

AIR LEAKAGE CHARACTERISTICS IN CRACKED CONCRETE

U. Greiner and W. Ramm

University of Kaiserslautern, Kaiserslautern, Germany

ABSTRACT

In the following paper a mathematical formulation for the air leakage rate through cracks in concrete is given. The formula works well in good approximation for crack widths up to 1,30 mm and overpressures up to 0,80 MPa. The formula was found by means of systematical air leakage tests using unreinforced test specimens with one "defined single crack". For thermodynamical formulation, isothermal changes of the gas state during the leakage through the crack was estimated and experimentally proved. By additional leakage tests using reinforced test specimens, practical usability of the leakage formula for reinforced panels with a "typical crack pattern" had been checked.

1 INTRODUCTION

Under accidental loading beyond design limits, containment vessels of prestressed concrete can fail by cracking due to high internal pressure. Average numbers, widths and lengths of such cracks, which develop in concrete membrane constructions as a result of tensile stresses, can be calculated with relative accuracy. By this crack pattern it is possible to determine the leakage area approximately. If the leakage area is known, it is now of great interest, to know, how much gas will flow per unit time through this cracked area from the inside to the outside of the containment.

To date, only a few experimental and theoretical investigations are available on the topic of air leakage characteristics through cracks in concrete. Generally known achievements are the works by BUSS (1972), RIZKALLA et al. (1984) and SUZUKI et al. (1989). With these previous experimental investigations the leakage through cracks in concrete structures was proved for crack widths from 0,05 mm up to 0,40 mm and overpressures up to 0,20 MPa.

Since 1989, additional experimental investigations had been undertaken at the University of Kaiserslautern (Germany). The objective was to clarify some open questions, especially regarding the behavior of leakage under high overpressures (up to 0,80 MPa) and in case of larger crack widths (up to 1,30 mm). The research program was sponsored by the German Ministry for Protection of Nature and Environment and Reactor Safety.

2 EXPERIMENTAL INVESTIGATIONS

Fundamental inherent laws of gas leakage through cracks in concrete and especially the determination of the characteristic wall friction coefficient were found by tests, referred in the following as "tests with a defined single crack". "Defined single crack" means, that the crack section, given by the flow through crack length (varied with 150, 300 and 450 mm) and the perpendicular crack extension (200 mm at all tests) as well as the crack width (0,20 mm and 1,30 mm), was given by experimental adjustments and therefore was well known. The

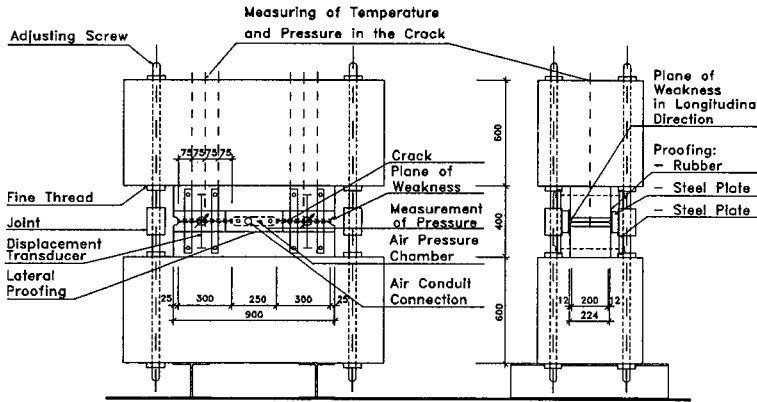


Fig. 1. Test setup "tests with a defined single crack"

overpressure at the beginning of the crack was raised in steps of 0,10 MPa up to a maximum overpressure of 0,80 MPa. The investigations included different concrete types produced by different grading curves of aggregate (AB 8, AB 16 and AB 32 (designations according to the German Code DIN 1045)). With some test specimens, the temperature and the absolute pressure of the gas was measured at several points along the flow through crack

Table 1. Programm of "tests with a defined single crack"

| test no. | concrete grading curve | used aggregate * | crack length L [mm] | crack width W [mm] | over-pressure Δp [MPa] | measurement of pressure in the crack | measurement of temperature in the crack |
|----------|------------------------|--|---------------------|--------------------|--------------------------------|--------------------------------------|---|
| - | - | - | [mm] | [mm] | [MPa] | - | - |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| 1 | AB 16 | sand, gravel | 300 | 0,2 - 1,3 | 0,1 - 0,8 | no | no |
| 1.1 | AB 16 | sand, gravel | 300 | 0,2 - 1,3 | 0,1 - 0,8 | yes | no |
| 2 | AB 16 | sand (0/2), gravel (2/8), chippings (8/16) | 300 | 0,2 - 1,3 | 0,1 - 0,8 | no | no |
| 3 | AB 8 | sand, gravel | 300 | 0,2 - 1,3 | 0,1 - 0,8 | no | no |
| 3.1 | AB 8 | sand, gravel | 300 | 0,2 - 1,3 | 0,1 - 0,8 | yes | no |
| 4 | AB 32 | sand, gravel | 300 | 0,2 - 1,3 | 0,1 - 0,8 | no | no |
| 4.1 | AB 32 | sand, gravel | 300 | 0,2 - 1,3 | 0,1 - 0,8 | yes | yes |
| 5 | AB 16 | sand, gravel | 150 | 0,2 - 1,3 | 0,1 - 0,8 | yes | no |
| 5.1 | AB 16 | sand, gravel | 150 | 0,2 - 1,3 | 0,1 - 0,8 | yes | yes |
| 6 | AB 16 | sand, gravel | 450 | 0,2 - 1,3 | 0,1 - 0,8 | yes | no |
| 6.1 | AB 16 | sand, gravel | 450 | 0,2 - 1,3 | 0,1 - 0,8 | yes | yes |

* Designation according to German Code DIN 1045

In a second test series, the gas leakage was tested using reinforced wall panels, which were cracked under uniaxial and biaxial loading. These tests are referred to as "tests with a typical crack pattern".

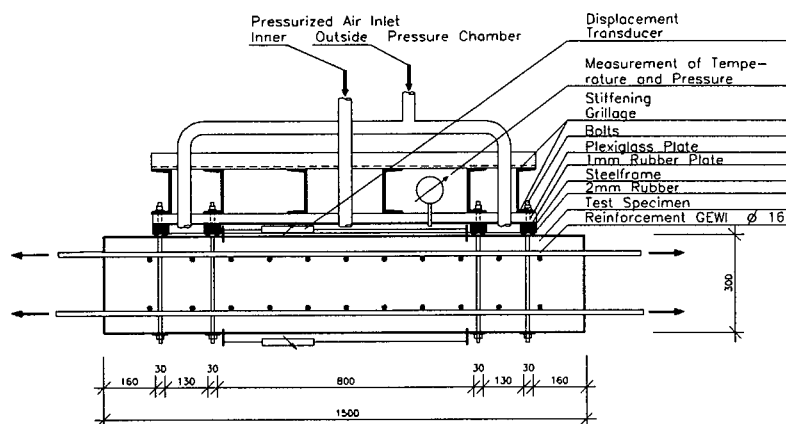


Fig. 2. Test setup "tests with a typical crack pattern"

The reinforcement percentage was $\mu = 1,00\%$. The maximum applied overpressure was 0,40 MPa, the average crack widths in the crack pattern were set between 0,15 mm and 0,45 mm. Similar to the "tests with a defined single crack", variations of concretes produced by different grading curves were investigated. Table 2. shows all investigated test parameters, which were investigated in the "tests

with a typical crack pattern". In fig. 2. a cross section through the test specimen and test setup is shown.

Table 2. Program of the "tests with a typical crack pattern"

| test no. | concrete grading curve* | crack length L [mm] | crack width W [mm] | overpressure Δp [MPa] | crack pattern |
|----------|-------------------------|------------------------|-----------------------|----------------------------------|---------------|
| - | - | 3 | 4 | 5 | 6 |
| 1 | 2 | 300 | 0,1 - 0,4 | 0,1 - 0,4 | uniaxial |
| 7 | AB 16 | 300 | 0,1 - 0,4 | 0,1 - 0,4 | uniaxial |
| 8 | AB 8 | 300 | 0,1 - 0,4 | 0,1 - 0,4 | uniaxial |
| 9 | AB 32 | 300 | 0,1 - 0,4 | 0,1 - 0,4 | uniaxial |
| 10 | AB 16 | 300 | 0,1 - 0,4 | 0,1 - 0,4 | biaxial |

* Designation according to German Code DIN 1045

3 TEST RESULTS AND THERMODYNAMICAL ANALYSIS OF GAS LEAKAGE THROUGH CRACKS IN CONCRETE

3.1 Tests with a defined single crack

For the "tests with a defined single crack" the following basic test results were obtained:

- Apart from the flow through crack length, the overpressure at the beginning of the crack and the crack width, the leakage rate of gas flow depends distinctly on the maximum size of the aggregate used in the concrete mixture. The leakage rate decreases noticeably with increasing diameter of the maximum aggregate size.
- The measurements of temperature in the inner crack area along the crack length and outside, in the immediate vicinity of the crack end have shown, that the temperature was nearly constant along the crack length.

Therefore, for the thermodynamical analysis of the leakage process isothermal changes of the gas state were assumed for the derivation of the leakage-formula. Using the equations of continuity,

momentum and state of gas for a perfect gas, the following equation for the gas leakage was obtained (for detailed derivation see RAMM et al. (1992)):

$$q_2 = \sqrt{(p_1^2 - p_2^2) \cdot B^2 \cdot W^2 \cdot \frac{R \cdot T}{p_2^2} \cdot \frac{2 \cdot W}{\lambda \cdot L}} \quad [1]$$

(with: q_2 = volume of leakage rate at the end of the crack, p_2 = absolute pressure at the beginning of the crack, p_1 = absolute pressure at the end of the crack, L = flow through crack length, B = flow through extent of the crack, W = crack width, R = constant of gas, T = temperature, λ = friction coefficient)

Leakage equations derived by RIZAKALLA (1984) and SUZUKI (1989) differ from Eq. 1 mainly in the formulation of the wall shearing stress. The friction coefficient λ used in Eq.1 was an empirical value and must therefore be determined by experiments.

With the flow of compressible fluid in constant-area ducts with friction, the friction coefficient λ is a function of the REYNOLDS-number Re and of the wall roughness $K = (k/D)$ (with: k = height of roughness (in ducts defined as the roughness of sand) and D = diameter of the duct) for both, laminar and turbulent flow:

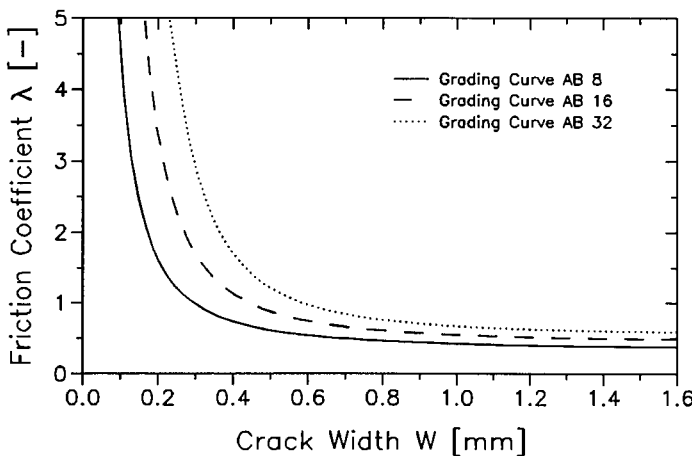
$$\lambda = \lambda (Re/K) \quad [2]$$

with $Re = \rho \cdot v \cdot D / \eta$ and $K = k / D$

With constant area ($D = const$) of the duct and constant mass rate of flow ($\rho \cdot v = const$), λ can only depend on values which determine the dynamic viscosity η . Because of $\eta = \eta(T)$ the friction coefficient depends only on the temperature of gas. For the thermodynamical analysis an isothermal change of gas state was assumed ($T = const$) and therefore λ depends only on the roughness of the crack:

$$\lambda = \lambda (k/D) \quad [3]$$

While the ratio k/D is not changing over the crack length, λ can be estimated as $\lambda = const$ over the crack length. If the diameter of the duct D is replaced by the equivalent diameter D_g given by the gap area in the crack, D_g can be written as $D_g \approx 2 \cdot W$. Because of experimental observations



which have shown, that the leakage rate depends on the grading curve of the used concrete, the value "height of the roughness k " may be defined as the maximum diameter of the used aggregate. In a general form the friction coefficient λ can be expressed as:

$$\lambda = \left(a \cdot \frac{k}{2 \cdot W} \right)^n + b \quad [4]$$

(where a , b and n are empirical values)

Fig. 3.: Friction coefficient λ as a function of the crack width W and the maximum aggregate size k .

parameter k as maximum diameter of the aggregate (as is shown in Fig. 3.), by nonlinear

If the friction coefficient λ is plotted as a function of the crack width W with the curve

regression analysis the following empirical equation of the dimensionless friction coefficient λ is obtained:

$$\lambda = \left(\frac{0,105 \cdot k^{0,409}}{W} \right) \left[\frac{1}{1,739} \cdot \ln \left(\frac{k}{0,414} \right) \right] + 0,20 \cdot k^{0,3043} - 0,024 \quad [5]$$

(with: k = maximum diameter of aggregate in mm, W = crack width in mm)

Because the friction coefficient is obtained by experiment, it can only be applied, remaining on the safe side, in the experimentally proved parameter ranges:

- Crack width: $0,20 \text{ mm} \leq W \leq 1,30 \text{ mm}$
- Overpressure at the beginning of the crack: $0,10 \text{ MPa} \leq \Delta p \leq 0,80 \text{ MPa}$
- Grading curves: AB 8, AB 16, AB 32

The comparison of test results with calculated results (as is shown in fig. 4.) reveals a very good correlation between test and calculations.

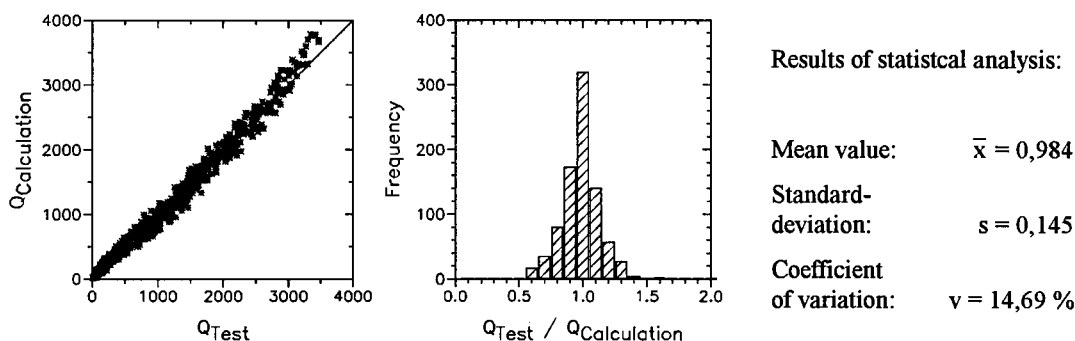


Fig. 4. Comparison of test results with calculated results for "tests with a defined single crack"

3.1 Tests with a typical crack pattern

By the "tests with a typical crack pattern" the following basic test results were obtained:

- The leakage rates were distinctly lower than with the "tests with a defined single crack" (one separate crack in unreinforced concrete). The reason for this observation is, that the reinforcement has a noticeable influence on the inner structure of the crack. The crack area was considerably strangled in the region around a single reinforcement bar (SCHIEBL et al. (1991)). Therefore the effective leakage area was considerably smaller than in comparable cracks in unreinforced sections.
- The aggregate grading curve of the used concrete has no verifiable influence on the leakage rate. The reason for this observation is, that the reinforcement had a major effect on the structure of the cracks.

Evaluation of the test results with Eq. 1 lead to a mean value 0,70 of the ratio between measured and calculated leakage rates with a coefficient of variation of 34 %. Evaluating the test results with the formulae of RIZKALLA et al. (1984), the mean value of the ratio between measured and calculated leakage rates was 0,75 with a coefficient of variation of 17,3 %.

Using both, Eq. 1 and the formula of RIZKALLA, the ratio of measured and calculated leakage rates was smaller than 1. Thus, the calculated leakage rates are on the safe side (comp. Fig. 5). On the other hand and first of all, it was important to determine the leakage area given by the crack pattern. With known crack formulae only a rough prediction of the leakage area was possible.

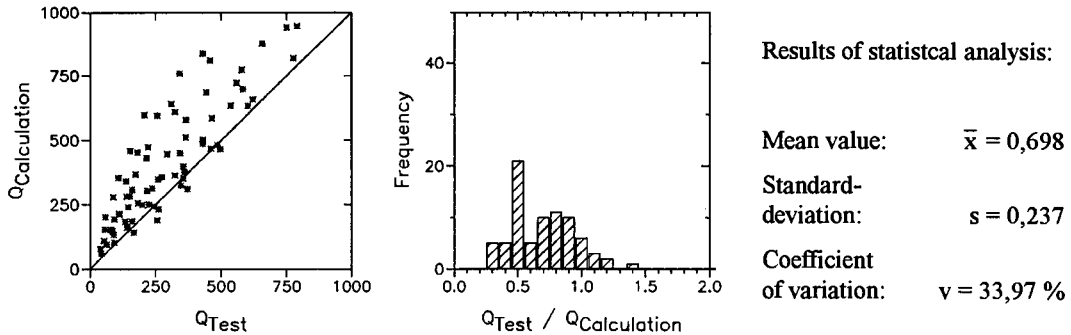


Fig. 5. Comparison of test results with calculated results for "tests with a typical crack pattern"

4 CONCLUSIONS

The formulae for the leakage rate (Eq. 1) and the friction coefficient (Eq. 5) established for unreinforced, cracked concrete specimens are in very good correlation with the measured experimental results of the "tests with a defined single crack". The formulae were experimentally proved for crack widths up to 1,30 mm and absolute overpressures up to 0,80 MPa. Application of the formulae to cracked, reinforced concrete elements is practicable. But it must be considered that because of the reinforcement, the inner crack width is smaller than the crack width observed at the surface, and consequently the leakage rate was reduced in the experiments.

REFERENCES

- Greiner, U., Ramm, W. (1991). *Air Leakage Characteristics in Cracked Concrete*, SMiRT 11th Transactions Vol. H, Tokyo, Japan, pp. 181-186.
- Ramm, W., Greiner, U. (1992). Final report of research project BMU SR 413: "*Grenztragfähigkeit von Stahlbetonumschließungen im Kernkraftwerksbau - Teilbericht 2a: Selbstentlastung*", University of Kaiserslautern, Department of Concrete Construction.
- Rizkalla, S.H., Simmonds, S.H., Lau, B.L. (1984). *Air Leakage Characteristics in Reinforced Concrete*, Journal of Structural Engineering, Vol. 110, No. 5, pp. 1149-1162.
- Suzuki, T., Takiguchi, K., Hotta, H., Kojima, N., Fukuhara, M., Kimura, K. (1989). *Experimental Study on the Leakage of Gas Through Cracked Concrete Walls*, SMiRT 10th Transactions, Anaheim, pp. 145-150.
- Schießl, P., Reuter, C. (1991). *Betonbau beim Umgang mit wassergefährdenden Stoffen, Teilbericht 3: Durchlässigkeit von gerissenem Beton gegenüber Flüssigkeiten und Gasen*, Heft 416 des Deutschen Ausschusses für Stahlbeton, pp. 46-111.
- Buss, W. (1972). *Proof of Leakage Rate of a Concrete Reactor Building*, Paper 3461, Concrete for Nuclear Reactors, ACI Special Publication Sp-34, Vol. III 1972, pp. 1291-1320.