SWISSMETRO - AIR PERMEABILITY OF CRACKED CONCRETE PLATES

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Abstract

The object of this paper is the prediction of the air flow through a cracked concrete wall element. Experimental data from permeability tests on large cracked reinforced concrete plates is used. The variation of the flow with the crack opening is investigated. A new empirical expression is developed for the calculation of the friction coefficient for the flow of air through a concrete crack. It is based on the general formulation of a turbulent or laminar flow of a gas between two parallel surfaces. It is a function of the crack width and of the maximum aggregate size of the concrete aggregate.

Background

Several studies have been conducted in the past 30 years to investigate air and water flow through cracked concrete (E.g. [Buss 72] and [Mivellaz 96]). Much of this research work was conducted in North America and Japan on behalf of the nuclear industry. It is clear form the review of the literature that there are still disagreements on the topic of the calculation of the air flow rate through cracked concrete [Fellay and Badoux 2001]. This paper focuses on the use of new experimental data to develop an expression for the friction coefficient for air flow through a crack in a reinforced concrete plate.

The research presented below was conducted in the context of a research program on the Swissmetro transportation system. Swissmetro is an innovative concept for a very high-speed underground passenger Maglev type transportation system. One of its features is that the tunnels are under permanent partial vacuum, thus requiring "air proof" tunnel liners. The first objective of the research project was the experimental investigation of the "air tightness" of reinforced concrete elements.

Experimental program

An experimental testing program in two phases was conducted to compare and quantify the air permeability of reinforced concrete elements which could be used for Swissmetro tunnel liners. The objective of the first phase was to assess the influence of the concrete mix design on the permeability to gas of uncracked concrete samples. The permeability of eighteen concrete mixes was tested for different humidity levels and under different pressure differentials.

The second phase dealt with cracked reinforced concrete plate elements and provided the experimental data used in this paper. The air flow through a single crack in large reinforced concrete plates specimen was measured for various crack width and various pressure differential. Four specimen with different concrete mixes (T1, T2 and T4), including one with steel fibers (T3) were tested. The specimen characteristics and the experimental tests set up are described in a companion paper [Badoux 2002] and in more detail in [Fellay and Badoux 2001].

Experimental measurements of air flow through a concrete crack

A summary of the experimental results of the air infiltration test are shown in Figure 1. It shows the measured air flow as a function of the width *w* of the single through crack which developed in the test area of the specimen middle section. The measured flow increases rapidely with the crack width once a through crack of 0.1 mm has opened. The air flow increases moderately as the pressure differential is increased from 500 to 700 mbar and to 900 mbar (the high pressure side is at about atmospheric pressure).

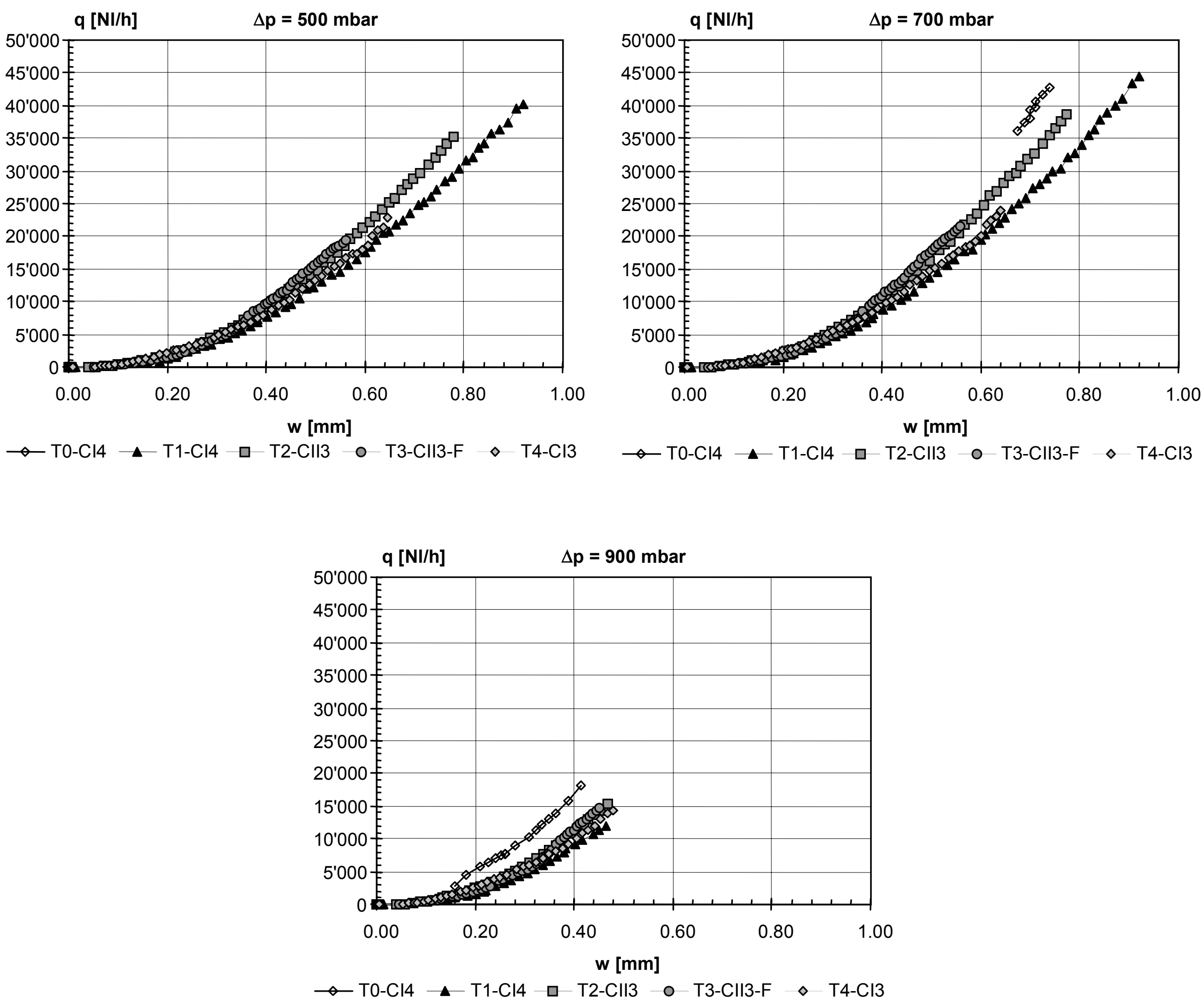

Figure 1 – Measured air flow q through cracks of width w for three pressure differentials Δp

General formulation for air flow through a crack

In the development of a theoretical formulation of the flow rate of gas through a concrete crack, it is assumed that it can be modeled as the rate through a gap between two parallel plates with surface friction. The following equation of the volumetric flow rate for a compressible gas is obtained [Rizkalla and al.; 1984]:

$$(1) \qquad q = \left[\frac{1}{\Lambda} \cdot \frac{2 \cdot (p_1^2 - p_2^2) \cdot B^2 \cdot w^3}{L} \cdot \frac{R \cdot T}{p_2^2} \right]^{1/2}$$

where

q:	flow [m^3/sec]
p_1, p_2:	pressure on both sides of the crack [Pa]
B:	thickness of the cracked element [m]
w:	crack width [m]
R:	gas constant [J/kg/sec]
T:	temperature of the gas [°K]
Λ:	coefficient of friction of the crack [dimensionless]
L:	crack length [m]

This formulation is valid for both laminar and turbulent flow, i.e. independently of the flow velocity. It is based on the following assumptions:

- isothermal air flow ((confirmed by [Greiner and al.; 1995]) and by this project's measurements of the air at the entrance and exit of the crack)
- steady and uniform flow in the gap (confirmed by this project's flow measurements),
- constant friction along the flow path,
- shear stresses expressed as in a duct of constant cross section,
- uniform crack width.

The last assumption is typically violated in concrete elements because of the irregularity of concrete cracks. It must be noted that the effective crack width is not simply the average width of the crack. Errors on the determination of the effective width of the crack for which air flow was measured is the main source of errors in the experimental results.

Determination of the friction coefficient Λ for a concrete crack

The calculation of a flow rate through a crack with expression (1) requires the determination of the friction coefficient Λ. Aside from the determination of the effective crack width, the determination of Λ remains the main issue in predicting air flow through a concrete crack, i.e. the air permeability of a cracked concrete element.

Several authors have developed expressions for Λ in a concrete crack as a function of the crack width w. The literature review in [Fellay and Badoux 2001] include those of [Rizkalla 84], [Suzuki 91], and [Greiner 95]. Figure 1 shows, for the four specimen, the comparison of the measured values of Λ with these formulations. The comparison shows significant discrepancies. There is a general agreement of Greiner for lower crack width (below 0.3 mm), and Suzuki for the wider cracks (above 0.3 mm), but none of the expression matches the experimental data well over the entire range of crack width.

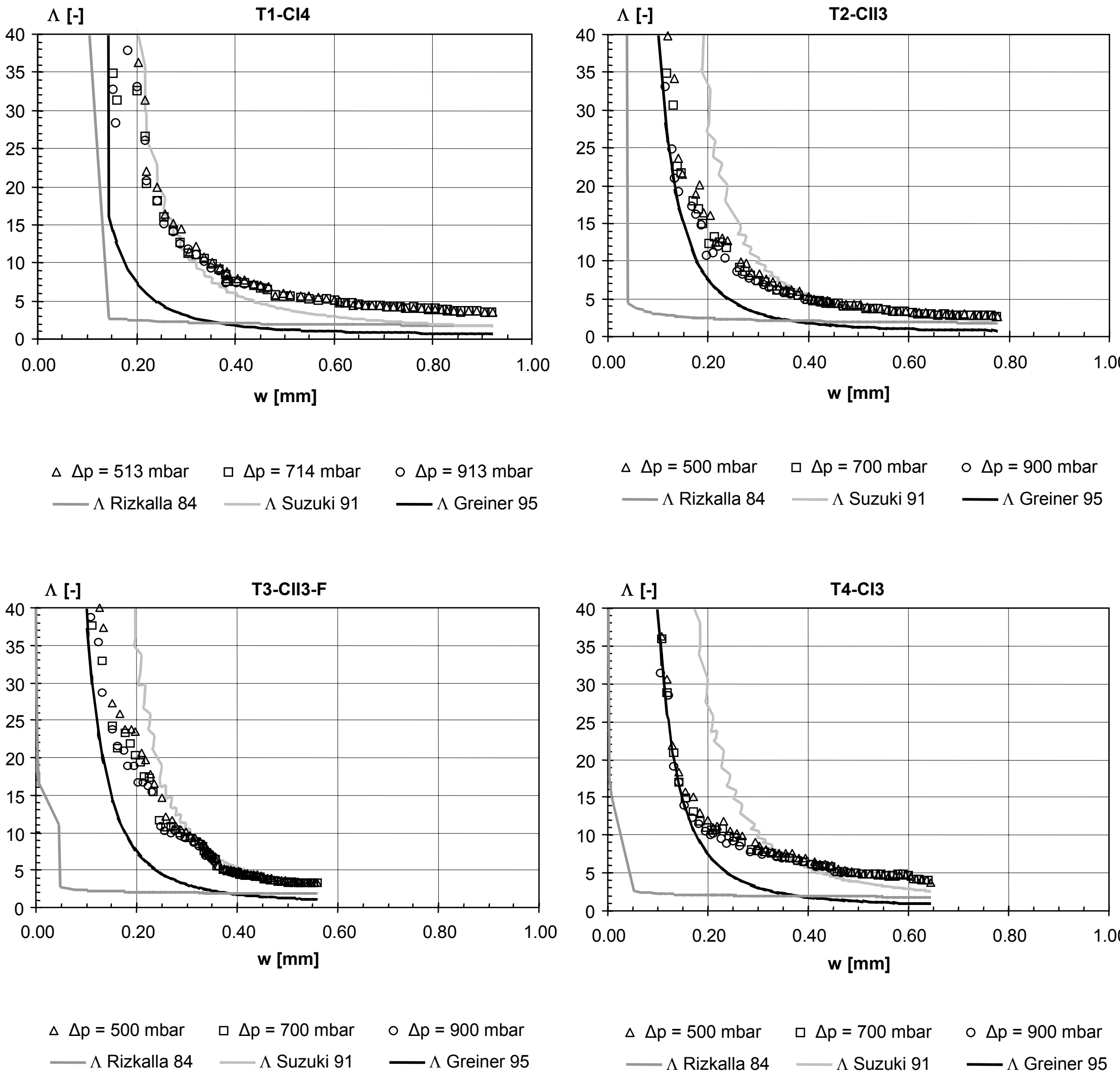

Figure 2: Experimentally derived values for friction coefficient Λ and predicted values from [Rizkalla 84], [Suzuki 91], and [Greiner 95].

On the basis of the experimental data obtained as well as previous work by others, a new formulation for Λ was sought. It was proposed that it would be of the following form:

$$\Lambda = a \cdot \left(\frac{d_{max}^{m}}{w^{n}} \right) + 1$$

This simple form introduces the dependence of Λ with the crack width and the maximum aggregate size. It has the advantage over other formulation of guaranteeing that Λ converges toward a value of 1 for large values of w. This corresponds to the fact that for increasing crack width, the roughness of the concrete crack surface is of decreasing influence on the flow. Conditions approach those of the flow between two smooth parallel surfaces for which the friction coefficient is one.

The selection of parameter m was done on the basis of experimental results reported in [Greiner 95]. Figure 2 shows the variation of Λ as a function of the maximum aggregate size d_{max} for four crack width w. A value of 1.4 for parameter m gives the best correlation with the experimental data.

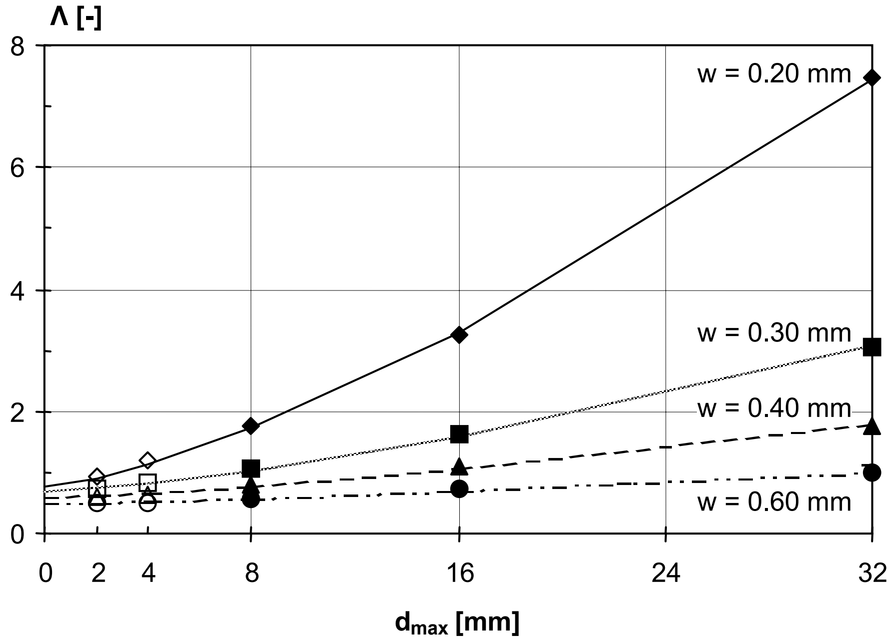

Figure 3: Measured friction coefficient Λ for varying maximum aggregate size d_{max} (data from [Greiner 1995])

The determination of parameter n was done empirically on the basis of the experimental data of Figure 1. The best match with the measured data was obtained for values situated between 1.67 and 1.93. An average value of 1.8 was selected. This leads to the following expression for the determination of the friction coefficient:

$$\Lambda = 0.0075 \cdot \left(\frac{d_{max}^{1.40}}{w^{1.8}} \right) + 1 \qquad (2)$$

where w is the crack width in mm and d_{max} is the maximal diameter of the concrete aggregate in mm (Λ is dimensionless).

This formulation gives credible results for a wide range of crack width and pressure differentials. Figure 4 shows a comparison of the measured air flow and the air flow calculated with expression (2) for Λ and expression (1) for q. The agreement is generally good as indicated by the fact that there is a linear relationship between the measured and calculated values for each of the four test specimen. The relationship is excellent for two of the specimen (T2 and T3). For the two others (T1 and T2), the proposed value for Λ is too small since it leads to an overestimation of the flow by up to 25%. Several causes for this error have been considered, including measurement errors (in particular on effective crack width).

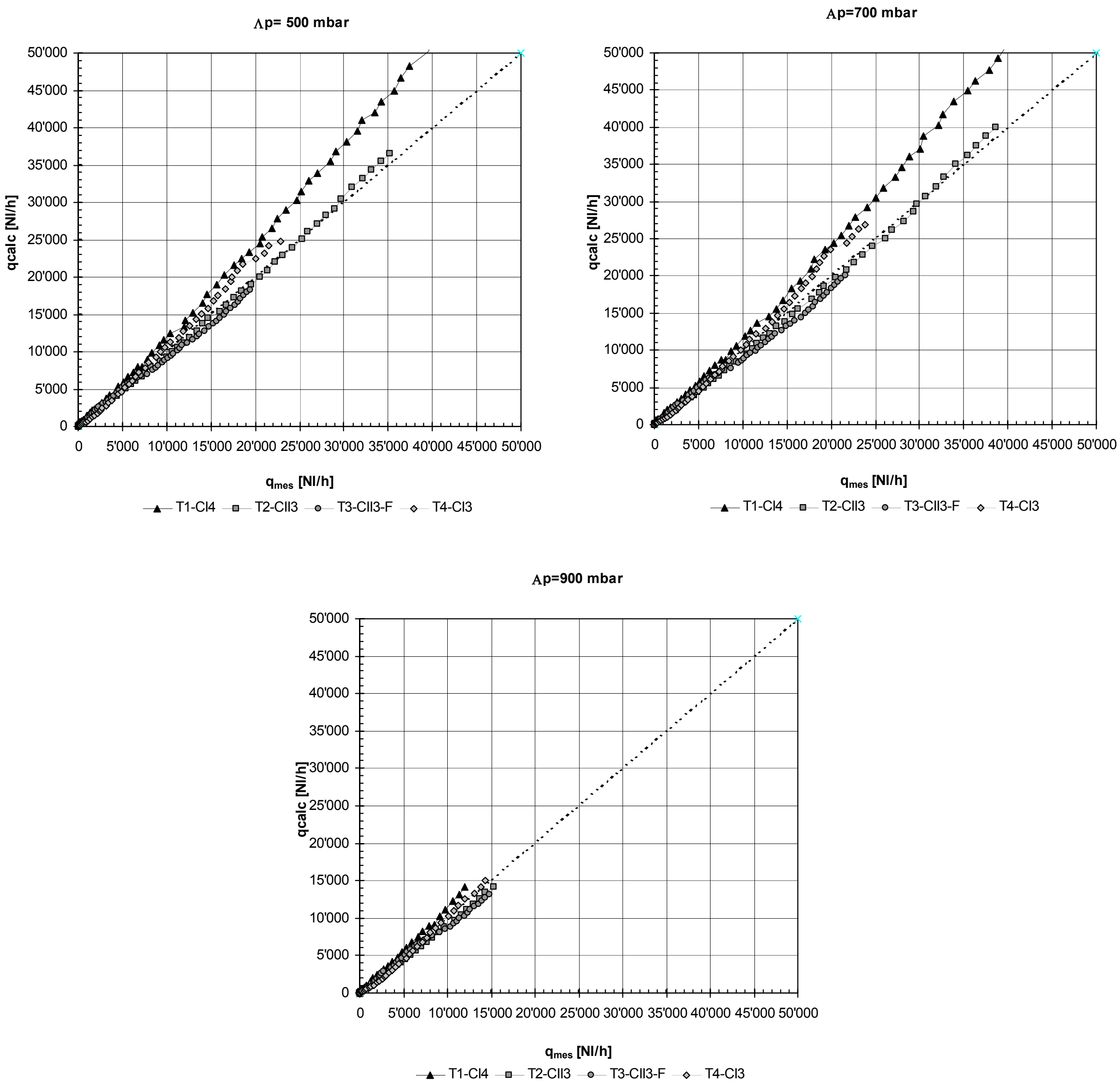

Figure 4: Comparison of measured and calculated air flows for three pressure differentials Δp

Findings

The main findings of the experimental projects regarding the air permeability of cracked reinforced concrete plates are as follow

- The experimental results on large-scale specimen confirm that the air flow through a concrete crack under a pressure differential can be predicted satisfactorily with the general formulation of the theory of flow of a fluid between two parallel surfaces. The measured flow varies regularly and exponentially as the width of the crack increases.
- For low flow speeds (Reynolds number smaller than 100), the flow can be considered to be laminar, and the flow varies with the cube of the crack width (simplified expression of flow). For faster flows (and higher Reynolds number values), the variation of the air flow with crack width is to the power 1.5 – 2.

- The main challenge in predicting the air flow is the definition of the friction coefficient Λ. The experimental results were used to develop a new proposition for the friction coefficient. Expression (2) above links Λ to the aggregate diameter and to the crack width. The friction coefficient increases with the maximum aggregate size and decreases with the crack width. For normal aggregate sizes and crack width above one millimeter, the friction coefficient tends toward one. As shown in the section above, this expression for the friction coefficient provides a good match between the experimental data and the predicted values.
  Clearly, the applicability of the expression beyond the conditions of the experimental measurements on which it is calibrated must be investigated. This validation should extend in particular to the study of the dependence of the friction coefficient on the granulometry of the concrete aggregate (maximum diameter and diameter distribution curve) and the investigation of the influence of higher pressures and higher pressure differentials.
- The coefficient of friction does not seem to vary significantly with the type of cement used (specimen T1, T2 and T4). Even the presence of metallic fibers (specimen T3) did not significantly impact the coefficient of friction. The flow measurements in different specimen for a given crack width shows a relatively low scatter (below 25%). This is relatively low in view of the uncertainty on the measurement of the effective crack width (irregularity).
- From a practical standpoint, the experimental research was a reminder of the difficulty in determining the effective width of the crack(s). The accurate prediction of the number and width of cracks in concrete element is notoriously difficult task. Because of the exponential relationship between crack width and air flow, the air flow is very dependent on the width of the larger cracks in an element with multiple cracks.

Summary

An experimental research program was conducted on the flow of air through cracked reinforced concrete plates. Measurements on four large scale specimen were used to confirm available prediction model for the air flow though concrete cracks and to develop a new empirical expression for the friction coefficient,. Besides the determination of the effective crack width, the coefficient is the critical factor in the quantitative prediction of air flow though a cracked reinforced concrete element such as the liners of the Swissmetro tunnels.

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