-scale analysis of internal desiccation crack formation. (a-b)

311 Suction-controlled shrinkage. (b-d) Crack nucleation and growth.

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313