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1 **Modelling of water evaporation from cracked clayey soil**

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19 **Abstract:**

20 A model for predicting water evaporation from clayey soil with desiccation cracks
21 was developed based on a general suction-related model. The effect of desiccation
22 cracks was accounted for by introducing a surface crack ratio (R_c) and a ratio of
23 relative humidity in cracks to that at soil surface (k). The model was validated on the
24 basis of two large scale evaporation experiments in an environmental chamber under
25 controlled atmospheric condition. The results show that soil cracking strongly affects
26 the actual evaporation rate, especially after the falling-rate evaporation stage. Ratios R
27 and k are two relevant parameters in describing the effect of cracks on water
28 evaporation in a simple fashion. The introduction of these two parameters allows the
29 three-dimension evaporation problem in cracked soil to be reduced to one-dimension
30 evaporation problem. Comparison between the model predictions and the
31 experimental results shows that with consideration of the effect of desiccation cracks,
32 the model can satisfactorily describe water evaporation from cracked clayey soil
33 under controlled atmospheric condition.

34

35 **Key words:** cracked clayey soil; actual evaporation rate; suction-based model; surface
36 crack ratio

37 *Notations*

a	Fitting parameter
A	Soil evaporation surface area
e	Base of natural logarithm, equal to 2.71828
E_a	Actual evaporation rate
E_p	Potential evaporation rate
h	Relative humidity
h_a	Air relative humidity at a reference height
h_{a_in}	Absolute humidity at inlet of the chamber
h_{a_out}	Absolute humidity at outlet of the chamber
h_s	Relative humidity at soil evaporating surface
h_{crack}	Relative humidity induced by water vapor from cracks
$h_{non-crack}$	Relative humidity induced by water vapor from non-cracked soil
$h_{surface}$	Soil surface relative humidity
k	Ratio of relative humidity in cracks to that at soil surface
m	Fitting parameter
n	Fitting parameter
q	Air flow rate passing through the chamber
R	Universal constant, equal to 8.31432 J/mol/K
R_c	Surface crack ratio, equal to the surface area of cracks over the total initial surface area of the drying soil column
T	Temperature

u	Wind speed at 50-mm height over soil/water surface
W	Water molecular weight, equal to 18.016 g/mol
α	Constant determined through evaporation experiment
β	Constant determined through evaporation experiment
θ_r	Residual Volumetric water content
θ_s	Saturated volumetric water content
θ_w	Volumetric water content
ρ_w	Water density
φ	Soil suction

38 **1. Introduction**

39 Water evaporation from clayey soil causes decrease of soil water content and increase
40 of soil suction, and hence induces desiccation cracks and changes in
41 hydro-mechanical behaviour of soil, giving rise to possible damage of geotechnical
42 structures such as pavements, embankments and shallow foundations of buildings
43 (Corti et al., 2011; Puppala et al., 2011; Harrison et al., 2012; Jahangir et al., 2013;
44 Fernandes et al., 2015; Wang et al., 2016), instability of slopes (Baker, 1981; Tang et
45 al., 2011, 2016), and landslide (Sharma and Nakagawa, 2010). For addressing these
46 problems, it is essential to well understand the soil water content and suction
47 evolutions by considering the soil-atmosphere interaction.

48

49 In the attempt of well describing the soil water evaporation process, more and more
50 attention has been paid to the prediction of changes in soil temperature, suction and
51 water content, the main parameters defining the boundary condition at
52 soil-atmosphere interface (An et al., 2017, 2018; Teng et al., 2014, 2016). Considering
53 that the evaporation process is triggered by the vapor pressure deficit which occurs
54 between evaporating surface and atmosphere, the mass transfer model (*i.e.* Dalton
55 type equation) was proposed for predicting water evaporation from water or wet soil
56 surface (Wilson et al., 1994, 1997). The evaporating surface temperature, the
57 temperature and relative humidity at surrounding air are involved in this model. It can
58 be used to calculate evaporative fluxes when combined with the liquid water and
59 water vapor flow transient equations and the heat transfer equation (Wilson et al.,

1994). Note that the mass transfer coefficient shows a strong correlation with the wind velocity (Gerard et al., 2016). In addition to the vapor pressure deficit mentioned above, the mass and energy balance also exist at the soil-atmosphere interface. Thus, the water balance model and energy balance model (Blight, 1997; Cui and Zornberg, 2008; Cui et al., 2010) were both used to predict the water loss through evaporation, supposing that the related parameters such as infiltration rate, runoff rate, interception, net radiation flux, soil heat flux and sensible heat flux are known. Furthermore, after introducing a wind function into the mass transfer model and using the air temperature to calculate the saturated vapor pressure, Penman (1948) proposed a model which is the combination of mass transfer model and the energy balance model, allowing prediction of the water evaporation rate from vegetated and bare soil surfaces when the water supply is unlimited. However, it usually overestimates the evaporation rate when the soil becomes unsaturated (Wilson et al., 1997). In view of the physical meaning of water vapor traveling from soil to atmosphere, that is, water vapor is transported from evaporating surface to the soil surface by molecular diffusion and then be transferred from soil surface to the atmosphere through laminar or turbulent (Kondo et al., 1990), the resistance models were proposed by introducing the aerodynamic resistance and soil resistance (Mahfouf and Noilhan, 1991; Daamen and Simmonds, 1996; Yamanaka et al., 1997). Additionally, in order to take into account the appearance of dry soil layer during evaporation, Aluwihare and Watanabe (2003) proposed a model involving the dry layer height. However, the determination of soil resistance is still a challenge of this model. Later, Smits et al. (2011) proposed

82 a numerical model to simulate coupled heat, water vapor, and liquid water flux
83 through sandy soil and the application of this model also shows the strong effect of
84 the dry soil layer on the evaporation process (Smits et al., 2012). Assuming that the
85 potential evaporation rate is known, Campbell (1985) proposed a simple formula only
86 involving relative humidity of soil and air to determine the actual evaporation rate,
87 based on both the atmosphere and soil parameters. According to Kelvin's equation,
88 the soil surface relative humidity can be replaced by the suction at the same position,
89 leading to the suction-related model (Wilson et al., 1997; Ta, 2009). Note that this
90 model is independent of soil nature (e.g., soil texture and mineralogy). Song et al.
91 (2018) extended the suction-related model by introducing a relative humidity
92 distribution function. In addition to the models mentioned above, many researchers
93 also proposed different analytical or semi-analytical models on the basis of the
94 Richards equation (Novak, 1988; Nasser et al., 2012; Yamanaka and Yonetani, 1999;
95 Teng et al., 2013, 2019). However, these models cannot well describe the evaporation
96 mechanism and may become inapplicable when the liquid water becomes discontinuous
97 with a dry layer formed on soil surface. In this regard, Teng et al. (2019) proposed a
98 physics-based analytical model which can describe the movement of the vaporization
99 plane during evaporation.

100

101 The above-mentioned studies constituted a solid basis for analyzing the process of
102 water evaporation from soils. However, the important effect of cracks to water
103 evaporation from clayey soil was rarely investigated, even though it is well

104 documented that cracks could greatly contribute to water evaporation due to the
105 relatively high water content of soil in the vicinity of cracks (Adams and Hanks, 1964;
106 Selim and Kirkham, 1970; Ritchie and Adams, 1974).

107

108 In this study, a new evaporation rate prediction model was developed for investigating
109 water evaporation from cracked clayey soil surface based on the general
110 suction-related model (see Campbell, 1985; Wilson et al., 1997; Ta, 2009 and Song et
111 al., 2018). The effect of desiccation cracks was accounted for by introducing the
112 surface crack ratio (R_c) (*i.e.* the ratio of the surface area of cracks to the total initial
113 surface area of the drying soil column) and the ratio of relative humidity in cracks to
114 that at soil surface (k). All the model parameters were determined using the data from
115 two large scale evaporation experiments conducted by Song et al. (2016) and Song
116 (2014). Comparison was made between calculation and measurement, showing the
117 relevance of the model.

118

119 **2. General suction-related model**

120 As discussed by Song et al. (2018), the general suction-related model (Campbell,
121 1985; Wilson et al., 1997; Ta, 2009) considering both the atmosphere and soil effects
122 on soil water evaporation process can be described as follows:

$$123 \quad \frac{E_a}{E_p} = \frac{h_s - h_a}{100 - h_a} \quad (1)$$

$$124 \quad \frac{E_a}{E_p} = \frac{h_{\text{surface}} - h_a}{100 - h_a} \quad (2)$$

125 where E_a and E_p are the actual and potential evaporation rates (mm/day), respectively;

126 h_s is the soil evaporating surface relative humidity (%); h_a is the air relative humidity
127 at a reference height (%) and h_{surface} is the soil surface relative humidity (%).

128

129 Generally, h_s and h_{surface} can be determined by Kelvin's equation (Eq. (3)):

$$130 \quad h = \exp \left[-\frac{\varphi W (1/\rho_w)}{RT} \right] \quad (3)$$

131 where h is relative humidity (%); φ is soil suction (kPa), W is water molecular weight
132 (*i.e.* 18.016 g/mol), ρ_w is water density (*i.e.* 1000 kg/m³ at 4 °C), R is the universal
133 constant (*i.e.* 8.31432 J/mol/K) and T is temperature (K).

134

135 **3. Modified suction-related model for cracked clayey soil**

136 For a clayey soil, upon water evaporation, the soil suction increases, resulting in soil
137 shrinking and eventually soil cracking. Once the desiccation cracks formed, water can
138 evaporate into the atmosphere through two different ways: (1) directly from the
139 non-cracked soil surface; (2) from the desiccation cracks walls (Fig. 1). As shown in
140 Fig. 1, the relative humidity at the soil surface can be defined as h_{surface} . It constitutes
141 two parts: the relative humidity induced by water vapor from non-cracked soil
142 ($h_{\text{non-crack}}$) and the relative humidity induced by water vapor from cracks (h_{crack}).
143 Note that h_{crack} is an equivalent relative humidity inside the desiccation cracks. When
144 the soil surface is becoming dry, the value of $h_{\text{non-crack}}$ is much lower than that of
145 h_{crack} . For simplicity, we assume:

$$146 \quad h_{\text{crack}} = kh_{\text{non-crack}} \quad (4)$$

147 where k is the ratio of h_{crack} to $h_{\text{non-crack}}$.

148 By considering the soil surface crack ratio (R_c), the ratio of the cracks area to the total
 149 initial surface area of the drying soil column (Tang et al., 2008), Eq. (5) can be
 150 obtained:

$$151 \quad h_{\text{surface}} = R_c h_{\text{crack}} + (1 - R_c) h_{\text{non-crack}} \quad (5)$$

$$152 \quad \text{or} \quad h_{\text{surface}} = [1 + (k - 1)R_c] h_{\text{non-crack}} \quad (6)$$

153 From Eq. (2) and Eq. (6), the following expression can be deduced, allowing the
 154 calculation of water evaporation with consideration of effect of cracks:

$$155 \quad \frac{E_a}{E_p} = \frac{[1+(k-1)R_c]h_{\text{non-crack}}-h_a}{100-h_a} \quad (7)$$

156 Particularly, when the soil is extremely dry and the water evaporation rate is low, the
 157 water evaporates from the desiccation cracks makes greater contribution to the soil
 158 surface relative humidity than from the non-cracked soil. Thereby, in that case,
 159 assuming $h_{\text{non-crack}}$ is equal to h_a , we obtain:

$$160 \quad h_{\text{surface}} = (1 + kR_c - R_c) h_a \quad (8)$$

161 It is noted that the unit in the equations mentioned above is percentage (%) for the
 162 relative humidity, and is in decimal for the surface crack ratio (R_c).

163 For the potential evaporation rate (E_p), it can be predicted using the model proposed
 164 and calibrated by Ta (2009) and Song et al. (2018) (Eq. (9)). Note that this model is
 165 derived from the general form of the existing mass transfer model (e.g., Singh and Xu,
 166 1997) based on the results from six free water evaporation experiments under
 167 controlled atmospheric conditions (various wind speeds and air temperatures) (Song
 168 et al., 2018).

$$169 \quad E_p = (\alpha + \beta u)(100 - h_a) \quad (9)$$

170 where E_p is the potential evaporation rate (mm/day); u is the wind speed at 50-mm
171 height over soil/water surface (m/s); h_a is the corresponding air relative humidity at
172 the same reference level as the wind speed (%); α and β are two constants determined
173 through free water evaporation experiment with different wind speeds, *i.e.* the
174 relationship between $E_p/(100-h_a)$ and the wind speed u (see Song, 2014). As shown in
175 Fig. 2, the experimental data exhibit a quite large scatter. The linear best fitting of all
176 data (Line 1) gives the values of α and β equal to 0.022 and 0.031, respectively. If the
177 largest data and the smallest data are considered, the linear best fittings (Line 2 and
178 Line 3) gives the range of α from 0.014 to 0.032, and the range of β from 0.025 to
179 0.037.

180

181 **4. Evaporation experiments on clayey soil**

182 *4.1 Materials*

183 The clayey soil used for investigating soil water evaporation process was taken from
184 an experimental embankment in Héricourt, France. Its geotechnical properties were
185 investigated by Song et al. (2016), and are presented in Table 1.

186

187 *4.2 Experimental set-up*

188 The soil water evaporation test was conducted in an environmental chamber system
189 proposed by Song et al. (2014). This environmental chamber system (see Fig. 3)
190 contains a model test chamber filled with soil sample and equipped with various
191 sensors for measuring both soil and atmosphere parameters, a wind simulating unit, an

192 air collection unit, an image capture unit, a water supply unit, and a data logging unit.
193 During the evaporation test, cool air was firstly heated and controlled by the wind
194 simulating unit, forming hot wind with different temperatures and speeds. Then, the
195 hot air passed through the model test chamber and removed the water vapor from soil
196 surface. Finally, the moist air was gathered in the air collection unit. It is noted that
197 the air temperature and relative humidity were measured before and after passing
198 through the chamber, being used for determining the actual evaporation rate.
199 Furthermore, the soil surface desiccation crack was monitored by the image capture
200 unit every 90 min; the water table at soil bottom was also kept constant using the
201 water supply unit during the whole evaporation test. All data were recorded by the
202 data logging unit.

203

204 *4.3 Test procedure*

205 The soil sample transported from the embankment construction site was firstly air
206 dried in the laboratory, and then crushed and passed through 2 mm sieve. Finally, it
207 was stored in sealed containers for further testing (Fig. 4(a)). Then, a gravel layer with
208 6.5 mm in thickness was compacted at the bottom of the chamber and covered by two
209 geotextile layer at both the surface and bottom of it, being termed as the drainage
210 layer. After that, the dry soil sample with the gravimetric water content of 6.4% was
211 compacted manually in layers to a target height of 250 mm corresponding to a dry
212 density of 1.4 Mg/cm³ (Fig. 4(b)). In the meantime, various sensors measuring both
213 the atmospheric conditions (e.g., the air temperature, the air relative humidity, the

214 wind speed and the air flow rate) and the soil response (e.g., the soil matric suction,
215 the soil temperature and the soil volumetric water content) were installed at various
216 positions of the environmental chamber or buried in the soil at different depths (Figs.
217 4(c) and 4(d)). Furthermore, a camera was hung over the soil surface at a certain
218 elevation, enabling the soil surface desiccation cracks to be monitored over time (Fig.
219 4(e)). Finally, the soil sample was saturated by the water supply unit and then the
220 evaporation experiment was started under controlled atmospheric condition (Fig.
221 4(f)).

222

223 As for the evaporation experiment, two controlled atmospheric conditions in terms of
224 air relative humidity, temperature and air flow rate were applied to the soil sample
225 (Table 2); the water table at its bottom (250 mm below the soil surface) was also kept
226 constant. The durations of the two experiments were 83 days and 41 days,
227 respectively.

228

229 For the actual evaporation rate, it was determined using the formula proposed by
230 Mohamed et al. (2000) and Aluwihare and Watanabe (2003), based on the
231 measurement of atmospheric parameters at the inlet and outlet of the chamber, as
232 follows:

$$233 \quad E_a = 86400 \frac{q(h_{a_out} - h_{a_in})}{\rho_w A} \quad (10)$$

234 where E_a is the actual evaporation rate (mm/day), h_{a_out} and h_{a_in} are the absolute
235 humidity at outlet and inlet of the chamber, respectively (Mg/m^3), q is the air flow rate

236 passing through the chamber (L/s), ρ_w is the water density (Mg/m³) and A is the soil
237 evaporation surface area (m²).

238

239 The surface crack ratio (R_c) was used to describe the evolution of desiccation cracks.
240 It was determined using the photographs of soil surface taken with the fixed time
241 interval (*i.e.* 90 min) by applying the digital image processing technique proposed by
242 Tang et al. (2008). Specifically, the original color image of surface crack pattern from
243 the image capture unit was firstly changed to the grey one, and then it was converted
244 into a binary black and white image through the binarisation process. Note that the
245 black zone in this binary image represented the crack and the white zone indicated the
246 soil aggregate without crack. Finally, the ratio of the area of black zone to the total
247 zone was determined using the software CIAS (Tang et al., 2008), that is, the value of
248 R_c . More details about this digital image processing technique can be found in Tang et
249 al. (2008).

250

251 *4.4 Typical results*

252 The relationship between the volumetric water content and soil suction at different
253 depths (*i.e.* 15, 20, 25, 77 and 173 mm depths) during the two experiments is
254 presented in Fig. 5 (Song, 2014; Song et al., 2016). At the same time, due to the
255 incomplete data, a fitting curve which covers the suction range being obtained in these
256 tests (*i.e.* less than 1.5 MPa) is described by the model proposed by Fredlund and
257 Xing (1994) (see Eq. (10)).

258
$$\theta_w = \theta_r + \frac{\theta_s - \theta_r}{\{\ln[e + (\varphi/a)^n]\}^m} \quad (11)$$

259 where θ_w is the volumetric water content (%); θ_s is the saturated volumetric water
 260 content (%); θ_r is the volumetric water content at residual state (%); φ is the soil
 261 suction (kPa); e is 2.71828, *i.e.* the base of natural logarithm; a , m and n are three
 262 fitting parameters, respectively.

263

264 The actual and potential evaporation rates calculated using Eqs. (10) and (9) are
 265 shown in Fig. 6. It can be observed that the actual evaporation values initially kept at
 266 a relative stable level (*i.e.* the constant-rate stage) around 2.3 mm/day (Test 1 and Test
 267 2), then decreased sharply (*i.e.* the falling-rate stage) and reached a new stable level
 268 (*i.e.* slow-rate stage) around 0.3 mm/day for Test 1 and 0.8 mm/day for Test 2. For the
 269 potential evaporation rate, it increased over time due to the decrease of air relative
 270 humidity. Notably, Test 2 started with six free water evaporations; therefore, the soil
 271 water evaporation started after $t = 12.8$ days.

272

273 Figure 7 shows the evolutions of surface crack ratio (R_c) and actual evaporation rate
 274 during two evaporation tests. It appears from this figure that the R_c increased with the
 275 decrease of actual evaporation rate and reached a stable value of 25.5 % in Test 1 and
 276 29.0 % in Test 2. The decrease of evaporation rate lagged behind that of the evolution
 277 of R_c , reflecting the effect of cracks on water evaporation, that is, providing water
 278 vapor and thus delaying the decrease of evaporation rate. Note that the calculation of
 279 surface crack ratio in this study considered the gap between the wall of chamber and

280 the soil body, because water vapor could migrate to the atmosphere through this gap,
281 affecting the total evaporation rate.

282

283 More details about the two experiments can be found in Song et al. (2016).

284

285 **5. Determination of parameters**

286 The ratio E_a/E_p can be determined using the measured actual evaporation rate and the
287 calculated potential evaporation rate for the two evaporation tests (see Fig. 6).

288 Generally, due to the sufficient water supply to the evaporation process, the value of

289 E_a/E_p is equal to 1 during the constant-rate evaporation stage. However, as shown in

290 Fig. 6, the potential evaporation rate was lower than the actual one during this stage

291 and thus E_a/E_p was not equal to 1. This was due to the accuracy of the determination

292 of parameters α and β in Eq. (9), indicating the necessity of adjusting the potential

293 evaporation rate calculated using Eq. (9) (Song et al., 2018). In a simple way, E_p was

294 multiplied by a constant (1.15 for Test 1 and 1.2 for Test 2), leading the average value

295 of E_a/E_p during the constant-rate evaporation stage to 1. The corresponding values of

296 α and β were 0.028 and 0.027 in Test 1, and were 0.029 and 0.031 in Test 2, falling in

297 the ranges of α and β determined previously from Fig. 2. This justified the

298 modification made on E_p .

299

300 To determine parameter k , the surface relative humidity (h_{surface}) was firstly predicted

301 using Eq. (2) with the adjusted potential evaporation rate, measured actual

302 evaporation rate and the relative humidity at 50-mm height and then compared with
303 the relative humidity measured at 50-mm height (see Fig. 8). Then, parameter k could
304 be calculated by Eq. (8) with the known surface crack ratio (Fig. 7). For Test 1, the
305 data shown in Fig. 8(a) from $t = 65$ days to $t = 84$ days were selected for the
306 determination of k . Note that the R_c value during this stage was 25.5 %. A value of
307 3.65 was obtained for k . For Test 2, the data shown in Fig. 8(b) from $t = 43$ days to $t =$
308 54 days were selected for the determination. The corresponding R_c value was 29 %
309 and a value of $k = 5.59$ was obtained. Note that the value of k was larger in Test 2 than
310 in Test 1, owing to more water vapor that entered the atmosphere through the deeper
311 zone in Test 2. Indeed, the direct measurement of the width and depth of desiccation
312 crack at the end of the two tests showed that the depths of cracks in Test 2 were
313 deeper than in Test 1 (see Fig. 9).

314

315 As observed in Fig. 8, the soil surface relative humidity deduced from Eq. (2) was
316 much higher than at 50-mm height, even at the end of the evaporation process. As
317 shown in Fig. 6, the actual evaporation rate at the slow-rate evaporation stage was
318 extremely low. Basically, once the evaporation rate was close to stabilization, the
319 relative humidity at the soil surface approached the one in the air. The phenomenon
320 observed in Fig. 8 might be attributed to the occurrence of desiccation cracks during
321 the soil water evaporation process, *i.e.* the cracks allowed water to evaporate from the
322 walls of them, increasing the relative humidity at the soil surface and converting the
323 one-dimension evaporation model (*i.e.* water evaporates only from the soil surface)

324 into the three-dimension one (*i.e.* water evaporates from both the soil surface and the
325 crack walls). This indicated the strong effect of cracks on the evaporation process.
326 Furthermore, we could deduce that predicting actual evaporation rate directly using
327 Eqs. (1) or (2) was not appropriate for cracked soils.

328

329 **6. Verification of the proposed model**

330 After determining the related parameter of the proposed model (*i.e.* Eq. (7)), two
331 methods (Method 1 and Method 2) were used for the verification. The details of the
332 two methods are described as follows and the results from Test 1 were taken as an
333 example firstly. The diagram of the two methods is shown in Fig. 10.

334

335 In Method 1, the volumetric water content at the soil surface (Fig. 11) was firstly
336 extrapolated from the water content profile obtained from the evaporation test (see
337 Song et al., 2016). Then, the soil surface suction was determined using the water
338 retention curve fitted by the model proposed by Fredlund and Xing (1994) (Eq.(11))
339 (see Fig. 5(a)). In this model, the saturated volumetric water content (θ_s) was
340 determined by averaging the initiation water content at different depths and was equal
341 to 58.8% and the residual volumetric water content (θ_r) was estimated to be 11.6 %, *i.e.*
342 the water content at 25-mm depth at the end of test. For the 3 fitting parameters a ,
343 n and m , they were 50, 0.55 and 25, respectively. After that, the suction at soil surface
344 was transformed into the surface relative humidity by Kelvin's equation (Eq. (3)).
345 Notably, this surface relative humidity corresponded to the one at the soil surface

346 without cracks, *i.e.* $h_{\text{non-crack}}$ in Eq. (7). Finally, with the determined R_c , k , $h_{\text{non-crack}}$,
347 E_p and h_a , the actual evaporation rate (E_a) could be calculated using Eq. (7) (Fig. 12).
348 Notably, as the water retention curve only involved suctions lower than 1.5 MPa (*i.e.*
349 the range of the high-capacity tensiometer for measuring soil matric suction, see Song
350 et al., 2013, 2014), the prediction of actual evaporation rate was conducted in the first
351 15 days. As can be seen in Fig. 12, large difference existed between the measured
352 value and the one predicted by Method 1, which could be attributed to the possible
353 inaccurate determination of the water retention curve for the surface soil. Indeed,
354 large heave was observed at the surface of the soil sample during the saturation
355 process, leading to a dry density of soil in surface zone lower than the one at deeper
356 zone. Thus, predicting the actual evaporation rate using water retention curve deduced
357 from the experimental data in deeper zone rather than from the surface was
358 unreasonable. Furthermore, the water retention curve which covered the full suction
359 range was also needed for a better evaporation prediction. In addition to the factors
360 mentioned above, the effect of desiccation cracks was also required to be taken into
361 account. Indeed, for a large scale cracked soil sample, the water content distribution at
362 soil surface is quite complicated and hence the water retention curve is also difficult
363 to determine.

364

365 In order to address the problems with Method 1, Method 2 was introduced with an
366 equivalent water retention curve at soil surface and a modified surface volumetric
367 water content. In this method, the cracked surface soil was assimilated to a thin layer

368 without cracks by introducing parameters R_c and k , allowing the three-dimension
369 evaporation problem in cracked soil to be reduced to one-dimension evaporation
370 problem. Firstly, the relative humidity at the non-cracked soil surface (*i.e.* the
371 equivalent thin soil layer) was determined by Eq. (7) with the measured data and the
372 values of k and R_c . Note that this was an equivalent surface relative humidity and was
373 equal to $h_{\text{non-crack}}$. Then, the corresponding surface suction (*i.e.* equivalent surface
374 suction) was calculated using Kelvin's Equation (Fig. 13). Afterwards, the equivalent
375 water retention curve (Fig. 14) was determined by the equivalent surface suction and
376 the surface volumetric water content extrapolated from the water content profile
377 during the evaporation process (see Fig. 11). This curve was also fitted by the model
378 proposed by Fredlund and Xing (1994) (Eq. (11)). The saturated volumetric water
379 content (θ_s) and the residual volumetric water content (θ_r) were determined by the
380 extrapolated surface volumetric water content, *i.e.* 66 % for the saturated one and 2.2 %
381 for the residual one. For the corresponding fitting parameters a , n and m , they were 50,
382 1.9 and 9, respectively. As shown in Fig. 14, large fluctuation was observed in the
383 high suction range, which could be attributed to the inaccurate determination of water
384 content when cracks developed. As a matter of fact, the development of desiccation
385 cracks led the volumetric water content sensor to expose to the air partly or totally,
386 leading to unreliable results (see Fig. 15). Furthermore, the suction used in this water
387 retention curve took the effect of cracks into account. Therefore, it is better to
388 consider this effect when determining the surface volumetric water content. Thereby,
389 the equivalent surface volumetric water content (Fig. 11) was calculated using the

390 equivalent surface suction (Fig. 13) and the water retention curve (Fig. 14). As shown
391 in Fig. 11, the equivalent surface volumetric water content thus determined was in
392 accordance with the one extrapolated from the water content profile before most
393 cracks were formed (e.g., $t = 15$ days), indicating the rationality of the method
394 proposed which considered the crack development. Therefore, the modified surface
395 water content could be divided into two stages: (1) Stage 1: the value was equal to the
396 one extrapolated from the water content profile (in the first 15 days); and (2) Stage 2:
397 the corresponding value was replaced by the equivalent one after most desiccation
398 cracks being formed. Note that the time $t = 15$ days corresponded to the end of the
399 constant-rate evaporation stage. Afterwards, the modified surface volumetric water
400 content was used to determine the surface suction with the equivalent water retention
401 curve. Hence, the relative humidity at soil surface (*i.e.* $h_{\text{non-crack}}$) could be obtained by
402 Kelvin's equation. Finally, with the determined parameters k , R_c , h_a , $h_{\text{non-crack}}$ and E_p ,
403 the actual evaporation rate (E_a) was determined by Eq. (7). It appeared from Fig. 12
404 that the predicted actual evaporation rate by Method 2 agreed well with the measured
405 one during evaporation experiment.

406

407 The relevance of the proposed model was also verified using the experiment data
408 obtained from Test 2. For clarity, only Method 2 was adopted for this purpose. Firstly,
409 an equivalent water retention curve was determined based on the experiment data
410 obtained during Test 2 (Fig. 16). The equivalent water retention curve was also fitted
411 by the model proposed by Fredlund and Xing (1994) (see Eq. (11)). More specifically,

412 the volumetric water content at saturated state (θ_s) was 67 %, and the volumetric
413 water content at residual state (θ_r) was 2.2 %. Furthermore, as for the related fitting
414 parameters a , n and m , they were 45, 1.5 and 7, respectively. Notably, no large
415 difference was identified in high suction range, as shown in Fig. 16. This is because of
416 the more significant development desiccation cracks in Test 2, allowing water content
417 in the surface zone to be more homogeneous over depth. Then, the surface volumetric
418 water content was modified by the equivalent one (Fig. 17). The modified surface
419 volumetric water content included two parts: the one directly extrapolated from the
420 water content profile (before $t = 19$ days, *i.e.* constant-rate evaporation rate stage) and
421 the second part from the equivalent one with the effect of most desiccation cracks
422 (after $t = 19$ days). Note that only the result of the extrapolated volumetric water
423 content before $t = 27$ days were shown in this figure, because the development of
424 cracks led to negative value when the water content profile was used. Afterwards, the
425 surface suction was determined by the equivalent water retention curve with the
426 modified surface water content and hence the corresponding surface relative humidity
427 could also be obtained using Kelvin's equation (see Figs. 18 and 19). Finally, with the
428 known k , R_c , h_a , $h_{\text{non-crack}}$ and E_p , the actual evaporation rate (E_a) could be determined
429 by Eq. (7). As can be seen in Fig. 20, the predicted evaporation rate was consistent
430 with the one measured during evaporation experiment, confirming the relevance of
431 the proposed model as well as the relevance of Method 2.

432

433 **7. Conclusions**

434 A new water evaporation rate model considering the effect of desiccation cracks was

435 proposed for clayey soils based on the general suction-related model. The surface
436 crack ratio (R_c) and the ratio of relative humidity from cracks and that from
437 non-cracked soil (k) were introduced for this purpose. This new model (Eq. (7)) was
438 verified based on the test results of Song et al. (2016) and Song (2014).

439

440 The soil desiccation cracks provide new paths (*i.e.* the crack wall) for the water vapor
441 entering the atmosphere. This converts the one-dimension evaporation pattern (*i.e.*
442 water evaporates only from the soil surface) into a three-dimension one (*i.e.* water
443 evaporates from both the soil surface and the crack walls), strongly influencing the
444 evolution of actual evaporation rate, especially after the falling-rate evaporation stage.
445 R_c and k are two key parameters for describing the effect of desiccation cracks on the
446 water evaporation process. The introduction of the two parameters in the model
447 allows the water evaporation to be described only using the parameters for the soil
448 surface without specifically considering water evaporation from each crack. In other
449 words, the proposed model allows the three-dimension evaporation problem in
450 cracked soil to be reduced to a one-dimension problem. This is important while
451 applying the model to field condition because only parameters which can be easily
452 determined are needed.

453

454 Adopting an equivalent water retention curve for the surface soil with desiccation
455 cracks appeared to be successful. This allowed the effect of desiccation cracks in large
456 scale soil sample to be considered indirectly and the suction range to be extended.

457

458 **Acknowledgments**

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464

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616 Fig. 19. Surface relative humidity in Test 2.

617 Fig. 20. Comparison between the measured and predicted actual evaporation rates.

618 **Table 1.** Physical properties of the soil studied (Song et al., 2016).

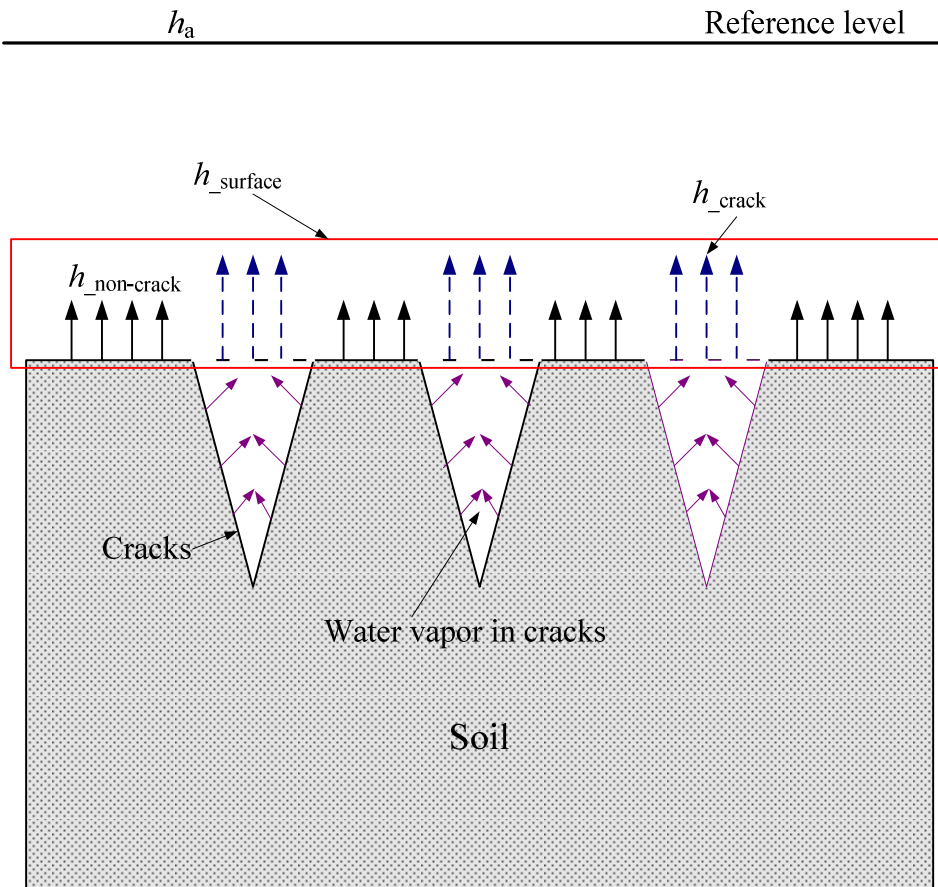
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Physical properties	Values
Specific gravity	2.7
Plastic limit (%)	37
Liquid limit (%)	76
Plastic index	39
Clay (<2 μ m) content (%)	78

620 **Table 2.** Evaporation test conditions.

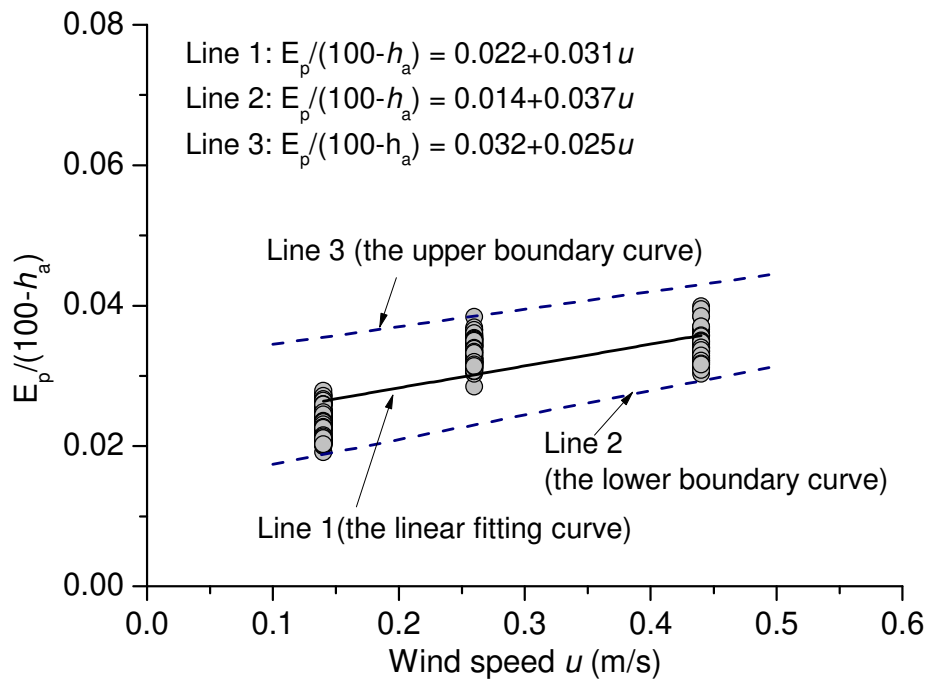
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Test number	Air flow rate (L/min)	Temperature in heating tube (°C)	Average wind speed (m/s)	Test duration (days)
1	155±5	200	0.4	83
2	140±5	200	0.36	41



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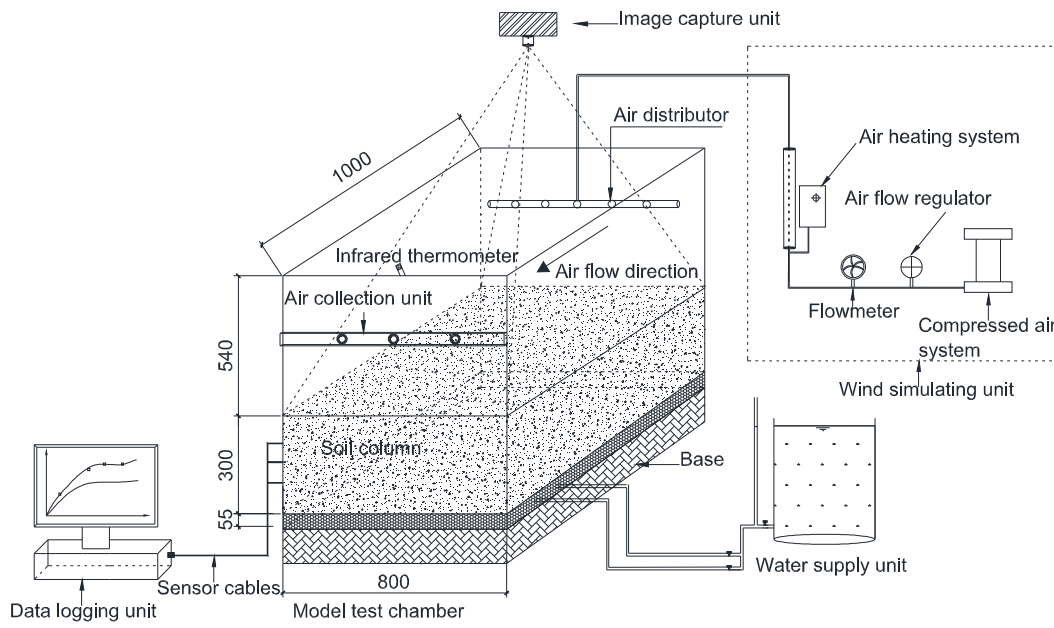
624 **Fig. 1.** Sketch of water evaporation from cracked soil.



626

627 **Fig. 2.** The determination of parameters α and β .

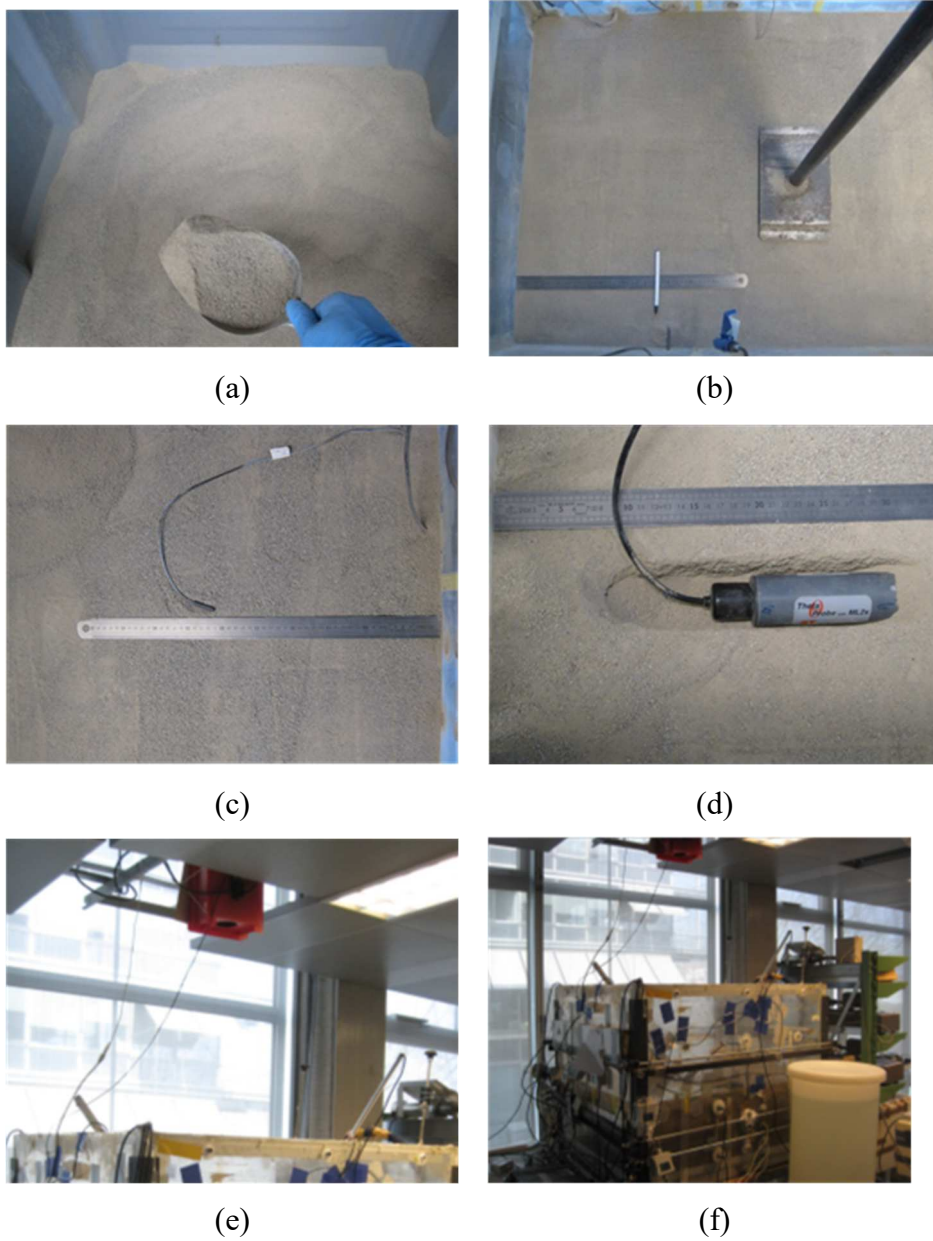
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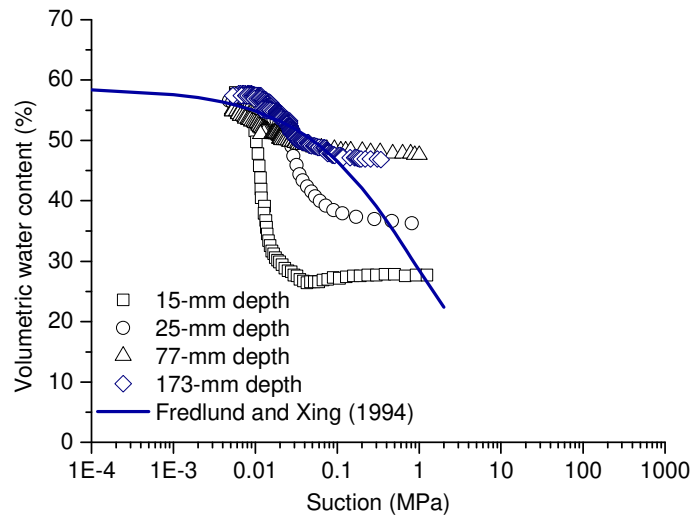
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631 **Fig. 3.** Sketch of water evaporation environmental chamber system (after Song et al.,
632 2016).

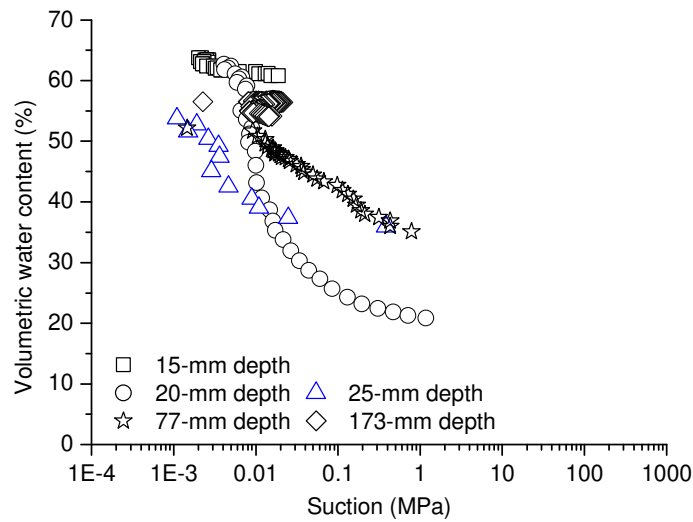
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635 **Fig. 4.** Experimental procedure: (a) air-dried soil sample preparation, (b) soil
636 compaction, (c) soil temperature sensor installation, (d) volumetric water content
637 sensor installation, (e) camera installation, and (f) evaporation test initiation.



(a)



(b)

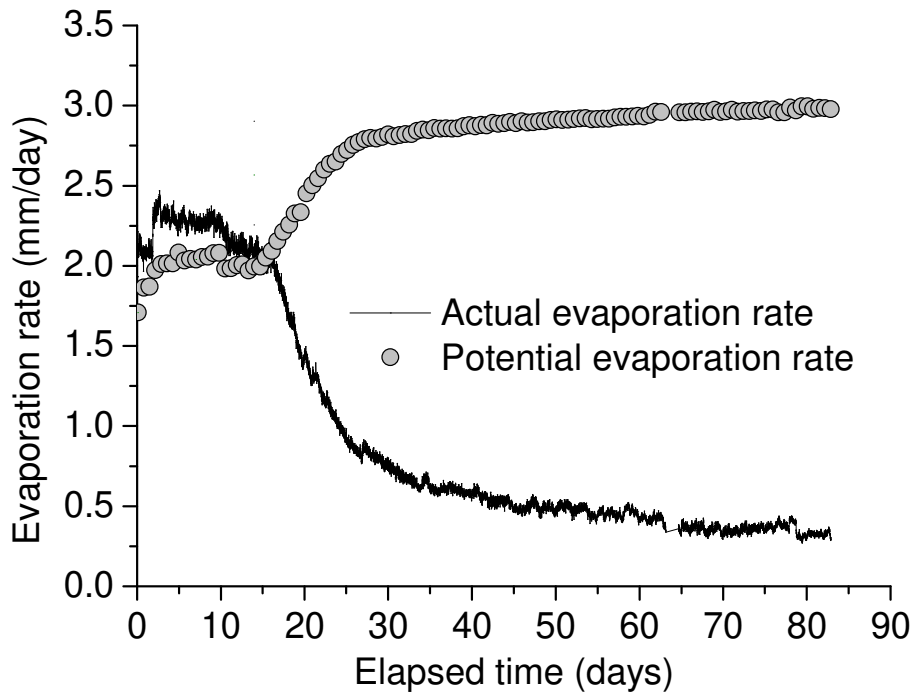
639 **Fig. 5.** Soil water retention curves obtained from evaporation tests: (a) Test 1, (b) Test

640 2.

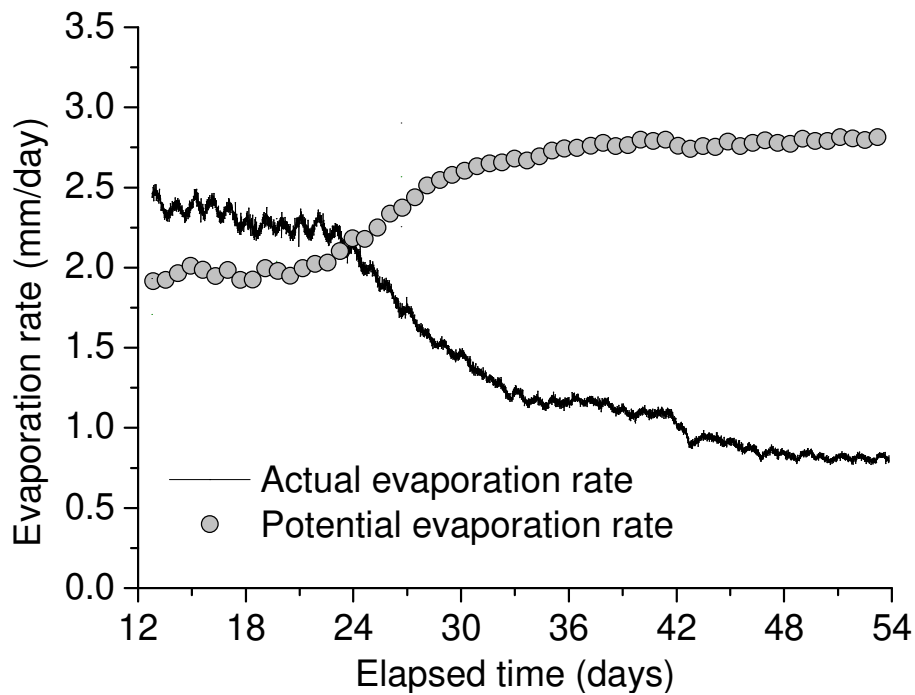
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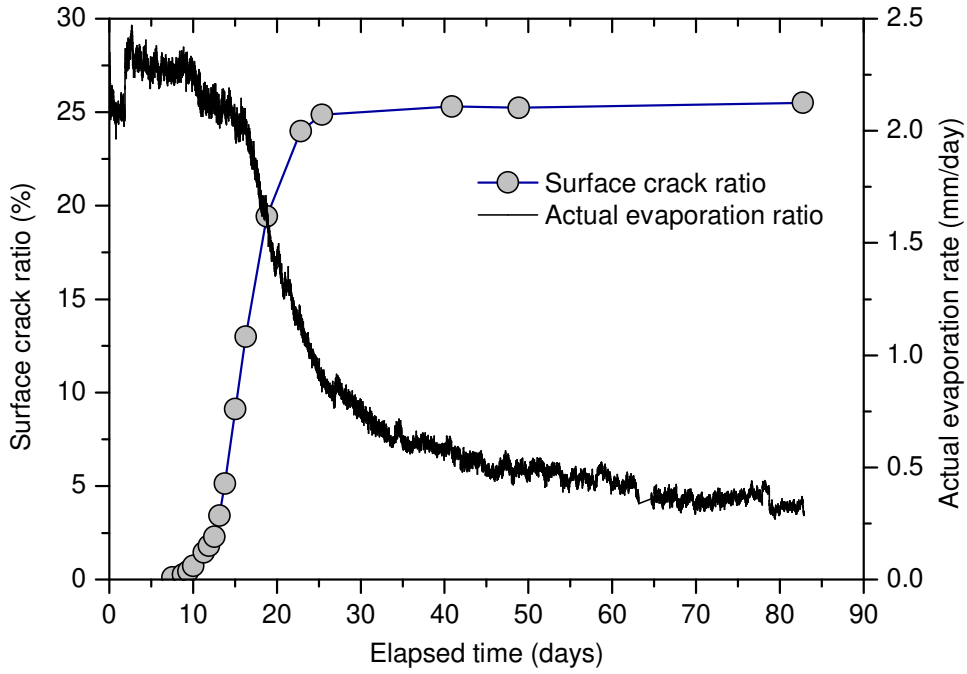


(a)

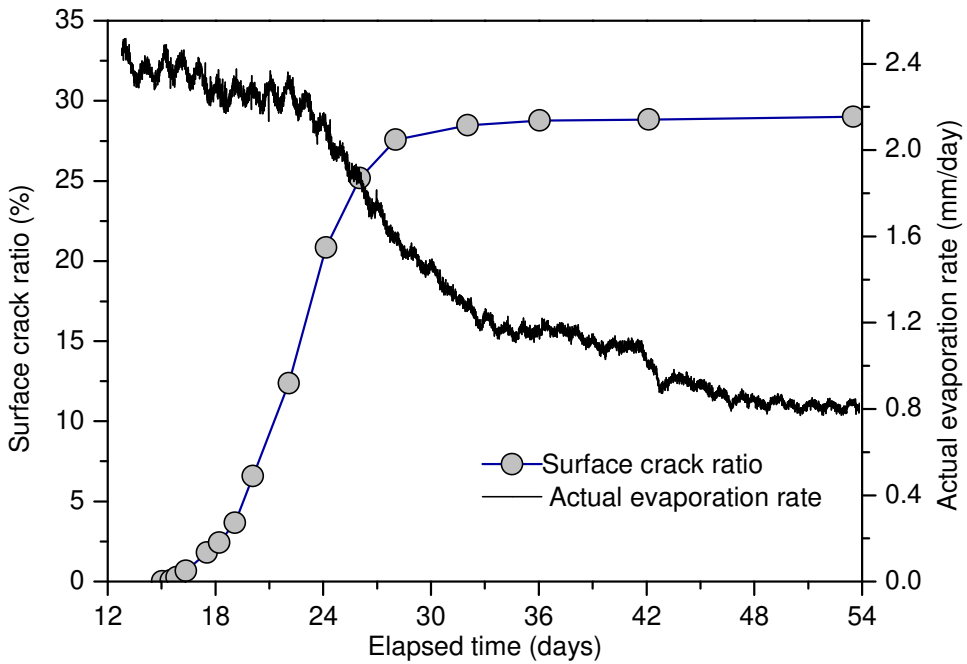


(b)

644 **Fig. 6.** Evolutions of actual and potential evaporation rates: (a) Test 1, (b) Test 2.



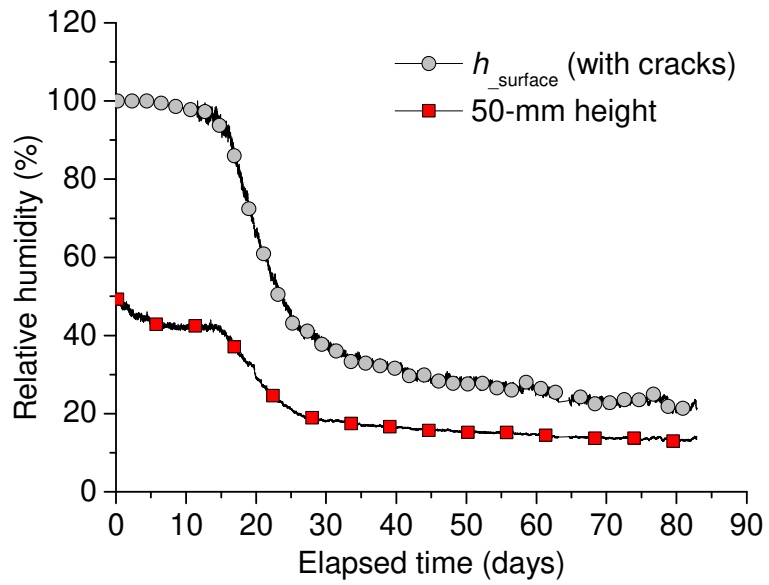
(a)



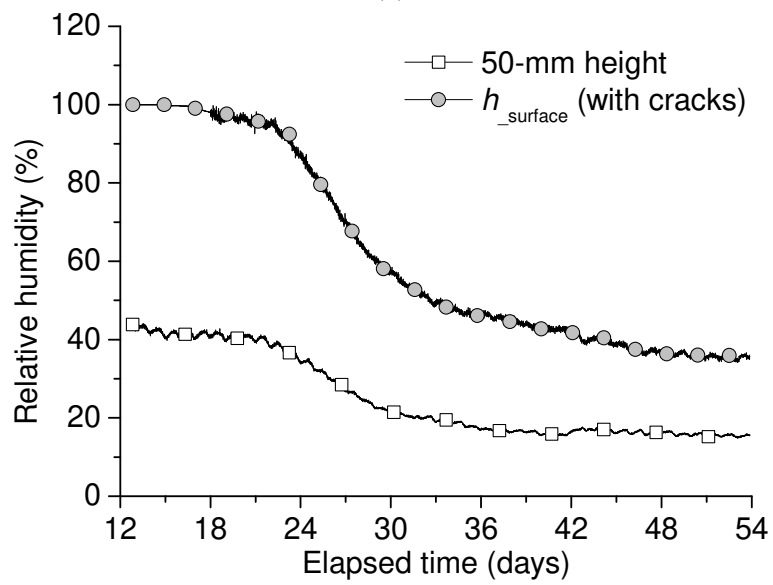
(b)

646 **Fig. 7.** Evolutions of actual evaporation rate and surface crack ratio: (a) Test 1, (b)

647 Test 2.



(a)

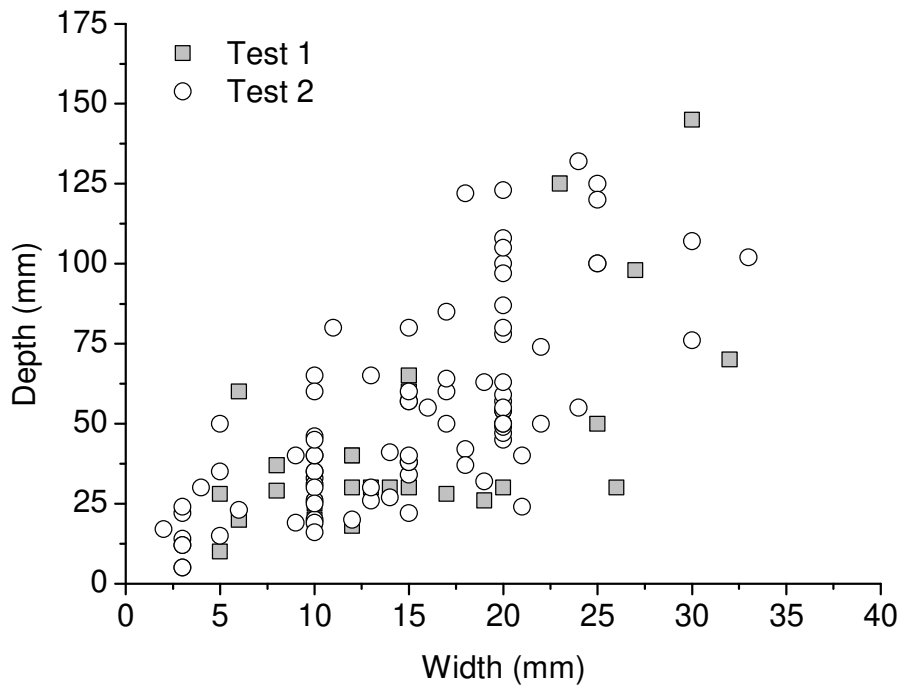


(b)

648 **Fig. 8.** Predicted relative humidity at soil surface and the measured one at 50-mm

649 height: (a) Test 1, (b) Test 2.

650

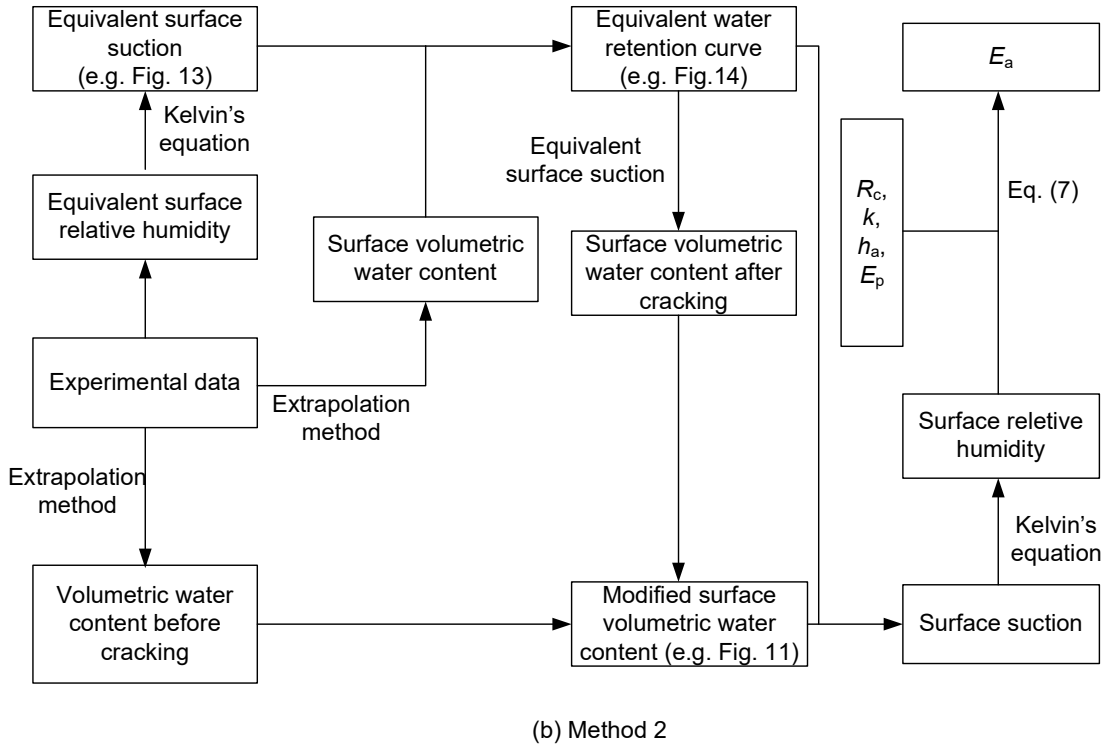
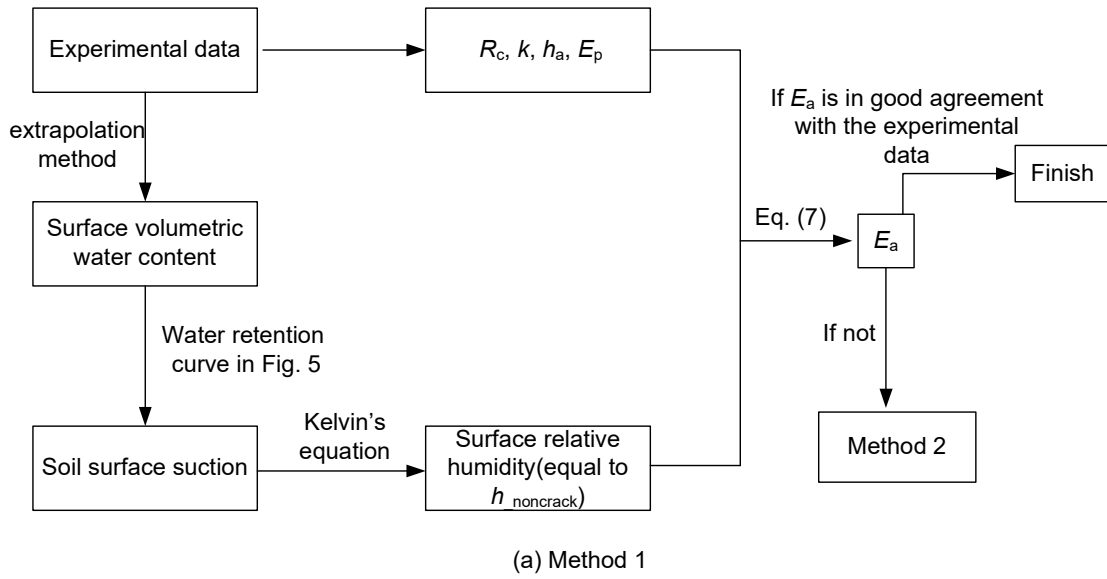


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652 **Fig. 9.** Depth versus width of crack.

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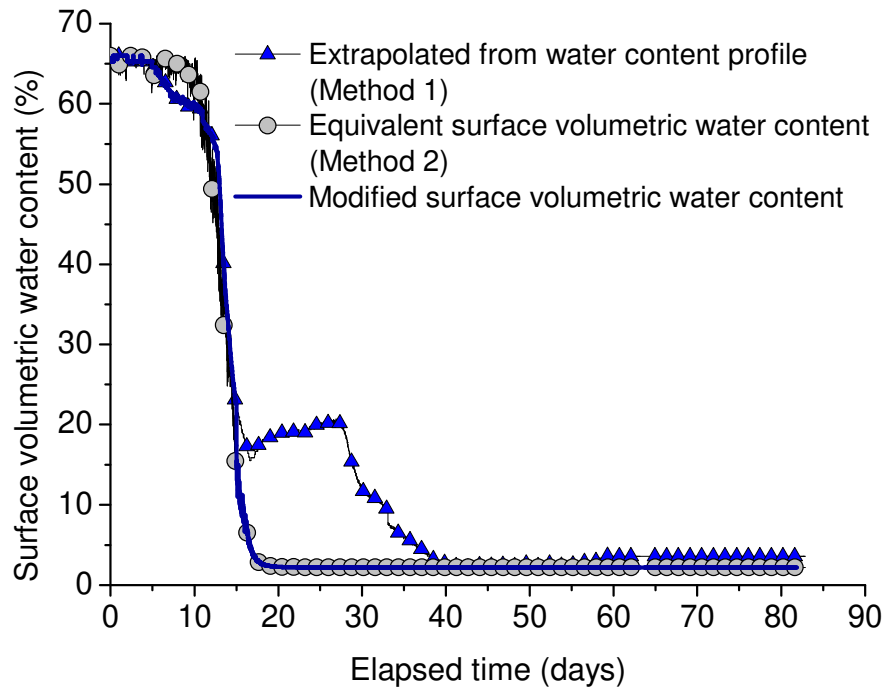
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656 **Fig. 10.** The diagram of the two methods: (a) Method 1 and (b) Method 2.

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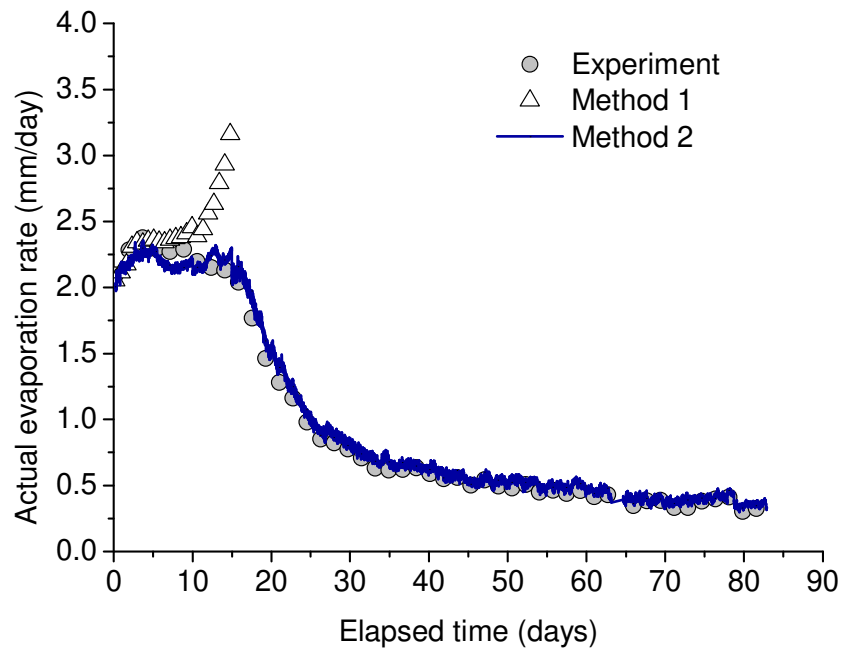
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659 **Fig. 11.** Surface volumetric water contents determined using Methods 1 and 2 in Test

660 1.

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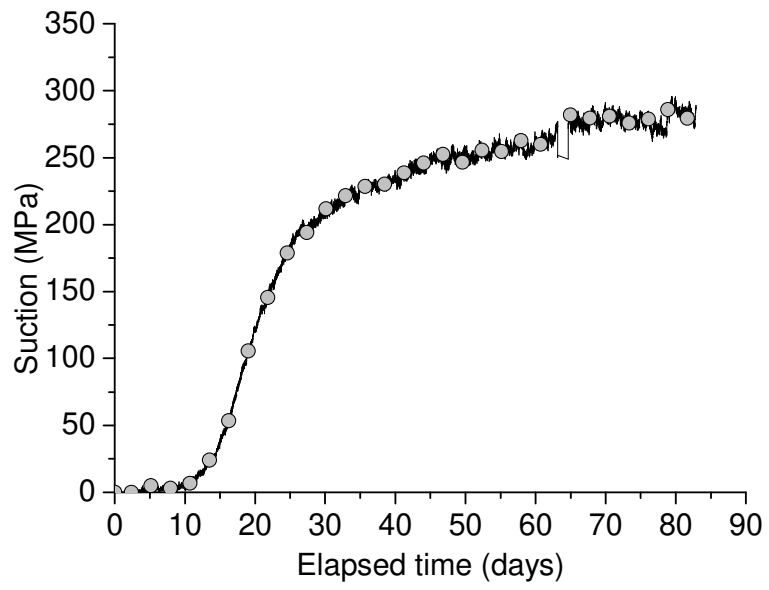


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664 **Fig. 12.** Prediction of actual evaporation rate by Methods 1 and 2 (Test 1).

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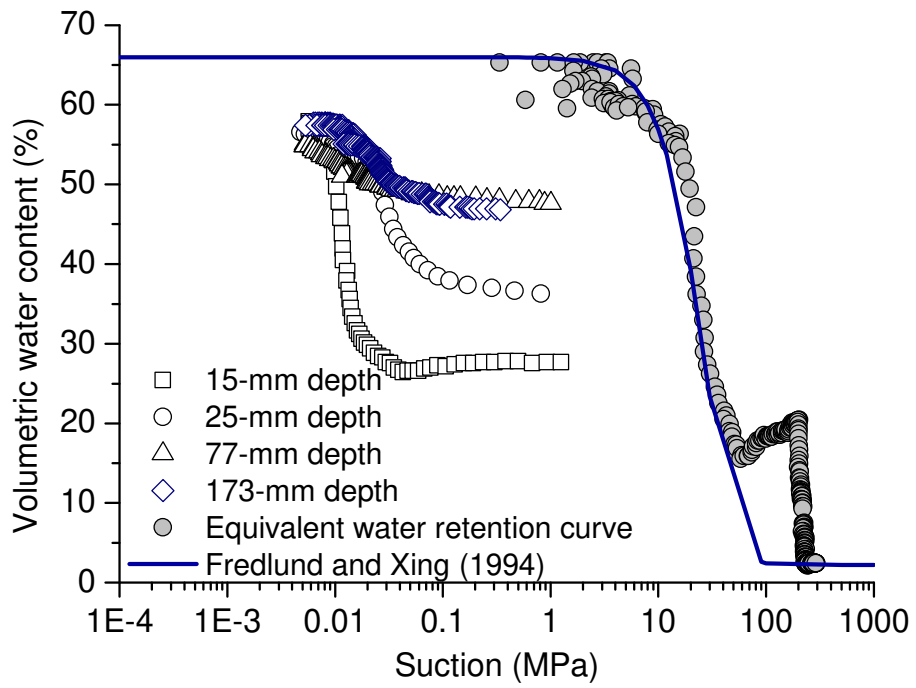
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668 **Fig. 13.** Equivalent surface suction in Test 1.

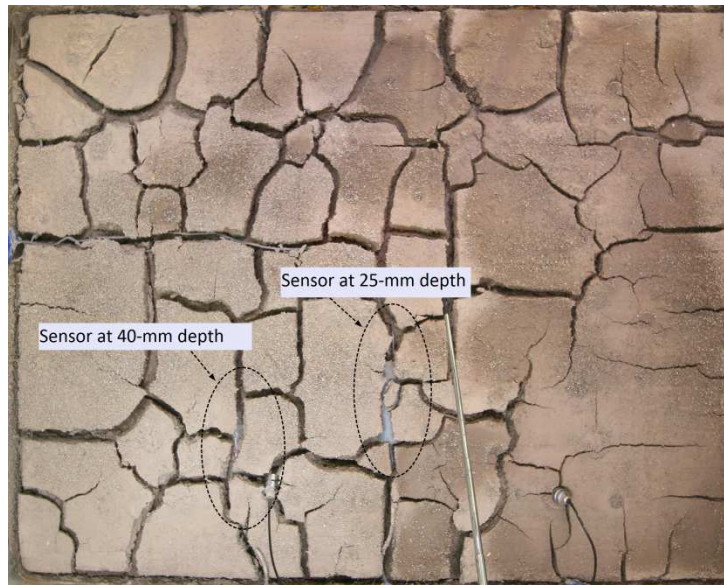
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671 **Fig. 14.** Equivalent surface water content retention curve in Test 1.

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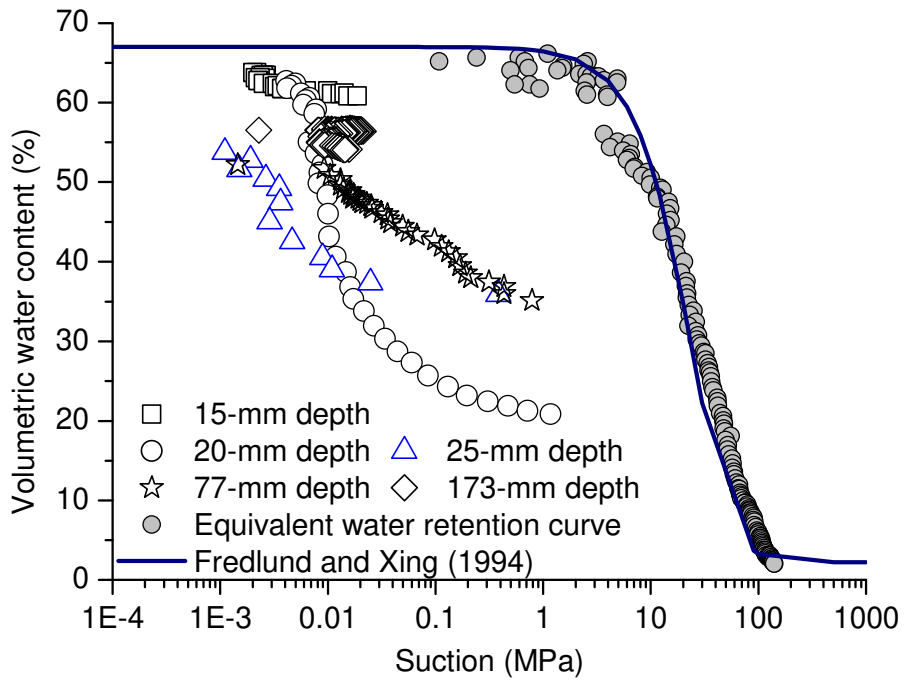


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674 **Fig. 15.** Typical desiccation cracks during Test 1 ($t = 19$ days).

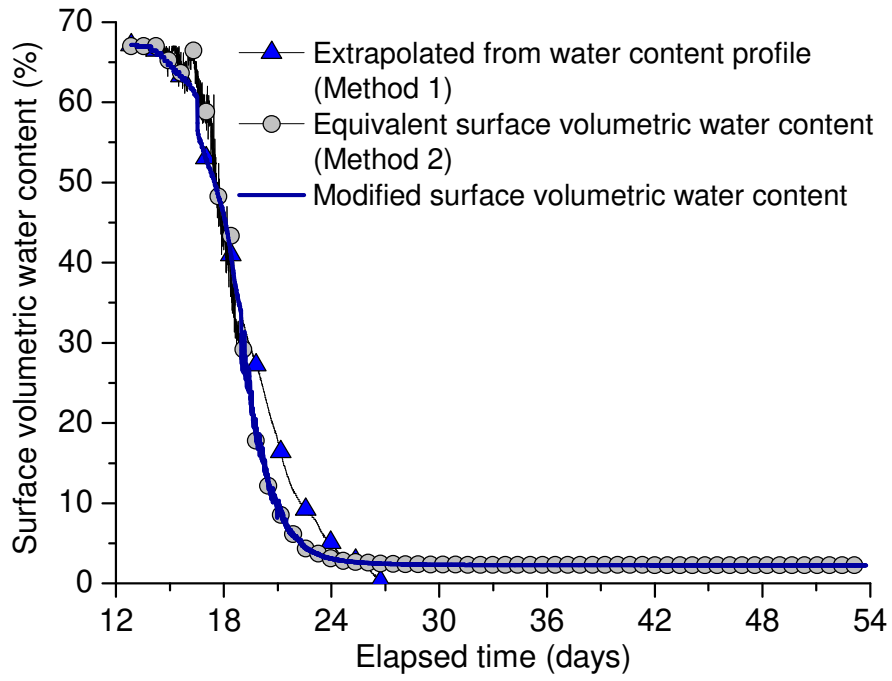
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678 **Fig. 16.** Equivalent surface water content retention curve in Test 2.

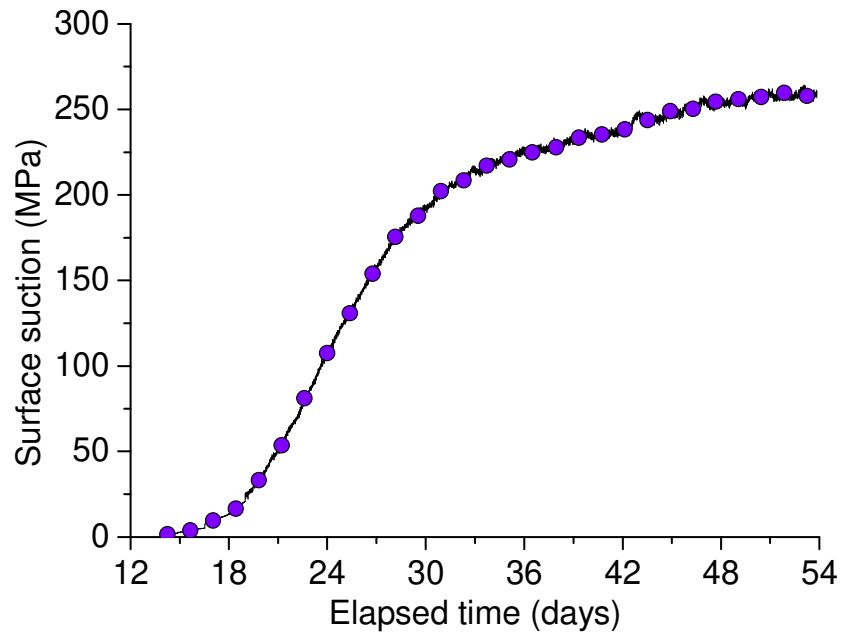


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680 **Fig. 17.** Surface volumetric water contents determined using Methods 1 and 2 in Test

681 2.

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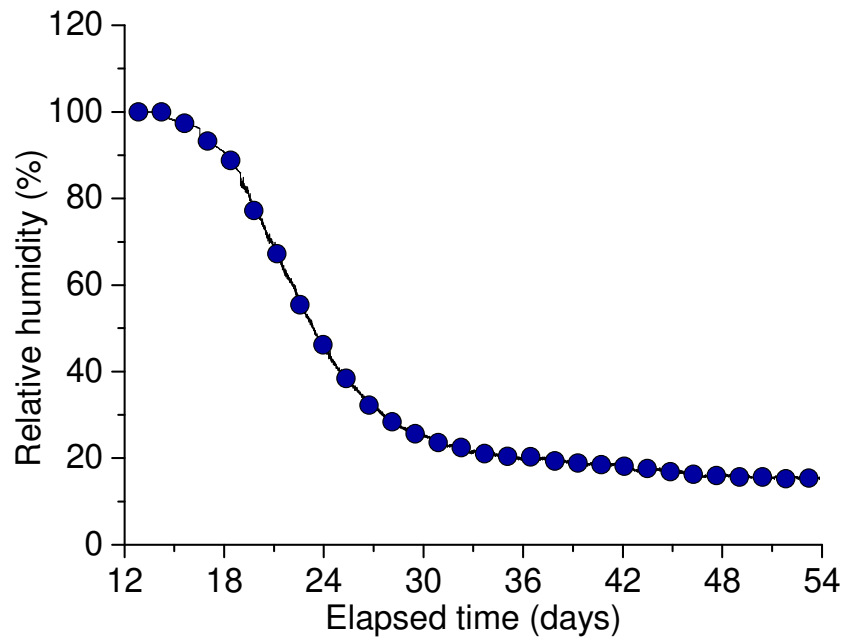
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684 **Fig. 18.** Surface suction in Test 2.

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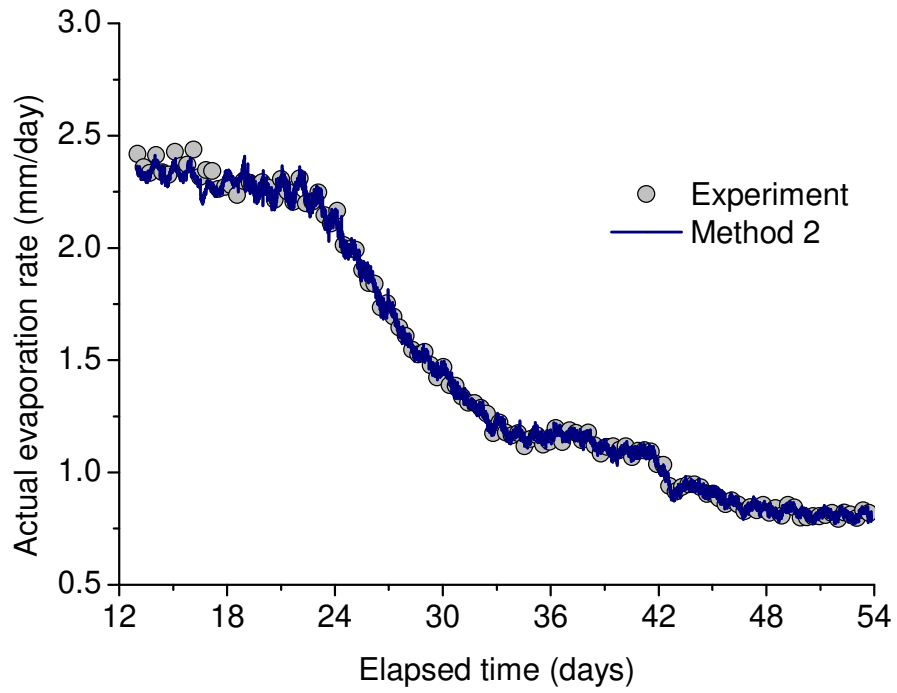


688

689 **Fig. 19.** Surface relative humidity in Test 2.

690

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692

693 **Fig. 20.** Comparison between the measured and predicted actual evaporation rates.

694

695