Multi-scale investigation of fracture apertures in clay rock subjected to desiccation

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Abstract
In the laboratory, the desiccation fracture apertures in Tournemire clay rock were investigated at different scales (millimetre and centimetre) and compared to the variations of the average water content and mean strains of the sample. The induced hydric strains and desiccation fractures were monitored by digital image correlation (H-DIC). At the centimetre scale, the results revealed the fracture aperture kinematics were separated into a first phase of opening and closure, and a second phase of only gradual closure. Closure of the cracks was only observed at the millimetre scale, revealing that the kinematics of cracks depend on the scale observed. The interpretation of the entire dataset emphasizes the need for a multi-scale approach to understand and model desiccation cracking mechanisms and their associated hydric strains in clay rocks.

Introduction
Clay rocks have been considered as potential repositories for high-level radioactive wastes at great depth in several countries, because of their mechanical and microstructural properties. Nevertheless, a significant cracking due to a desaturation process of the argillaceous medium is observed on the gallery walls in several underground research laboratories, such as the experimental platform of Tournemire in France [1,2]. This desiccation cracking takes part in the so called excavation damaged zone (EDZ). The initiation and extension of the EDZ are governed by a range of parameters including the material anisotropy, the initial stress field, the geometry of the gallery and the mineralogy [3,4]. In the Underground Laboratory at Tournemire, the desiccation cracking at the decimetre scale is organised in a network of sub-horizontal cracks separated by 64-100mm and lying parallel to the bedding planes [1,5,6], and a vertical network which shows more complex orientations. The mean crack aperture of these cracks is correlated with the relative humidity in the gallery [5,7]. At a much lower scale, some desiccation fractures with apertures of 1 µm were observed under ESEM on Callovo-Oxfordian clays rocks from Bure laboratory (France) [8,9]. However, these observations were obtained at very different spatial scales, and the phenomenological links or causal relationships between the two scales of fracture network are unclear. Consequently, the main objective of this laboratory investigation was to provide new correlations between hydric strains, desiccation crack apertures and state variables (relative humidity (RH) and water content) at the millimeter and centimeter scales, which are rarely compared in the context of clay rocks. The methodology is based on the combination of a new experimental setup and a new DIC algorithm H-DIC [6] in order to allow the measurement of the kinematic field and patterns for the two considered scales to improve the identification of the micromechanisms governing desiccation cracking [10,11].

Material and Methods
A 20x20x20mm3 cube of Tournemire clay rock (Aveyron, France) was used as the sample in this study. The sample was extracted from the FD90 drill core in the East 96 gallery, at a depth of 4.20-4.40 meters, where the rock is considered to be saturated and outside of the EDZ. The clay rock has a mineralogical composition of 20-50wt% clay minerals, 10-20wt% quartz, 10-30wt% carbonates and 2-7wt% sulphides [1].

The experimental setup is composed of an impermeable cell in which humidity and temperature are controlled by saline solutions and an air-conditioning unit at 22°C, respectively. Two cameras image a small zone of 5.5x4.1 mm on one face of the sample every two minutes at the millimetre scale (images of 2560x1980 pixels with a resolution of 2.2 µm²/pixel1), and a large zone of 20x20 mm on another face (images of 2560x1980 pixels with a resolution of 10 µm/pixel1). The bedding planes are perpendicular to the camera planes. The sample was placed on Teflon© slices on a precision balance to obtain its average water
content $<\Delta W>$. The DIC software (X-Correl [6]) was used to calculate the mean plane strain $\varepsilon_m$ (as a qualitative indicator of the volume) and fracture apertures [14,15] on these zones during a fast desiccation from 98 to 33% relative humidity (over 10 days), in free deformation conditions.

Results and Discussion

During desiccation, different types of fractures were defined as a function of the scale, their orientation relative to the sample bedding planes and their continuity in the zones at the beginning of the test (Table 1).

Table 1: Definition of the different types of desiccation fractures.

<table>
<thead>
<tr>
<th>Type of fracture</th>
<th>Number of fractures analyzed</th>
<th>Zone</th>
<th>Orientation relative to Bedding planes</th>
<th>Continuity</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>2 (I-1 and I-2)</td>
<td>Large zone (centimetre scale)</td>
<td>parallel</td>
<td>Crossing the large zone</td>
</tr>
<tr>
<td>II</td>
<td>3 (II-1, II-2 and I-3)</td>
<td>Large zone (centimetre scale)</td>
<td>perpendicular</td>
<td>Not crossing the large zone</td>
</tr>
<tr>
<td>III</td>
<td>1 (III-1)</td>
<td>Small zone (millimetre scale)</td>
<td>parallel</td>
<td>Connected to types I and II</td>
</tr>
<tr>
<td>IV</td>
<td>3 (IV-1, IV-2 and IV-3)</td>
<td>Small zone (millimetre scale)</td>
<td>parallel</td>
<td>Crossing the small zone</td>
</tr>
</tbody>
</table>

Figure 1 shows the crack aperture as a function of compared to the average water content and the mean strain of the sample during the desiccation process (Figure 1).

![Figure 1: Variation of the fracture apertures as a function of a) $<\Delta W>$ on the large zone, b) $<\Delta W>$ on the small zone, c) $\varepsilon_m$ on the large zone and d) $\varepsilon_m$ on the small zone, during desiccation and for different types of fractures [10,11].](image)

The desiccation of the sample is divided in two important steps (Figure 1). At the centimetre scale, Step 1 is characterised by the simultaneous opening of types I and III and the closure of type II, whereas all fractures are closing at the millimetre scale (type IV). The loss of water content is very low (3.16 to 3.00%), as is the mean strain reduction (2.1 to 1.8%). This step was interpreted as a desiccation only on the surface of the sample. The fracture opening and closure cause opposing deformation from the shrinkage of the solid matrix, leading to the low reduction of the mean strain [10,11].
At both scales, Step 2 is characterised by an important closure of all cracks, with large reduction in water content and mean strain. This step is interpreted as desiccation deep inside the sample, causing a global shrinkage.

**Conclusion**

During a fast desiccation process from 98 to 33% relative humidity, the apertures of different types of fractures were quantitatively compared to the average water content and the mean plane strain of a Tournemire clay rock sample. In free conditions of deformation, the results highlight two important steps of desiccation: a first step of simultaneous opening and closure of cracks, and a second step with closure of all fractures. These two steps correspond to the progression of the desiccation from the surface to the centre of the sample. These results were compared to other scales and desiccation processes [10,11], and the microstructure of the sample was mapped over the entire small zone allowing quantitative comparison between the local strains and the proportion of rigid inclusions and clay matrix [11].

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**References and Citations**