# Experimental Study on the Leakage of Gas Through Cracked Concrete Walls

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## INTRODUCTION

The air-tightness of concrete walls is important for nuclear-related facilities. A concrete wall has very high probabilities of developing cracks due to shrinkage, seismic forces or other factors. It is therefore essential to be able to predict the amount of gas which will leak through a cracked concrete wall.

In the previous paper published in SMiRT-9, the experimental equation on the gas leakage through a single crack occurred in concrete was presented based on two-dimensional Poiseuille's flow.

In this paper, the experimental results were examined again considering the compressibility of gas, and new equation is presented. The experiments which were similar to ones in the previous paper were carried out on several kinds of concrete using several kinds of gases, and the effects of the kinds of gaseous body, particle size of aggregates and shape of aggregates were examined.

## EXPERIMENTAL METHOD AND SPECIMENS

Twelve specimens listed in Table-1 were tested. The specimens were divided into

Table-1 List of Specimens

| Name | Wall Thickness | Concrete | Fine Aggregate | Coarse Aggregate |
|---|---|---|---|---|
| 60-A-1 | 60 (cm) | A | Sand ∼ 5 (mm) | Crushed Gravel 10 ∼ 20 (mm) |
| 60-A-2 | 60 (cm) | | | |
| 30-A-1 | 30 (cm) | | | |
| 30-A-2 | 30 (cm) | | | |
| 15-A-1 | 15 (cm) | | | |
| 15-A-2 | 15 (cm) | | | |
| 30-B | 30 (cm) | B | Sand ∼ 2.5 (mm) | Crushed Gravel: 10 ∼ 25 (mm) |
| 30-C | 30 (cm) | C | | Crushed Gravel: 2.5 ∼ 15 (mm) |
| 15-D | 15 (cm) | D | | Spherical Aluminium: D=24.8 (mm) |
| 15-E | 15 (cm) | E | | Cubical Aluminium: 20×20×20 (mm) |
| 60-F | 60 (cm) | F | Sand ∼ 5 (mm) | Crushed Gravel 5 ∼ 15 (mm) |
| 15-F | 15 (cm) | | | |

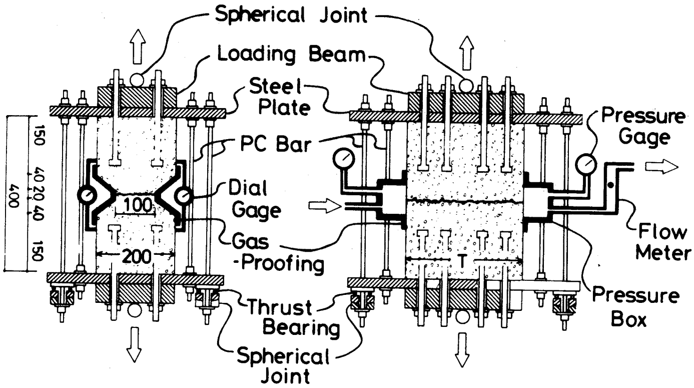



Fig.-1 Outline of Tesing Setup

Table-2 Properties of Gases

| Gas | Density $\rho$ ($Kg\cdot m^{-3}$) 20°C 1atm | Viscosity $\mu$ ($10^{-6} Pa\cdot s$) 20°C 1atm |
|---|---|---|
| He | 0.1663 | 19.6 |
| $N_2$ | 1.165 | 17.6 |
| $O_2$ | 1.331 | 20.4 |
| $CO_2$ | 1.842 | 14.7 |

six groups (A-F series) for the concrete used. A-concrete was produced using the coarse aggregates whose maximum particle size was 20 mm. The maximum particle size of the coarse aggregates was 25 mm in B-concrete, and was 15 mm in C-concrete. Two types of aluminum model gravel were used in D and E-concrete as the coarse aggregates, spherical aluminum of 24.8 mm diameter in D-concrete and cubical aluminum of 20×20×20 mm in E-concrete. They were used in A to E series specimens in order to examine the effects of the coarse aggregate on the leakage rate. Oxygen gas was used in A - E series specimens. Four kinds of gaseous bodies, oxygen, nitrogen, carbonic acid gas and helium were used in F series specimens. The properties of the gases are indicated in Table-2.

The outline of the experiment is described in Fig.-1. The specimen was notched so that a single crack would occur along the notch. Each specimen was prestressed with PC bars at four corners of the specimen not to be cracked before testing. PC bars were also used to control the crack width during the leakage test. Both notched sides of the specimen were gas proofed with gum, and two pressure boxes were set on the flat sides. Pressure at inflow side $P_1$, at outflow side $P_2$ and flow rate Q were measured under controlling the crack width W.

ONE DIMENSIONAL COMPRESSIBLE FLOW

One dimensional compressible flow in a rectangular tube of the extent B × the gap between two plates W is shown in Fig.-2. Next differential equation is given applying the momentum-balance theorem

$$\bar{\rho}\cdot\bar{u}\cdot d\bar{u} = d\bar{P} - \frac{2\tau_W}{W}\cdot dx \qquad (1)$$

in which $\tau_W$ = shear stress due to wall friction; $\bar{u}$ = velocity of gas at any section; $\bar{\rho}$ = density of gas at any section; $\bar{P}$ = absolute pressure at any section. Now the friction coefficient f is defined as follows;

$$f \equiv \tau_W/(\frac{1}{2}\cdot\bar{\rho}\cdot\bar{u}^2) \qquad (2)$$

Assuming the flow is isothermal, using eq.(2) and integrating eq.(1) along the length of the tube gives

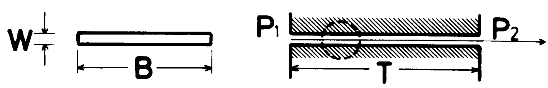
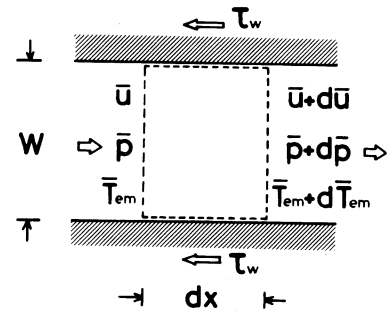



Fig.-2 One Dimensional Flow through a Rectangular Tube




$$f \cdot \frac{T}{W} = \frac{W^2 \cdot (P_1^2 - P_2^2)}{2 \cdot \rho_0 \cdot P_0 \cdot Q^2} + \ln \frac{P_2}{P_1} \qquad (3)$$

in which T = the length of the tube; $P_0$ = 1 atm; $\rho_0$ = the density of gas under the temperature 20°C and the pressure 1 atm; Q = the flow rate per the length of crack under 20°C and 1 atm. When the velocity of gas is relatively slow, the second term of eq.(3), which is very small compared to the first one, can be neglected. Therefore the compressible flow between two parallel plates can be expressed by the next equation.

$$f \cdot \frac{T}{W} = \frac{W^2 \cdot (P_1^2 - P_2^2)}{2 \cdot \rho_0 \cdot P_0 \cdot Q^2} \qquad (4)$$

## EXPERIMENTAL RESULTS

The friction coefficient f was calculated by eq.(4) using measured Q, $P_1$, $P_2$ and W. The parts of the results of A series specimens , the relationship between Q and the product of f and Q are illustrated in Fig.-3 and Fig.-4. The f·Q – Q relation can be expressed by the linear equation as follows;

$$f \cdot Q = a + b \cdot Q \qquad (5)$$

in which a and b are experimental constants. The relationship between a and the crack width W, and the one between b and W of the specimens from A to E series are shown in Fig.-5 and Fig.-6. The experimental constants a and b can be regarded as the function of the crack width W.

Fig.-7 shows the f·Q – Q relation of F series specimen. Though the f·Q – Q relation can be expressed by eq.(5), the functions are different on the gaseous bodies. That suggests other factors concerned with the gaseous bodies are required.

The flow between two parallel plates whose surface is very smooth can be considered two dimensional Poiseuille's flow, and the friction coefficient f can be given as following equation at that time;

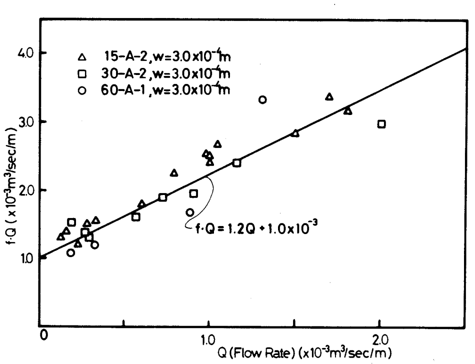



Fig.-3 f·Q-Q Relationship of A Series Specimens ( W= 0.3mm)

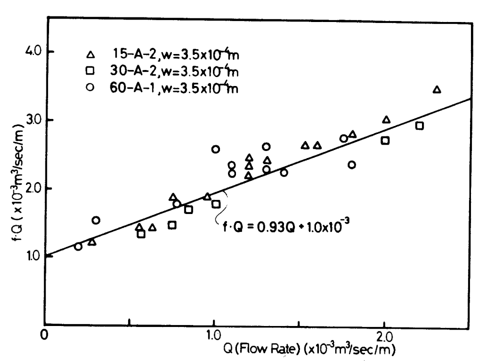



Fig.-4 f·Q-Q Relationship of A Series Specimens ( W= 0.35mm)

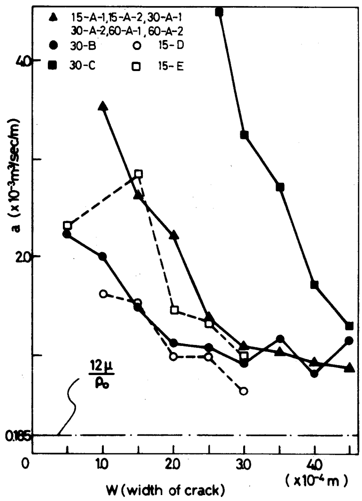



Fig.-5 a-W Relationship of A-E Series Specimens

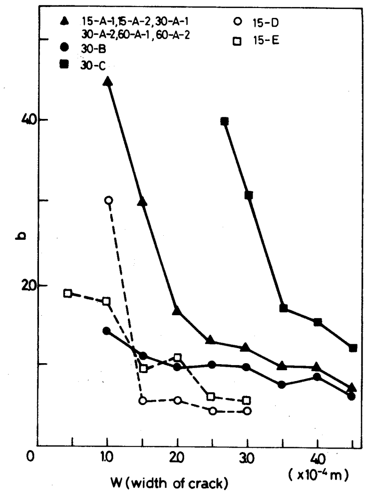



Fig.-6 b-W Relationship of A-E Series Specimens

$$f = \frac{12 \cdot \mu}{\rho_0 \cdot Q} \tag{6}$$

in which $\mu$ = viscosity of gas. Fig.-8 and Fig.-9 show the relationship between a,b and W of F series specimens, in which the experimental function a is normalized by $12\mu/\rho_0$ considering eq.(6). The values of $\bar{a}(W)$ and b(W) are almost equal at the same crack width W in any gaseous bodies.

According to the above discussion, it can be concluded that the friction coefficient f is given as follows;

$$f = \bar{a}(w) \cdot \frac{12 \cdot \mu}{\rho_0 \cdot Q} + b(w) \tag{7}$$

in which $\bar{a}(W)$ and b(W) are the experimental function of the crack width W in Fig.-8 and Fig.-9. The experimental functions $\bar{a}(W)$ and b(W) can be approximately expressed by the next equations on F series specimen.

$$\bar{a}(W) = 6.5 \times 10^{-4}/W + 1 \tag{8}$$

$$b(W) = 9.2 \times 10^{-5}/W \tag{9}$$

In Fig.-10, the flow rate measured in the tests is compared with the one calculated using eq.(4),(7),(8) and (9). The flow rate can be predicted using eq.(4) and eq.(7) in the range of differential pressure$\leqq$ 1 atm.

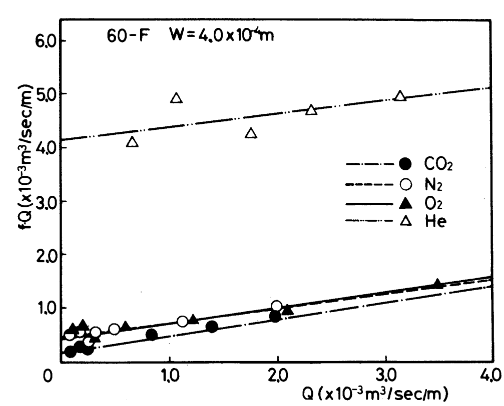



Fig.-7 f·Q-Q Relationship of 60-F Specimen

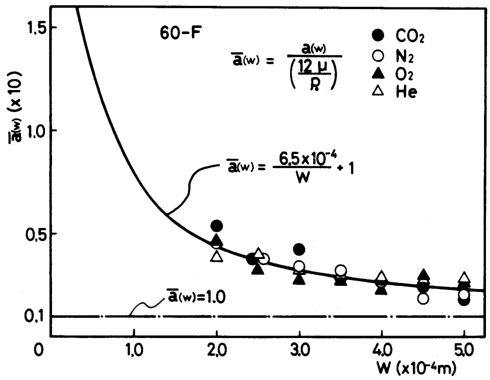



Fig.-8 a-W Relationship of 60-F Specimen

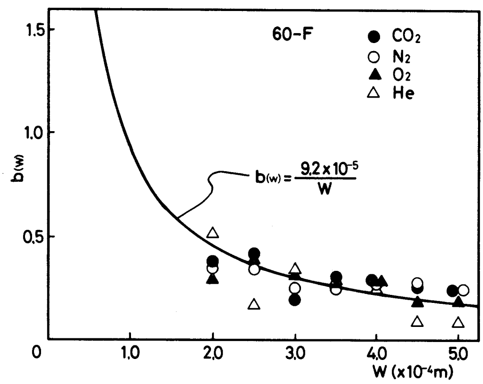



Fig.-9 b-W Relationship of 60-F Specimen

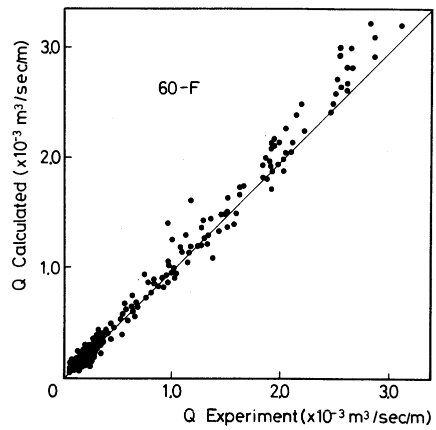



Fig.-10 Comparison of Measured Flow Rate to Predicted Flow Rate by eq.(4) and eq.(7)

## PRACTICAL EQUATION FOR THE PREDICTION OF LEAKAGE RATE

The flow rate calculated by eq.(4) and (7) is in conformity with the experimental results in relatively wide range of differential pressure. However, the practical problems of the nuclear related facilities are often limited in a small region like the differential pressure is smaller than 0.1 atm or the absolute pressure is very close to 1 atm. Therefore the authors present the practical equation.

Eq.(4) above mentioned can be rewritten as follows

$$Q = \frac{1}{\rho_0 \cdot (f \cdot Q)} \cdot \frac{(P_1 - P_2) \cdot W^3}{T} \cdot \frac{(P_1 + P_2)}{2P_0} \qquad (10)$$

Substituting eq.(7) into eq.(10) yields

$$Q = \frac{1}{\bar{a}(W) \cdot 12 \cdot \mu + \rho_0 \cdot Q \cdot b(W)} \cdot \frac{(P_1 - P_2) \cdot W^3}{T} \cdot \frac{(P_1 + P_2)}{2P_0} \qquad (11)$$

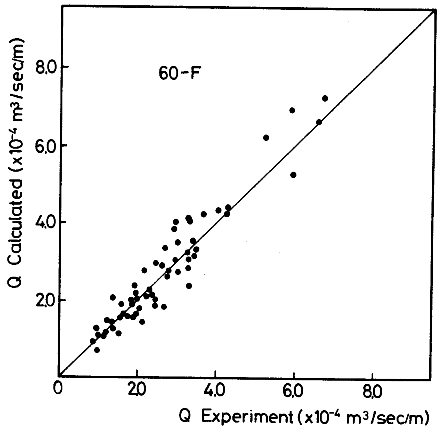
In the case the absolute pressures $P_1$ and $P_2$ are close to $P_0$, and Q is very small, $(P_1+P_2)$ can be regarded as $2P_0$ and $\rho_0 \cdot Q \cdot b(W)$ can be neglected. Hence

$$Q = \bar{\alpha}(W) \cdot \frac{\Delta P \cdot W^3}{\mu \cdot T} \qquad (12)$$

in which $\bar{\alpha}(W) = 1/(12\bar{a}(W))$; $\Delta P = P_1 - P_2$(differential pressure.) Eq.(12) is the same as the equation presented in the previous paper.

The flow rate calculated using eq.(12) were compared with the one measured in the tests for F series specimen in the following region.

$0.8$ atm $\leqq$ P(absolute pressure) $\leqq$ 1.2 atm



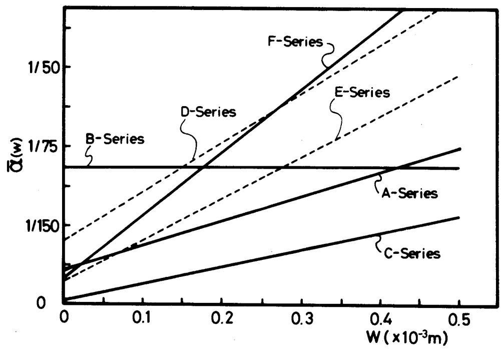




Fig.-11 Comparison of Measured Flow Rate to Predicted Flow Rate by eq.(12)

Fig.-12 α-W Rlationship of All the Specimens

ΔP(differential pressure) ≦ 0.2 atm
apparent Reynolds' number ≦ 100

The results are shown in Fig.-11. The experimental functions $\overline{\alpha}(W)$ of A to F series specimens are shown in Fig.-12.

THE EFFECT OF COARSE AGGREGATE ON THE LEAKAGE RATE

It can be found that the leakage rate differs according to the concrete under the same crack width as shown in Fig.-5,6 or Fig.-12. However, the reasonable differences according to the size or the shape of the coarse aggregate cannot be found out. Though it is considered that the irregularity of crack surface may affect the leakage rate, the leakage rate should be grasped in a certain region because the shape of crack may disperse even in the same concrete.

CONCLUSION

(1) The leakage rate through cracked concrete wall can be predicted by eq.(4) and eq.(7) accurately.
(2) In the range of 0.8 atm≦ P(absolute pressure)≦ 1.2 atm, ΔP(differential pressure)≦ 0.2 atm and apparent Reynolds' number≦ 100, eq.(12) is applicable for the prediction of the leakage rate also. Eq.(12) is recommendable as the practical equation under the condition above mentioned.
(3) The experimental functions $\overline{a}(W)$,b(W) and $\overline{\alpha}(W)$ differ according to the kinds of aggregate used in concrete. The accumulation of the experimental data is necessary to define the above functions.

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