H08/2

Leakage of Gas through Concrete Cracks

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1。 Introduction

Some concrete walls in nuclear-related facilities require air tightness。 Concrete walls have very high probabilities of cracking due to earthquakes, drying shrinkage or other factors。 It is therefore important to predict the amount of gas which will leak through cracked concrete walls。

There was, however, only one orthodox paper (ref。1), to the authors' knowledge, on gas leakage through cracked concrete walls。 The authors of this paper began to study gas leakage through concrete cracks in 1985。 Experimental and analytical research is still being continued。 Six papers (refs。2 - 7) have been published。

The previous papers (refs。2 - 7), which are outlined in the next section, formulated the data of the gas leakage rate through a crack in a concrete wall。 This paper extends the previous papers (refs。2 - 7) and discusses the following three items。

(1) Dispersion of test data
(2) Influence of the aggregate
(3) Effect of a reinforcing bar

With respect to macroscopic configurations of cracks, inevitable differences might exist。 Four examples of different crack shapes across the wall section are shown in Fig。-1。 These differences cannot be averaged and causes the dispersion of gas leakage when handy-sized specimens are used。 The microscopic properties of crack surfaces are influenced by the aggregate used。 As a reinforcing bar is an obstacle itself and decreases the crack width around the bar, it consequently disturbs the gas flow。

This study deals with comparatively slow gas flow through concrete cracks。 The crack width of smaller than 0。5mm, and a differential pressure across the wall of smaller than 2.5×10^5 Pa are discussed in this paper。

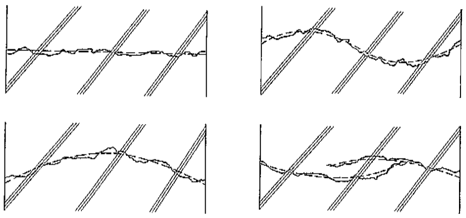

Fig.-1 Examples of crack configuration

2。 Outline of the previous papers

References 2 and 3 describe the leakage tests which were carried out in 1985。 Six specimens were tested using oxygen gas。 Two of them had 15cm thickness, two 30cm and two 60cm。

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Dimensions of the specimens, the concrete used, details of the pressure boxes, the gas-proofing system, the controlling method of crack width and procedures of the leakage test are detailed in refs.2 and 3 . References 2 and 3 conclude that the gas leakage rate through a crack in the concrete wall can be formulated using an equation modified from the two-dimensional Poiseuille's flow equation when the gas flow is relatively slow.

Reference 4 reports the results of the tests carried out in 1986 and discusses the influences of the size and shape of the coarse aggregate. Spherical aluminum, cubical aluminum and crushed gravel were used as the coarse aggregate. Reference 4 concludes that the empirical function in the above equation should be defined for each type of concrete.

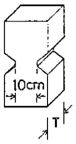
Reference 5 presents a new equation whose applicable range is wider than that of the equation based on the two-dimensional Poiseuille's flow equation. The newly presented equation is derived from isothemal compressible gas flow between the parallel plates. Experimental results indicate that the product of the friction coefficient multiplied by the flow rate can be formulated by a linear equation of the flow rate. In this linear equation, the intercept and the slope can each be defined by functions of the crack width. Reference 5 discusses the relation between the equation based on the two-dimensional Poiseuille's flow equation and the equation based on the isothermal compressible flow equation. The applicable range of the equation presented in refs.2 and 3 is defined.

References 6 and 7 report the results of the tests conducted in 1987. In the leakage tests, helium (He), nitrogen (N_2), oxygen (O_2) and carbonic acid (CO_2) gases were used. References 6 and 7 improve the experimental equations so as to be applicable to any gaseous bodies.

3. Specimens and experiments

In 1989, the eighteen specimens listed in Table-1 were made and tested. Dimensions of the specimens are roughly illustrated in Fig.-2, together with the test setup. Experimental variables in the specimens were sand (land sand smaller than 2.5mm, standard sand of Japan), gravel (crushed gravel of 10-20mm, crushed gravel of smaller than 10mm) and reinforcement (none, 1-D13). The standard sand grain is very fine. The size of particles comprising 94 weight % ranges from 105μm to 297μm. The mix proportions of concrete are shown in Table-2. The crack width was controlled by tensile load and fastening

Table-1 List of test specimens

Name of Specimen	Wall Thickness	Fine Agg.	Coarse Agg.	Reinforcing Bar
15-H- 1 2 3 4	(T) 15cm  	Land Sand Size: ~2.5mm	Crushed Gravel Size: ~10mm	—
15-I- 1 2 3 4		Standard Sand Size: 105~297μm(94wt%)		
15-J- 1 2 3 4 5		Land Sand Size: ~2.5mm	Crushed Gravel Size: 10~20mm	
15-J-R- 1 2 3 4 5				D-13

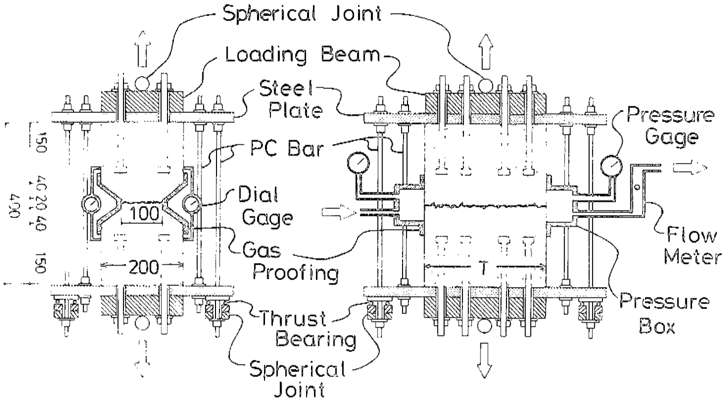


Fig.-2 Dimensions of specimen and test setup

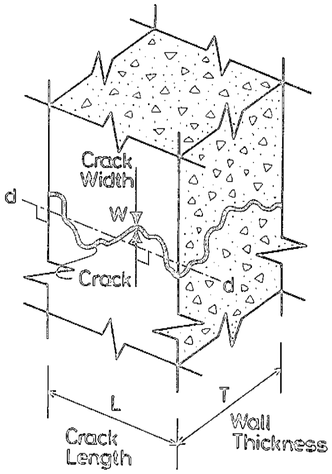


Fig.-3 Definition of crack length and crack width

Table-2 Mix proportions of concrete

Concrete	W/C(%)	Mix Proportion(kg/m^3)				Slump(cm)
		Water	Cement	Fine Agg.	Coarse Agg.	
H	45	170	378	803	997	3.8
I	52	180	347	818	997	2.0
J	45	170	378	803	982	4.0

or loosening of the four PC bars, each of which had a thrust bearing. Oxygen gas was used and it was supplied into the pressure box of the inflow side from an oxygen cylinder. The crack width, leakage rate, inflow-side pressure, outflow-side pressure and atmospheric temperature were measured. The crack width was smaller than 0.5mm, the differential pressure was less than 2.5×10^5 Pa and the apparent Reynolds' number ($Re = 2\cdot\rho_0\cdot Q/\mu_0$) was smaller than 300. In the equation expressed Reynolds' number, Q, ρ_0, μ_0 are the volumetric gas flow rate, density of gas and viscosity of gas at the standard pressure and the standard temperature. The standard temperature is 20°C and the standard pressure is 1.013×10^5 Pa.

In this study, the crack width and crack length are defined as follows. First, on the cracked wall surface, along the crack, the crack length is defined as in Fig.-3. The crack length should have a certain dimension. The minimum crack length is defined as four times as long as the maximum diameter of the coarse aggregate. The maximum dimension depends on engineering judgement. Then, in the defined crack length, a straight line which can suitably represent the crack is assumed. The straight line d-d in Fig.-3 is an example. The crack width W is in the direction perpendicular the straight line d-d on the wall surface.

In the experiments, a crack does not always occur in the direction perpendicular to that of tensile load. The measured crack width includes some error. This error was neglected in the experimental data analysis. The width of the specimen was defined as the crack length.

4. Formulation using compressible flow equation

Isothermal compressible gas flow between two parallel plates is expressed by the following equation:

$$f = W^3\cdot(P_1^2-P_2^2)/(2\cdot\rho_0\cdot P_0\cdot T\cdot Q^2) \qquad (1)$$

where Q is the volumetric gas flow rate at the standard pressure P_0 and the standard temperature t_0。 P_1 is the inflow-end pressure, P_2 the outflow-end pressure, T the length between the inflow and outflow ends, W the space between two parallel plates and f the friction coefficient。 Replacing W with the crack width and T with the wall thickness, the experimental results were analyzed by the above equation (1)。 The test data plotted in the f·Q-Q plane indicate that the relationship between f·Q and Q is linear, as shown in Fig.-4。 The following equation is obtained。

$$f \cdot Q = b \cdot Q + a \tag{2}$$

Experimental coefficients a and b were both arranged as functions of crack width W, i.e., a=a(W) and b=b(W)。 Further, function a(W) was replaced with the following function $\bar{a}(W)$, according to the previous results。

$$\bar{a}(W) = a(W)/(12 \cdot \mu_0/\rho_0) \tag{3}$$

From the discrete experimental values of $\bar{a}(W)$ and b(W), functions $\bar{a}(W)$ and b(W) were formulated to the following forms。

$$\bar{a}(W) = m/W^n + 1 \tag{4}$$

$$b(W) = m/W^n \tag{5}$$

Experimental values m and n were induced for each specimen, i.e., for each identified crack。 In the above equations (4) and (5), m and n are just experimental values。 This does not mean that the values m and n of equation (4) are equal to those of equation (5)。 The following units are definitely used in this paper, W:m, P_0:Pa, P_1:Pa, P_2:Pa, ρ_0 :kg/m^3, T:m, μ_0 :Pa sec, Q:m^3/sec/m。 Non-dimensional parameters are f, $\bar{a}(W)$, b(W) and Re。

The experimental values and formulated lines of a(W) and b(W) are shown for the specimen 15-J-2 in Figs.-5 and 6。 For the specimen 15-J-2, the accuracy of the formulations is indicated in Fig.-7。 Plotted solid circles indicate the relationship between the experimental result and the value calculated by equations (1) through (5)。 The dispersion of the test results of all of the specimens to the formulated equations is shown in Fig.-8。 This indicates the frequency distribution of the Q(measured)/Q(calculated) value, where Q(measured) is a test result and Q(calculated) is from equations (1) through (5)。 As for the identified crack, the experimental results can be formulated with sufficient accuracy by equations (1) through (5)。

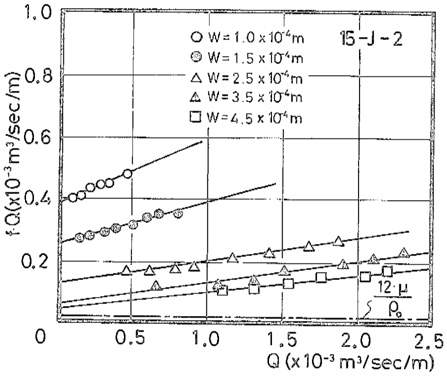


Fig.-4 Relationship between f·Q and Q of specimen 15-J-2: experimental values and their linear regressions

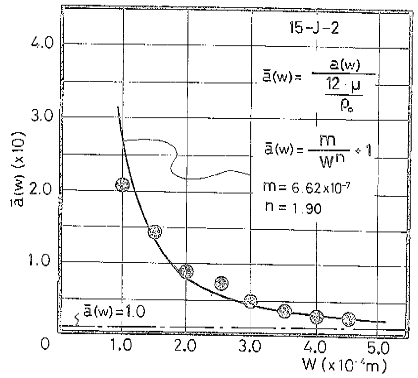


Fig.-5 Relationship between $\bar{a}$(W) and W of specimen 15-J-2: experimental values and the logarithmic regression

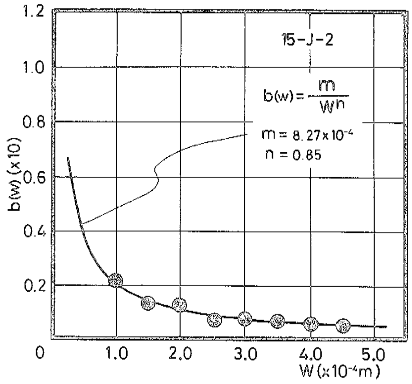


Fig.-6 Relationship between b(W) and W of specimen 15-J-2: experimental values and the logarithmic regression

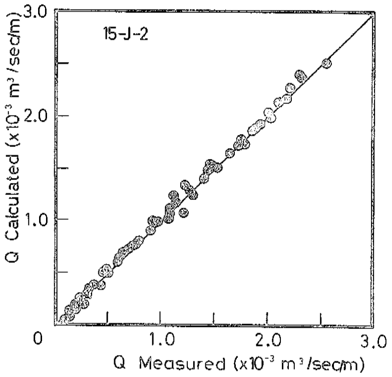


Fig.-7 Comparison of leakage rate calculated by eq.(1) with measured value

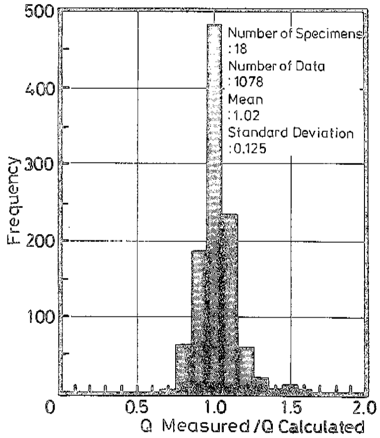


Fig.-8 Frequency distribution of the value (Q measured/ Q calculated) calculated by eq.(1) for each identified crack

5. Empirical Equation

As described thus far, the gas leakage rate through an identified crack in concrete can be formulated with sufficient accuracy. However, it does not necessarily mean that the amount of gas which will leak through concrete cracks can be predicted with sufficient accuracy, because it is very difficult to suppose the configuration of a crack which will occur in a concrete wall either on a macroscopic scale or on a microscopic scale. Macroscopic configurations of cracks cannot be averaged in a handy-sized specimen. Experimental data with handy-sized specimens should include a certain dispersion. Taking the average of the H, I and J series specimens, the empirical equations were obtained as follows:

$$Q = \left(\sqrt{a(W)^2+4\cdot b(W)\cdot C\cdot W^3} - a(W)\right)/(2\cdot b(W)) \qquad (6)$$

where $C= (P_1^2-P_2^2)/(2\cdot\rho_0\cdot P_0\cdot T)$

$a(W) = \bar{a}(W)\cdot 12\cdot\mu_0/\rho_0$

$\bar{a}(W) = 4.33\times10^{-5}/W^{1.5} + 1$

$b(W) = 3.41\times10^{-4}/W$

Frequency distribution of the value Q(measured)/Q(calculated) using equation (6) is shown in Fig.-9. The upper graph is for all of the specimens of the H, I and J series, the middle graph for the J series, the lower graph for the J-R series. Solid inverted triangles indicate the mean values. The influence of a reinforcing bar D-13 is evident as the difference between the J series and J-R series. The mean value of Q(measured)/Q(calculated) of the J-R series is approximately 80 percent of that of the J series. Deformed bar D-13 decreases the leakage rate of gas through a crack。 The bar is an obstacle itself to the gas flow, and it may decrease the crack width around the bar。

6。 Conclusions

(1) The leakage rate of gas through a crack in a concrete wall can be formulated accurately by the experimental equation based on compressible flow between two parallel plates。

(2) The effects of the type of fine aggregate and of the size of coarse aggregate are negligible。

(3) The leakage rate of gas through a crack in ordinary concrete with crushed gravel can be estimated by the experimental equation (6)。

(4) Deformed reinforcing bars decrease the leakage rate of gas。

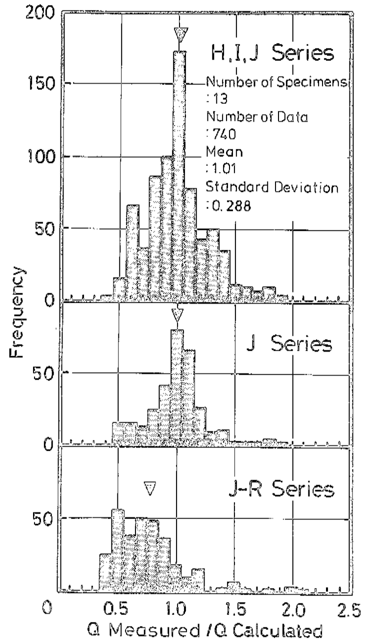


Fig.-9 Frequency distributions of the value (Q measured/Q calculated) calculated by eq.(6)

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