Fracture Mechanics of Concrete and Concrete Structures -
Assessment, Durability, Monitoring and Retrofitting of Concrete Structures- B. H. Oh, et al. (eds)

Real time monitoring of concrete resistivity in cracking concrete

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ABSTRACT: Cracks are almost inevitable in a heterogeneous material such as concrete. However their presence weakens the porous matrix resistance and constitutes a preferential flow path for fluid, gas and pollutants: material durability is therefore seriously affected. This paper deals with the feasibility of transfer properties measurement tests during the post-peak cracking phase of concrete. A proper description of the evolution of these properties should be monitored in real-time as cracks open in the specimen. In this work, attention is focused on the mechanical test and the geometrical characterization of the cracks by means of a displacement measurement system together with a digital image correlation technique. The mechanical test is then enhanced in order to establish a real-time relation between the evolution of the electrical resistance and the crack width opening in a saturated concrete sample. The experimental results show that the electrical resistance is constant before the peak (when no crack is observed) and decreases only when the peak of load is reached and when a crack is initiated. No threshold value and no phase shift between the crack opening and the resistance evolution have been observed, even in the case of a breathing crack. The evolution of the conductance has then been modeled by taking into account the (simplified) morphology of the crack and assuming a constant value for the electrolyte conductivity. The model and the experimental conductance through a traversing crack have proved to be in good agreement.

1 INTRODUCTION

This paper deals with the feasibility of transfer properties measurement tests during the post-peak cracking phase of concrete. Observations on pre-cracked concrete evidenced a sharp increase of parameters such as chloride diffusivity or gas/water permeability (Saito&Ishimori 1995), (Wang et al. 1995), (Aldea et al. 1999). However, a proper description of the evolution of these properties should be monitored in real-time as cracks open in the specimen. In such a way, parasite effects related to time (e.g. crack healing, external ambient conditions changes, crack breathing,…) or post-treatments (e.g. modifications of the hygrometric conditions of the sample) can be avoided. In this paper, attention is focused firstly on the mechanical test and the geometrical characterization of the cracks by means of a displacement measurement system. Usually, mechanical tests used to explore the post-peak phase lead to distributed multiple crack patterns or to single well-defined crack. The former geometry is obviously more difficult to characterize than the latter. Given our objective, tests leading to a unique crack were chosen. Direct tensile test, bending test or Brazilian test are good candidates but, for the sake of simplicity and with the aim of performing original real time transfer properties measurements during the loading, the Brazilian splitting test has been retained and enhanced. Moreover such a test leads to strong stress gradients though ensuring a less tortuous visible crack. For the purpose of the feasibility test, the crack width has been limited to 0.1 mm. This threshold has been chosen to avoid multiple cracks generally observed when the opening of the crack becomes important. Moreover, a 100μm width is sufficient for evaluating the existence of an eventual threshold effect and is comparable to the crack widths suggested when dealing with leakage problems in nuclear vessels or containment structures.

In the second part of the paper, a set-up measuring electrical resistance / conductivity of the cracked specimen will be presented. Electrical resistivity is usually considered as an indicator of concrete pore connectivity and is commonly enumerated among the tools used for evaluating the performance of a

structure in terms of service life (Djerbi et al. 2008). Moreover, a relation exists between resistivity and chloride diffusion. In this paper, a macroscopic-measurable quantity such as the electrical resistance of the system concrete specimen-ionic solution has been monitored in

real time during concrete cracking. The experimental results showed that the electrical resistance is constant before the peak (when no crack is observed) and rapidly decreases only when the peak of load is reached and when a crack is initiated.

2 MECHANICAL TEST

2.1 *The mechanical set-up*

Cylinders with 100 cm^2 in cross section and 22cm in height were cast in steel molds for the sake of a good geometry, i.e. common non-steel moulds can lead to misshapen generatrixes. They were removed from the steel moulds at 24 h and cured rapped in a self-adhesive aluminium tape and aged of more than three months at the time of the tests. Each cylinder was sliced in discs (fig.1 ref.4) and each face was grounded to reach a thickness of 5cm (three samples can be drawn from one cylinder). Splitting tests were performed on a ±500kN hydraulic press equipped with a feedback control and a ball-socket joint (fig.1 ref.2-9). Displacements are measured on each side of the horizontal diameter. Cracks generally open on one face and then propagate towards the other face. Hence, two pairs of LVDTs (stroke = ±1mm) (fig.1 ref.5) were maintained by a rigid frame (sustained by the lower plate of the press) (fig.1 ref.6), in order to measure the variations of two diameters. The tips of the LVDTs are not directly in contact with the sample lateral surface but lie on glass blades (fig.1 ref. 7).The frame geometry can be influenced by temperature variations during the test so thermal displacements can affect the measurements. For this reason, the temperature of the frame is measured with a platinum probe. The thermal coefficient of the frame is 0.00317mm/K. Load distribution into the sample is usually obtained using plywood or cardboard, nevertheless we observed that in such a case displacements were strongly not symmetric, even in the pre-peak (elastic) zone. The use of adhesive tape stripes replacing the plywood led to more symmetrical cracks.

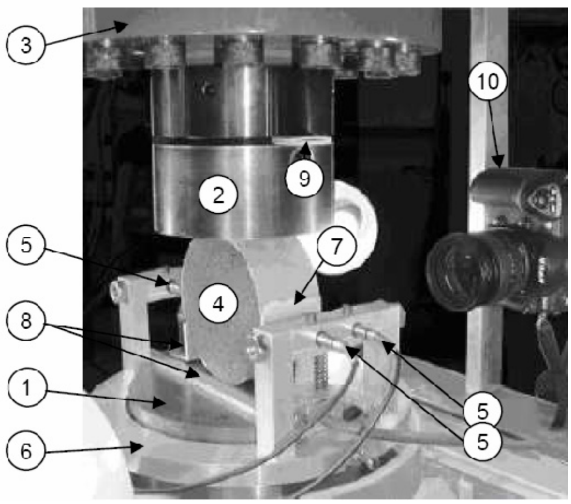

Figure 1. Mechanical set-up.

2.2 *Crack opening displacements measurements*

The Crack Opening Displacement (COD) is calculated from the measured displacements in two steps. In the first step, the diameter variations on each face of the sample are calculated from the diameter variations in the axis of LVDTs. For this purpose, it is supposed that plane sections remain plane. This calculation emphasizes the discrepancy between the rear and the front face after the peak. The second step consists in removing the elastic part of these variations provided that, after the peak, the sample is split into two elastic blocks without damaged zones on the lips of the crack. The elastic part is obtained via the pre-peak behavior.

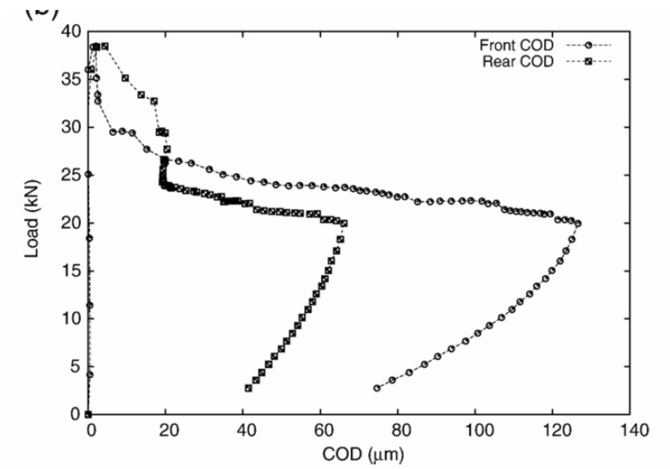

Figure 2. Load vs front and rear COD.

In Figure 2 a typical result is presented. One can observe that while the front COD increases just after the peak, the rear COD is nearly blocked. At about 19 μm for the front COD, the crack stops and snaps back while the rear COD starts to increase. This scenario, also observed on other samples, illustrates that this asymmetrical cracking process is not an exception but the rule and is related to the heterogeneous nature of the concrete. The crack propagates from one side to the other in the first few micrometers of COD. During the further crack opening, frictions through the crack (between aggregates and matrix) are involved in the opening mechanisms. These frictions are attributed to both autogenous shrinkage of the cement paste restrained by the aggregates and roughness itself of the aggregates. Depending on the place where the more important friction occurs, the movements involved in the crack opening process lead to snaps back on one side or the other. Snaps back occur as long as the lips of the crack are in contact. This mechanism should be taken into account in

numerical modeling, i.e. a full 3D analysis is preferable when dealing with cracking concrete.

3 ELECTRICAL RESISTIVITY

3.1 *The set-up*

The electrical resistance of concrete is the parameter which is actually measured (during the mechanical loading) between electrodes placed on each side of the specimen. In the following we will also refer to resistivity and conductivity (the inverse of resistivity) as these parameters are often used in the literature concerning concrete durability (Andrade 2004).

3.2 *Conditioning of the specimen*

After sawing and grinding, the surfaces of the disc (fig.4, ref 1) are dried and PVC containers (standard sewer pipes) are glued on it with silicon rubber. The titanium platinum-coated electrodes (grids) for voltage measurements are fixed in the containers. When silicon rubber is polymerized, specimens are placed in a vacuum container (1-5kPa) for 4 hours in order to remove the air from pores of concrete (i.e. create vacuum conditions). An insulating paint is applied on the specimen's diametric surface in order to avoid drying during the test.

The container (fig.4, ref 2) is then filled with a ionic solution (NaOH/6.01g/l-KOH/8.94g/l) so as to immerse completely the specimen for 48±2 hours. During this phase, the temperature is maintained at 20°C±0.5° C. Thanks to the two vessels filled with the interstitial solution (fig.4, ref 2-4), the concrete disk soaks in the solution during the whole test.

3.3 *The electrical scheme*

The electrical scheme is presented in Figure 3.

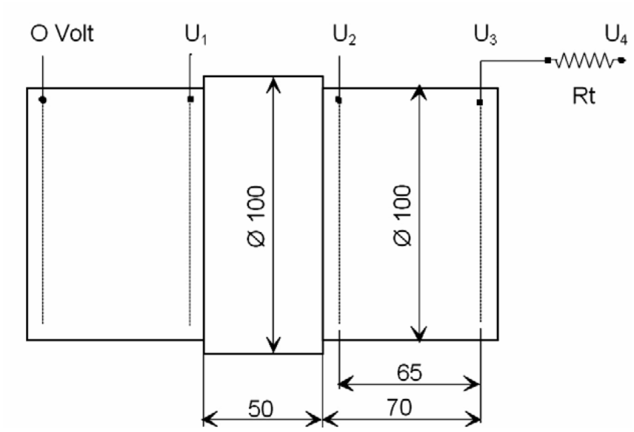

Figure 3. The electrical scheme.

To complete the circuit with the electrodes, a reference resistance R_t =732Ω is added in series in order to determine the applied current i. The resistance of the uncracked specimen has been evaluated at about 450-500 Ω while the initial resistance of the electrolyte solution is negligible (<5 Ω).

3.4 *Global set-up*

After the preconditioning, the specimen is placed on the press and the apparatus installation is finalized according to Figure 4. The sample is centered on the press and electrical connections are done (fig.4, ref 3). Finally, the testing protocol is followed as described in sec.2.

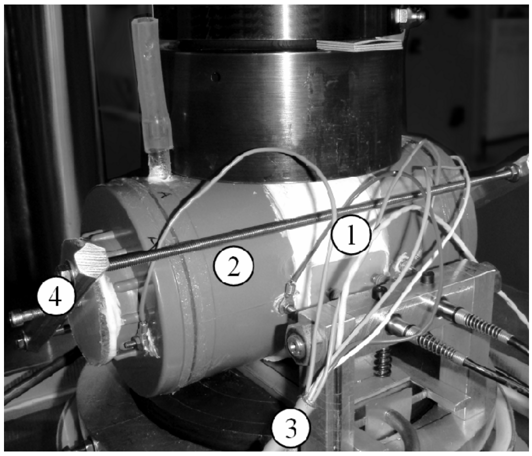

Figure 4. Final set-up.

4 RESULTS AND DISCUSSION

Tests were performed using a DC supply at 5mA. This current value gave a satisfying "signal/noise" and was retained for the purpose of the present analysis. Despite the good results of the 5mA test, a drift of U1 and U2 was observed. This evidence is well-known and is attributed to a polarization of the electrodes in DC measurements which can be avoided by using AC supply. Nevertheless, this drift does not affect the determination of the resistance through the specimen as the drifts of U1 and U2 are similar. However, this drift can affect the determination of the electrolyte resistance in DC measurements. Another apparatus (based on AC measurements) was then used in conjunction with DC measurements, before and after the mechanical test, in order to determine the resistivity of the electrolyte. No variation was found over the period of the mechanical test. All the tests were controlled (see sec.2) with the mean value of the 4 LVDTs but two cycles were added between 0 and 100 μm in order to check the effect of a breathing of the crack on the electrical resistance.

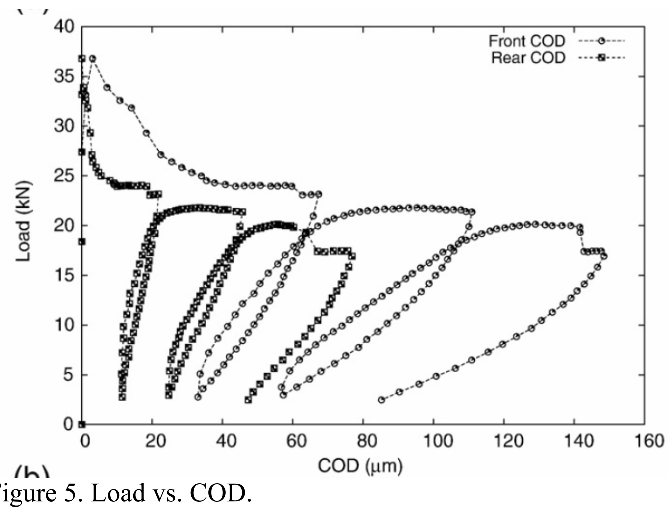

Figure 5. Load vs. COD.

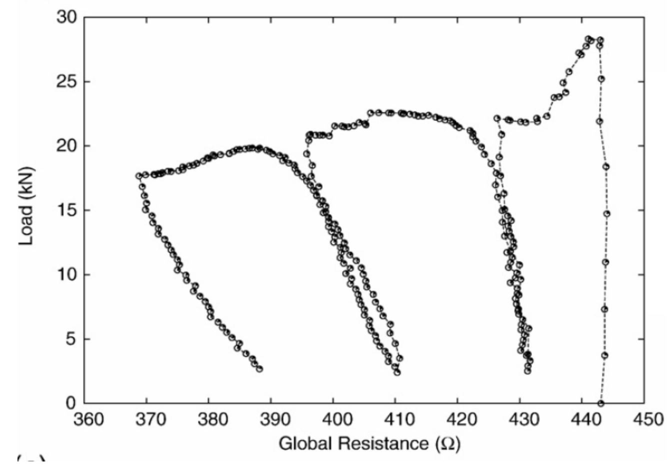

Figure 6. Load vs. global resistance.

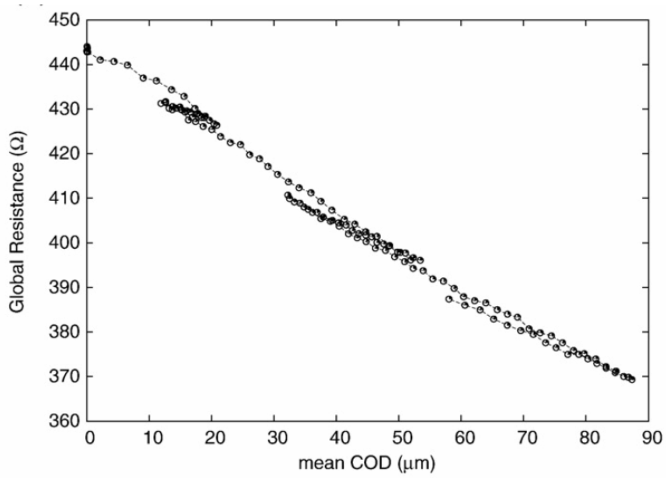

Figure 7.Global resistance vs. mean COD.

Figure 5 shows the evolution of the COD during the loading. The COD starts increasing just after the peak of load. The electrical resistance does not change before the peak of load and starts to decrease as soon as the peak of load is reached. It is supposed that when the crack initiates, the electrolyte fills instantaneously the gap and the resistance through the crack is the resistance of the ionic solution inside the gap. It can be seen on the Figure 6 that the evolution of the overall resistance ((U2-U1)/i) follows a path quite similar to the one followed by the COD without threshold effect. During the cycles, the two parameters evolve similarly without any delay between them (see fig.7), thus confirming the above hypothesis of the ionic solution filling almost instantaneously the crack. The flow of ionic solution, when the crack is initiated, comes from the vessels and its flow rate is estimated at about 0.5mm^3/s.

The overall resistance defined as above (based on electrical measurements) can be considered as a combination of the resistance of the sound sample and the resistance through the crack. One can consider that this combination can be calculated as two electrical resistances in parallel. The resistance of the sound sample is considered equal to the initial resistance (before the peak). This calculation allows to isolate the resistance through the crack and deduce the crack conductance (CCE) determined by electrical measurements.

As a conductance depends on the geometry of the conductor, the crack conductance could possibly be determined with geometrical considerations and assuming a constant value for the conductivity of

the ionic solution through the crack. A simple model (CCM) is then proposed in order to identify the key parameters describing the evolution of the conductance depending on the COD. Firstly, it has been observed that the crack opening mechanism is asymmetrical. The COD measurements via the LVDTs prove to be effective as this measuring system allows to evaluate the crack width on both sides of the specimen. It is important to underline that the visible real crack is tortuous. This crack can be modeled as a succession of parallelograms whose surfaces depend only on the local COD and elementary heights, i.e. despite the tortuosity, the surface of the modeled crack is almost equivalent to the surface of the real one. Microscopic mapping observations have highlighted the fact that the COD is almost constant on the crack height except on the zones close to the crack tips. Given these experimental observations, the global surface has then been modeled via an equivalent rectangular section (neglecting the tips) which area is similar to the area of the real crack, (though the height is smaller than the real one). This height is unknown but can be obtained by fitting. The full crack geometry is then modeled as a truncated prism which allows to take into account all the above considerations.

The electrical resistance, R_c, of the prism is modeled assuming that the sum of the elementary resistances dr_c of slices of thickness dy and area S(y) = h×o(y) where o(y) is a function giving the width:

$$o(y) = \alpha y + \beta$$

where $\alpha = (o_2 - o_1)/b$ and $\beta = o_1$, o_1 and o_2 being respectively the front and rear crack openings.

R_c can be then obtained by integrating

$$dr_c = \rho\, dy / S(y)$$

between 0 and the thickness b:

$$R_c = \rho / (\alpha h) \left[\ln(\alpha b + \beta) - \ln(\beta) \right]$$

The conductance CCM can then be calculated. In this relation α, β and b are known or measured geometrical parameters and the electrolyte resistivity ρ is determined by a measurement of the conductivity of the solution at the beginning and at the end of the test. The value of the conductivity is unchanged during the test thanks to the low current intensity. The height, h, of the prism is fitted by minimizing the difference between CCM and CCE. These values are shown in Figure 8, with a fitted value of h equal to 0.066m. Such a value seems realistic given the sample dimensions and the hypothesis made on the crack shape.

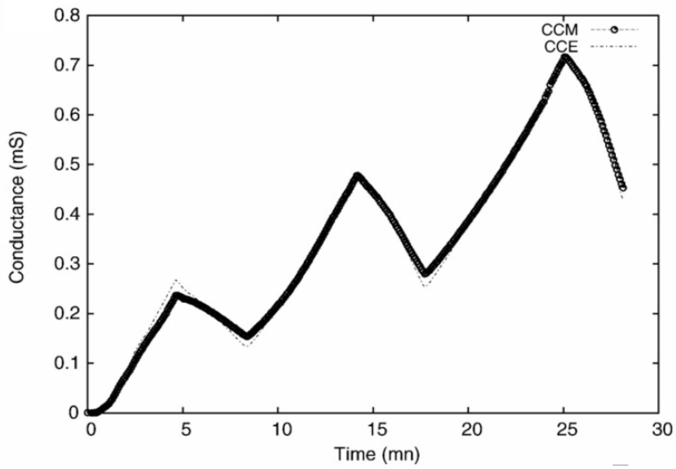

Figure 8. Model and Experimental Conductances vs. time.

This h adjustment is sufficient to show that this simple model is in good agreement with experimental observations. This model is based on the hypothesis of a traversing crack, i.e. the transition when the crack starts from one face and propagates to the other, is not taken into account (Ismail et al. 2008).

5 CONCLUSIONS

In order to perform transfer properties tests on cracked concretes under loading, a displacement controlled splitting test has been designed. This test gives crack openings derived from diameter variations measured via LVDTs at mid height of the cylindrical sample. Electrical measurements were then performed in order to monitor the evolution of the electrical resistance of samples, saturated with a basic solution, before and after the peak of load. These measurements were taken in real-time so that parasite effects can be minimized. It has been observed that the electrical resistance is constant before the peak and decreases just when the peak of load is reached and when a crack is initiated. It means that, as small as it is, the crack is always filled with the ionic solution (through which ions are completely mobiles) for the chosen displacement rate of the test.

A simple model describing the conductance and taking into account the geometrical evolution of the crack is proposed. This model and the electrical determination of the conductance through a traversing

crack are in good agreement so the hypothesis of a constant value for the electrolyte conductivity is verified for a crack width up to 100µm. In this range, the conductance can be considered instantaneously proportional to the mean crack width without any delay between the two parameters (see also (Boulay et al. 2009)).

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