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An innovative experiment for air pressure measurements in crack models representative of real cracks in concrete

J.-L. Tailhan¹[0000-0001-6642-9318], G. Rastello²[0000-0003-2970-6755], J.-C. Renaud¹
and C. Boulay³

¹ MAST-EMGCU, Université Gustave Eiffel. F-77447, Marne-la-Vallée, France

² Université Paris-Saclay, CEA, Service d'études mécaniques et thermiques, 91191,
Gif-sur-Yvette, France

³ Former researcher at MAST, Université Gustave Eiffel.
jean-louis.tailhan@univ-eiffel.fr

Abstract. Assessing fluid leakage rates through cracks in concrete structures is essential in many fields (nuclear safety, fluid storage, durability of structures). In previous works, the authors proposed experimental setups and procedures to study water and air leakage through cracked concrete specimens under Brazilian loading conditions. In the present contribution, the previous setup for air leakage is adapted to measure fluid pressure inside a so-called "realistic" crack representative of an actual crack surface geometry. The specimen is made by precisely casting a concrete crack surface. The procedure allows to realize it in two blocks (upper and lower) separable along this reproduced surface. The lower block is drilled with four thin cylindrical holes opening into the crack and which, once the specimen is installed on the press, are connected to pressure sensors. The specimen is inserted into an airflow circuit, and particular attention is paid to avoiding parasite leaks. Different inlet/outlet pressure conditions combined with different crack openings are imposed. Two different crack surface geometries are tested: plane and realistic. The results show non-linear air pressure distributions inside the realistic crack and non-negligible head losses at the inlet and outlet sections of the flow. Consequently, additional non-linear effects appear in the relationship between mass flow rate and squared pressure gradient due to the geometry of the realistic crack. These results demonstrate that measuring only the pressures in the upstream and downstream reservoirs, as classically done in standard protocols from the literature, can lead to a misinterpretation of the experimental results.

Keywords: Realistic concrete crack, Crack transmissivity, Air flow, Pressure measurement, Head loss.

1 Introduction

Some concrete structures have, among their various functions, that of constituting a sealing barrier against possible leaks of their contents. For fields such as the nuclear

industry, the storage of fluids, and the durability of structures, for which this sealing function is essential, the estimation of leak rates through cracks in concrete structures is a fundamental subject. The abundant literature is also evidence of the significant activity around this subject [1-10].

At the Gustave Eiffel University, there is a history of approximately 10-15 years of investigations and experimental studies carried out on the flows of fluids through localized and "active" cracks (i.e., subjected to stresses related to mechanical loading) in concretes [11-14]. In these studies, specific hydro-mechanical tests have been developed with the following characteristics: (1) control the creation of a single crack within the sample and precisely determine its characteristics (especially in terms of opening); (2) keep this opening constant during fluid flow measurements; (3) impose different flow conditions through this controlled crack.

We started from previous works. In particular, Boulay et al. in 2009 [11], focused on establishing in real time of a relationship between the evolution of the electrical resistance and the opening of a crack in a sample of saturated concrete. Then, Rastiello et al. [12,13], established a statistical link between apparent water permeability and crack opening used as input data for coupled cracking-transfer modeling. This work was carried out for liquid flows, so we have adapted them to gas transfers [14]. All these tests are based on pressure measurements in upstream and downstream vessels sandwiching the cracked specimen (Fig. 1).

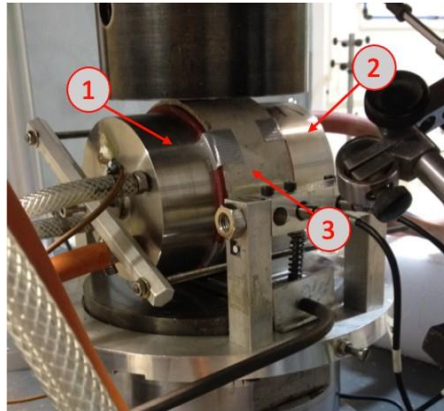


Fig. 1. The initial experimental setup (from [13]).
(1/2) Upstream/downstream vessels, (3) concrete specimen.

These last works, however, showed that the measurements carried out on the gas flows led to a significant variation in the results compared to the theory. Therefore, it was necessary to discern in the results what came from the setup itself and from the peculiarity of the flow in the crack. Tailhan's 2020 study [15] was carried out in a model configuration where the crack is replaced by a thin space between two parallel planes inside which pressures could be measured. Results corroborated the theory. This study showed the importance of measuring the pressures within the flow in the idealized crack because pressure drops at the inlet and the outlet are significant. We decided to adapt

this experiment to the case of a flow in a realistic crack, representative of a real crack in the concrete. The paper presents this adaptation.

2 Materials and methods

2.1 Preliminary remarks

We know that it can be complicated, if not almost impossible, to measure the pressures of a fluid flow in a real crack. Our goal is, however, to get as close to it as possible. So, first, let us define what a crack model can be. A crack model, or a realistic crack, must be a flow space whose geometry comes as close as possible to that of a natural crack. However, this geometry must be mastered. Its overall size (length and width) and its opening (i.e., the distance between its opposite faces, which must remain parallel) are known (i.e., it can be measured). Also, that the crack must be initially closed, and no fluid flow must pass through it. The crack opening must be sudden, and the relative displacement between the two opposite crack surfaces must be (as best as possible) the same everywhere.

2.2 Samples' realization

The manufacturing method chosen is based on a precise molding of one of the surfaces facing a real crack. For this, a half piece of a splitting test specimen (11cm in diameter by 5cm thick) is used (Fig. 2, mark a). We first take an imprint of the natural surface with an RTV silicone specially adapted for precision moldings. The imprint made makes it possible to manufacture the first part of the specimen: the lower block (Fig. 2, mark b). Next, the upper block (Fig. 2, mark c) is made by casting directly on the lower block, which has been greased beforehand to facilitate their separation along the crack surface during the test. A sealing system integrated into the sample (Fig. 2, marks d,e,f) is also provided for in the procedure. Reserves are made during pouring and then injected with a sealant that is both adherent and highly deformable. Finally, before casting the upper block, the lower block is drilled with four holes (Fig. 2, mark g), 2mm in diameter, for pressure measurement. These holes are temporarily protected by the insertion of cylindrical seals of the same diameter, which will be removed later.

Fig. 3 details the realistic crack relief obtained by molding. Note that this image was taken after fully opening a tested specimen.

2.3 Experimental device and procedures

The specimen thus produced is glued between two metallic blocks. Fig. 4 gives the geometric dimensions of this assembly. This latter is then positioned on a hydraulic press.

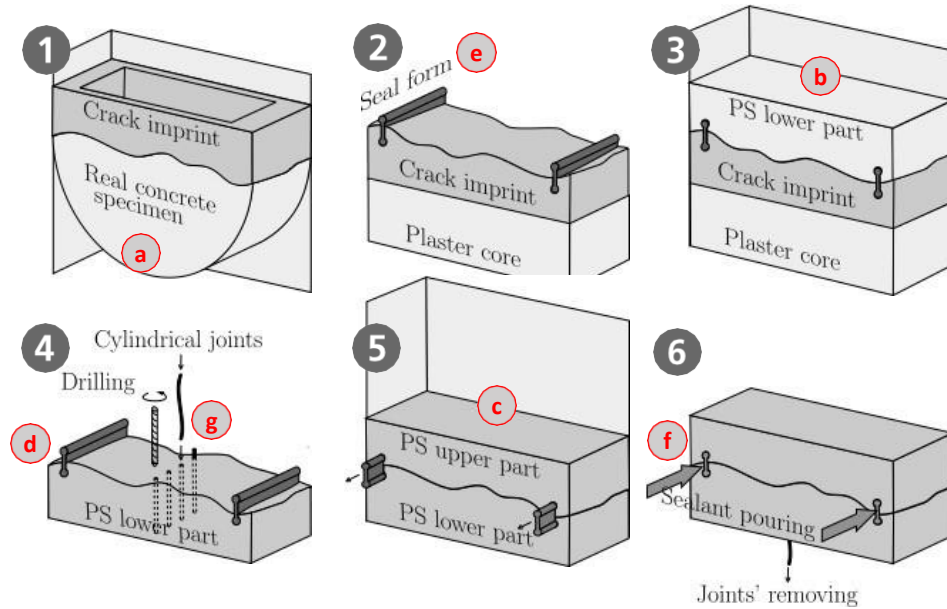


Fig. 2. Step-by-step method for the specimens' realization



Fig. 3 Realistic crack surface relief after complete opening of the specimen.

Therefore, the experimental device (Fig. 5) consists of two chambers, upstream and downstream, sandwiching the specimen. The tightness between the chambers and the specimen is ensured using flat low stiffness annular seals 2 mm thick. A retaining screw system maintains sufficient pressure on the flat seals against the faces of the specimen, guaranteeing a good level of sealing. Four LVDTs allow measuring the relative displacement of the two blocks of the specimen and calculating the crack opening. The (filtered) air pressure is checked upstream and/or downstream by the intermediary of a regulator (upstream) and a vacuum pump (downstream). Two mass flowmeters are used to measure the fluid flow upstream and downstream of the specimen and check for leaks.

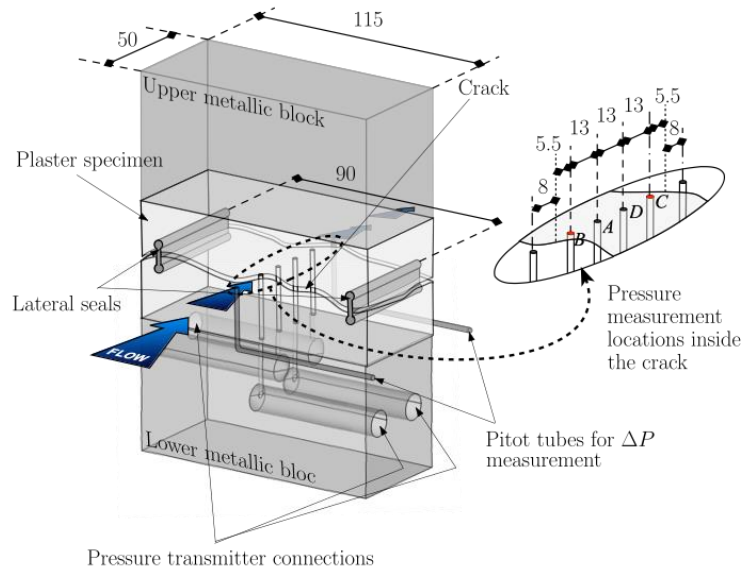


Fig. 4. Assembly of the realistic crack with the two metallic blocks

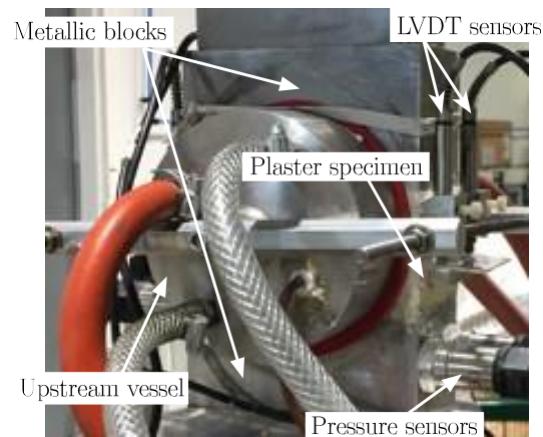


Fig. 5. The experimental setup with the realistic crack specimen.

Fig. 4 also specifies the position of the various pressure taps in the flow. The lower metallic block has holes for measuring pressures, which are positioned facing those of the specimen during bonding. This step is particularly tricky to perform. These holes are connected to the external pressure sensors using dedicated connectors. A differential pressure sensor also measures the difference in pressure between the upstream and downstream vessels.

The experimental procedure implemented is, broadly, as follows:

- First, the specimen is preloaded in compression (-25 kN), and the gas is pressurized (2 bars). It is thus checked that the circuit does not present any parasitic leakage
- Then, after setting the displacement sensors to 0 μm , the press is controlled by the average of the 4 LVDTs (average displacement on both sides of the upper block of the specimen).
- At a fixed increment of displacement kept constant (μm : 12.5, 25, 35, 50, ..., 200), different pressure conditions upstream (P1) or downstream (P2) are imposed (see Table 1a and Table 1b).
- The procedure is repeated up to a limit value of the average displacement.

Table 1. Imposed pressure conditions

Cond n°	P_1 (bars)	P_2 (bars)	P_1/P_2	Cond n°	P_1 (bars)	P_2 (bars)	P_1/P_2
	1	0.83	1.2		1.2	1.0	1.2
	1	0.67	1.5		1.4	1.0	1.4
1	1.2	0.8	1.5	2	1.6	1.0	1.6
	1.2	1.0	1.2		1.8	1.0	1.8
	1.5	1.0	1.5		2.0	1.0	2.0

(a)

(b)

3 Results and discussion

Before moving on to the results, it should be noted that three experimental tests were carried out in this study: one with an idealized flat crack to compare the results with the previous study of 2020 and validate the process for producing the test specimens; and two tests with realistic cracks, using two identical casts of the same natural crack surface.

The first graph, Fig. 6, compares the three tests' upstream and downstream mass flow rates. It can be concluded from this graph that there is no parasitic leakage in the circuit, the two flows being equal. Furthermore, the sealing systems, particularly the side seals inserted into the specimen, work perfectly.

Let us now introduce the results obtained with a plane crack. Fig. 7a shows the mass flow rate as a function of the squared pressure gradient obtained for the different crack openings. The pressures are measured at points B and C in the crack, as shown in Fig. 4. It should be noted here that the crack opening is obtained according to a procedure developed by [15] from the history of the displacement increments imposed during the test. The curves (Fig. 7a) are linear and verify the theory, which, in the hypothesis of an isothermal flow of quasi-incompressible fluid, is reduced to the first term of the second member of Eq. (1):

$$(P_i^2 - P_j^2)/l = 2rT [4fQ / (bw^3) (Q/bw) + 1/l \ln(P_i/P_j) (Q/bw)^2] \quad (1)$$

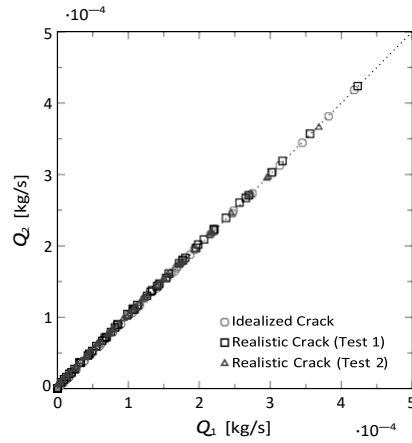


Fig. 6. Upstream (Q_1) and downstream (Q_2) mass flow rates comparison.

A term that must be constant, as shown in Fig. 8, reporting the evolution of the Fanning coefficient (f) as a function of the Reynolds number (Re). Its expression is deduced from the previous relation, Eq. (1). The plateau reached in this graph corresponds to the theoretical value of $Re \cdot f$ equal to 24, a constant term.

These results perfectly corroborate those of [15] and show the feasibility and validity of the test and the proposed experimental procedure.

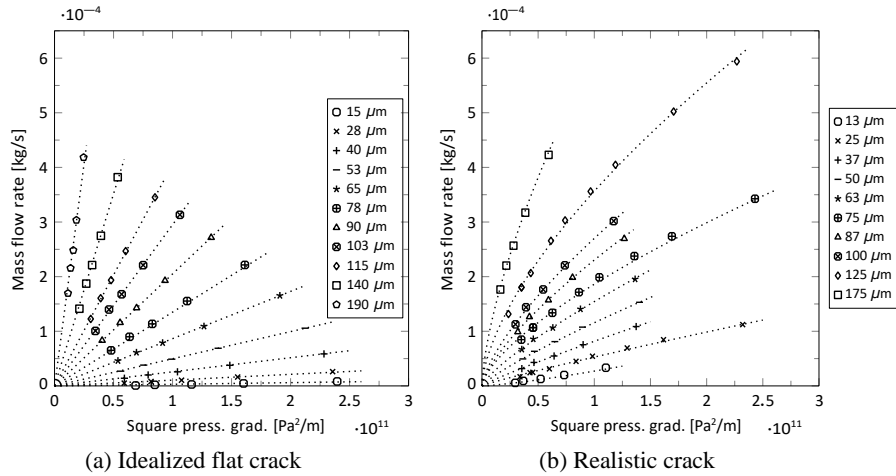


Fig. 7. Mass flow rate vs. square pressure gradient curves.

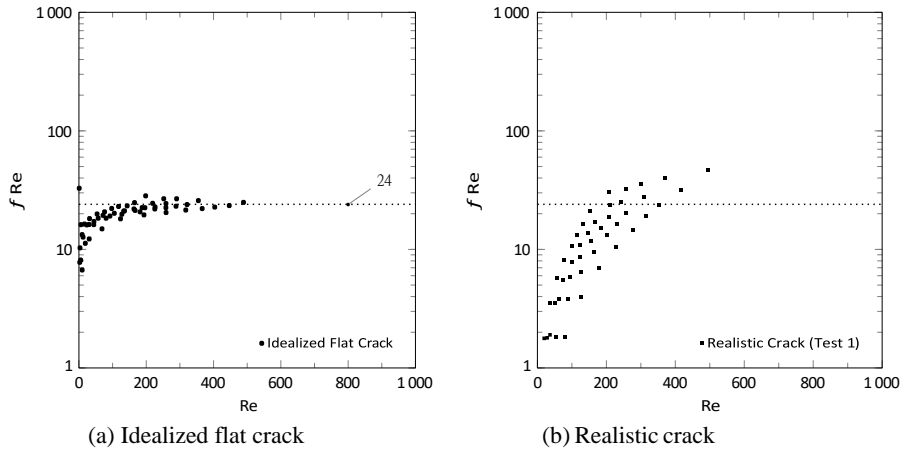
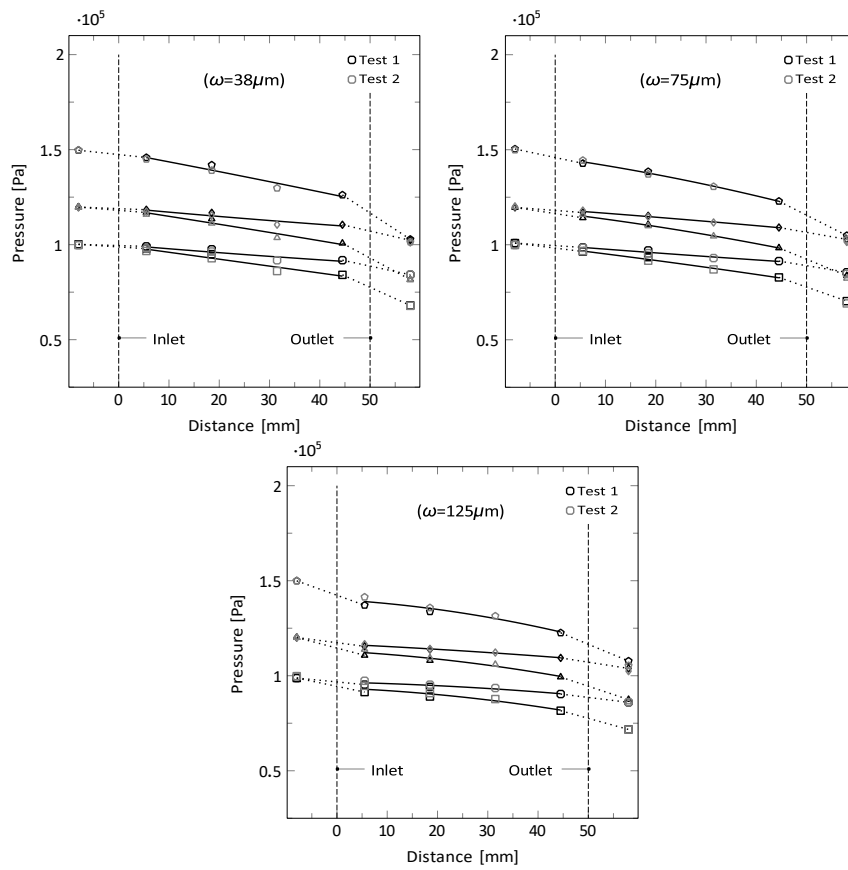
Fig. 8. $f Re$ vs. Re curves.

Fig. 9. Pressure distribution in the realistic crack (for three different openings).

Let us now consider the realistic crack test results. Fig. 9 gives the pressure distributions measured within the flow for three different crack openings. The results of the two tests are grouped on the same graphs. Indeed, the procedure for gluing the specimen to the lower metal block is relatively delicate. It turns out that for each of the two tests, a little glue came to obstruct a measurement point. However, the superposition of the two test results is perfect. One notices on these graphs a light nonlinearity of the pressure profiles for the three crack openings considered. This nonlinearity increases with the crack opening. It can be due to the fluid's compressibility, the crack geometry's effect, or both combined. Nevertheless, this remains sufficiently light to preserve points B and C (Fig. 4) as points of measurement of the macroscopic pressure gradient in the crack.

In the same way as previously, Fig. 7b shows the mass flow rate curves as a function of the squared pressure gradient obtained for the case of the realistic crack. Fig. 8b shows the Fanning coefficient's evolution as a function of the Reynolds number. The comparison of curves between plane crack and realistic crack, Fig. 7a and Fig. 7b, respectively, leads to noticing the strong nonlinearity of the second, all the more marked as the crack opening is large and the flow rate is high. This aspect is related to the perturbed flow geometry in the case of the realistic crack. A more detailed comparison between the two cases also shows that, for small openings and at the same squared pressure gradient, the flow rates are more significant within the realistic crack than in the plane crack. However, for large openings, the trend is reversed.

These trends are also confirmed on the Fanning coefficient curves. The Fanning coefficient of small realistic cracks is lower than those of small plane cracks indicating that the friction in the flow at the level of the walls of the crack is comparatively reduced, and the mass flow is, therefore, more significant there. For plane cracks, it is known that the limiting value of 0.001 for the Knudsen number, at which rarefaction effects and wall slips occur, is reached for openings less than about 50 μm . In the case of the realistic crack, the measurement of the relative displacement of the two separate plaster blocks always overestimates the actual crack opening encountered by the flow. Consequently, the Knudsen number can be very locally underestimated.

4 Conclusions

The study proposed a procedure of faithful reproduction of a real crack geometry and an experimental test of pressure measurement of a flow of gas in the obtained realistic crack. This study makes it possible to highlight the effect of an irregular geometry on the characteristics of a flow and on the relation mass flow/squared pressure gradient, the latter being strongly nonlinear in the case of the realistic crack.

Such a procedure makes it possible to avoid head losses between the inlet and the outlet of the crack. Indeed, [15] has demonstrated that the only measurement of pressures in upstream and downstream boxes leads to a poor estimation of the flow pressures in the crack.

However, it remains to clarify the physical phenomena occurring in tiny cracks and better quantify the pressure drops.

Finally, we must also think about going from a still-modeled vision of a realistic crack, as we have presented it, to the reality of a crack in the concrete.

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