Real-time evolution of water permeability in cracking concrete

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ABSTRACT: The aim of this paper is to present a study on the relationship between crack geometrical properties (width and area) and water permeability evolution in a cracking saturated concrete sample. The tensile splitting (Brazilian) test is enhanced and adapted so that the monitoring of a single crack opening of the specimen and the water-flux through the crack is possible. The complete description of the crack geometry is firstly obtained. The crack opening displacement (CODm) at mid-height of the sample is derived from LVDTs measurements while the crack path on the whole height is obtained by means of the digital imaging correlation (DIC) technique. For both sides of the sample the complete description of the displacement field is obtained. The COD all along the path of the crack is then computed and a statistical relationship between the computed mean crack area and measured CODm is developed. This relationship is used, during the second series of tests, to relate at each time step of the test the mass flux of water through the cracked samples (under loading) and the mean crack area through the measured CODm. Finally, some considerations about the feasibility of a test for the real-time monitoring of permeability in cracking concrete are presented.

1 INTRODUCTION

Concrete durability is strongly affected by flow of fluids, gas and pollutants (Dal Pont et al (2007)). Presence of cracks weakens the resistance of the porous matrix of concrete and constitutes preferential flow path for aggressive components. A proper numerical modelling of concrete subjected to severe loading conditions requires the definition of experimental constitutive laws relating the classical durability indicators to the crack geometry.

A typical sequence of operations, in order to find the relationship between cracks and transfer properties, consists in a first step where cracks are produced, a second step of geometrical description of the cracks and a third step leading to the characterization of transfer properties (resistivity, fluid permeability or ionic diffusivity) on residual cracks (Wang et al (1997), Aldea et al (1999), Rodriguez et al (2003), Djerbi et al (2008), Ismail et al (2008)).

A different sequence described by Boulay et al (2009a) and by Boulay et al (2009b), allowing the real-time permeability monitoring on a cracking concrete, consists in realizing a permeability test while the specimen is under loading. In that case the control of the mechanical loading (a Brazilian test) is ensured by displacement transducers placed laterally while, for the purposes of the permeability test, two vessels are placed on the faces of the cylindrical sample.

The presence of the equipment for permeability test does not allow the observation of the crack geometry while the transfer test is in progress. Therefore, in such a protocol the geometrical characterization of the crack must be realized during a test series, different from the series dedicated to permeability tests.
Table 1. Mix design.

<table>
<thead>
<tr>
<th>Components</th>
<th>Mass (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement: CEM I 52.5 N PMES CP2 / Lafarge / Le Havre</td>
<td>340</td>
</tr>
<tr>
<td>Water</td>
<td>184.22</td>
</tr>
<tr>
<td>Sand (river)</td>
<td>739.45</td>
</tr>
<tr>
<td>Gravels (river): Bernières 0/4</td>
<td>1072.14</td>
</tr>
</tbody>
</table>

This paper mainly deals with the mechanical protocol that allows the complete description of the crack geometry in relation with the crack opening displacement (CODm) calculated from the lateral measurements. The crack geometry is characterized using a digital imaging correlation (DIC) technique. After this characterization, some qualitative results of a first permeability test are presented.

2 EXPERIMENTAL SETUP

The mix design of the concrete used for this study is given in table 1. Cylindrical samples (Ø 11.3 cm by 22 cm in height) were cast in steel molds to avoid any geometrical defects. After a 3 months curing at room temperature, specimens were cut in 3 slices and grounded to reach a thickness of 5 cm each.

An axial splitting test is used to obtain a single crack centered on the faces of the sample. Such a test is unstable after the peak of load. For this reason, lateral measurements of the length variations of two diameters along two axes are used for the control of the servo-hydraulic testing machine. The distance between the axes is 30 mm and they are situated symmetrically with respect to the median vertical plane of the sample. Each diameter variation measurement is achieved by the mean of two opposite linear variable displacement transducers (LVDTs). This diameter variation is the sum of the two measurements.

In order to take into account the asymmetrical crack opening (Wang et al (1997)) in the post peak, the test is controlled with the mean value of the diameter variations. Tips of LVDTs are not directly in contact with the sample but with glass blades glued on each side (axial displacements of each LVDTs are of the same order of magnitude than orthogonal displacements close to the tip of the transducers). For permeability tests, the same control techniques are used. More details on this experimental setup can be found in (Boulay et al (2009b)).

Figure 1. Test setup for the crack geometrical characterization.
In order to proceed with the DIC analysis, prior to the test, white painting is applied on each sample face followed by the application of a random pattern of black dots. Pictures are taken by means of two cameras fixed in front of the faces of the sample, with optical axis collinear with the axis of the sample.

The successive steps, during the test, were as follows. The docking is manual until a pre-load of about 0.5 kN. The first two pictures are taken by the two cameras. A ramp is started at a rate of $\Delta \theta / \Delta t = 10 \mu m/min$ and pictures are automatically taken every $\Delta \theta = 20 \mu m$. When the mean displacement reaches the maximum value of 300 $\mu m$, the ramp is reversed down to unload the specimen.

Results obtained with 1 of the 9 specimens tested are herein analyzed.

3 RESULTS AND DISCUSSION

3.1 Measurements

3.1.1 Displacement transducers measurements

The diameter variation on each face of the sample is computed as function of the measured displacements in axis of LVDTs, under the hypothesis that plane sections remain plane.

Once this transformation is done, it can be observed (figure 2a) that variations are almost similar before the peak of load, in the elastic zone. Just before the peak, the rear displacement diverges from the front one. It can be assumed that a crack appeared first on the front face. In the post-peak zone, rear and front displacements continue to progress separately indicating an asymmetrical crack opening process. The CODm can be calculated from the last calculated displacement on the faces after having removed the elastic part, deduced from the pre-peak measurements (figure 2b). The curves are similar to the previous one and an asymmetry in crack opening is still present.

3.1.2 Digital Image Correlation results

Pictures taken during the test are compared by pairs. The commercial software ARAMIS® developed by GOM Optical Measuring Techniques is used. For each side of the sample, the software is able to monitor the displacement of similar elementary facets from one picture to the
other. Pictures taken on each face, at the beginning of the test, are considered as the references states for DIC computations. The dimensions of the facets, chosen by the operator, must be large enough in front of the resolution of the camera and small enough in front of the required accuracy of the displacement. For a single time step, two representative horizontal displacement fields are given, for each face of the sample, on figure 3. On this figure, it can be seen the two chronometers used to correlate the recorded data (time, load, displacements) and the pictures.

![Image](image.jpg)

Figure 3. Representative horizontal displacement fields on each face of the sample for a particular time step.

3.2 Results analysis

3.2.1 Comparison of the two techniques

An additional script used as a data post-processing is necessary when the COD has to be calculated from the displacement field given by the software. For the two techniques (LVDT and DIC), the recordings, in term of COD at the mid-height of the sample, are compared for
both the front and the rear faces in figure 4. A good agreement between the results given by the
two techniques can be observed. This is partly due to the fact that the two techniques are
calibrated properly. LVDT’s are regularly calibrated and the DIC technique is calibrated
knowing the initial diameter of the sample. This is due also to the fact that removing the elastic
part of the diameter variations on the faces of the sample is a valid protocol.

Figure 4. Comparison of the evolutions with time of the COD obtained with LVDTs measurements and
the DIC computations at mid-height of each face of the sample.

3.2.2 Crack opening distribution along the path

For the five time steps indicated on the figure 4, drawings of the COD along the crack path are
given by the figure 5. Focusing on only one face of the sample, these drawing clearly indicate
how the crack opening starts from the bottom of the sample and rapidly propagates up to the top
of the sample. COD is always larger at the bottom of the face.

A comparison between the crack patterns computed for both the faces of the sample show how,
despite a qualitative analogy between the evolutions of the two cracking processes, a clear
dissymmetry (in terms of COD) between the faces can be observed.

Figure 5. COD along the crack on the faces of the sample (F = front face; R = rear face;).
3.2.3 Correlation between the COD and the crack surface

Once the COD along the path of the crack is known, the crack surface for each time step of the test can be immediately computed. As shown in figure 6, for such a test, a linear relationship between the crack surface and the crack opening displacement at mid-height of the sample can be observed. For low values of the CODm (pre-peak and peak conditions) the surface of the crack is quite negligible. It grows up in the post-peak period when, as shown in figure 5, the specimen is cracked along its entire height.

![Figure 6. COD at mid-height - surface of the crack for a single sample.](image)

3.3 Preliminary results after a water permeability test

The mass of distilled water in a container upstream of the saturated sample is monitored in real time. The container is suspended at the free end of an aluminum cantilever beam, which acts as a balance equipped with strain-gauges. The hydrostatic pressure is thus upstream of the specimen; while downstream a negative pressure is applied by means of a vacuum pump. The test is carried out in controlled temperature conditions.

The control variable of the test is the average change in diameter. Since the main objective is to correlate the permeability of the sample to the crack opening, the CODm is blocked at regular intervals of 50μm. For each level of CODm, different levels of pressure gradient are imposed for a sufficient time to allow stabilization of the flux through the crack. The velocity of the time variation of the mass upstream is then evaluated. Such a velocity is equal to the flow rate through the crack.

Nine tests were conducted. Only some preliminary results of one test are herein discussed.

In Figure 7 representative curves of the time evolution of the mass of the upstream water and of the CODm are shown.

Let observe, that when the specimen is loaded to have a crack opening displacement smaller than 50 – 100 μm the flow rate through the crack is extremely low, even in presence of strong pressure gradients. Such a CODm represents a threshold level beyond which crack openings accelerate water flow rate in concrete and permeability increases rapidly. The observations of Aldea et al (1999), that reports a threshold level for crack opening of 50 μm, and Wang et al (1997), that found a threshold value of 100 μm, are then confirmed.
CONCLUSIONS

Some preliminary results of a study on the relationship between crack geometrical properties (width and area) and water permeability evolution in a cracking saturated concrete sample has been presented.

The tensile splitting (Brazilian) test has been enhanced and adapted so that the monitoring of a single crack opening of the specimen and the water-flux through the crack is possible.

In order to prepare transfer properties tests on cracked concretes under loading the protocol proposed by Boulay et al. (2009b) has been adopted.

The complete description of the crack geometry has been obtained by means of the digital imaging correlation (DIC) technique. After validation of the DIC technique by comparison with the measurement of the LVDTs, the COD all along the path of the crack has been computed. The area of the crack on both sides of the specimen has been obtained and a linear relationship between measured crack opening and area has been pointed out.

The elaboration of the results of all the 9 tests that have been carried out will allows finding a statistical relationship giving a mean crack area vs. the CODm obtained with LVDTs and the position along the crack path.

Some preliminary results of a second series of tests for the measurement of the real-time evolution of the water permeability through a cracked concrete sample (under loading) have been finally presented. The observation of Aldea et al. (1999) and Wang et al. (1997), about the existence of a threshold level for crack opening, has been confirmed.

Additional qualitative information may be obtained by post-processing the results of all tests of permeability. The aforementioned statistical relationship CODm vs. Area, obtained by means of the DIC, will be used in order to determine a real-time evolution law of the permeability of a cracked concrete under loading.

REFERENCES


