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A STUDY ON THE QUANTITATIVE EVALUATION OF AIR PERMEABILITY OF CONCRETE

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SYNOPSIS

The objective of this study is to investigate the behavior of air flow through concrete due to a pressure difference, and to evaluate the air permeability of concrete quantitatively. Different mix proportions and curing conditions are used so as to detect the dominant factors affecting air permeability. it is found that the coefficient of air permeability can be used as index of air permeability of concrete. And the air permeability coefficient of concrete placed under drying condition increases with the lapse of time. The increase of air permeability coefficient can be explained by the porosity based on the amount of evaporated water, because air permeability of concrete is independent of the total capillary pores in concrete, but dependent on the dried capillary pores without moisture. Futhermore, in the case of different mixture, it can be quantitatively estimated by mean of capillary pore radius in addition to the porosity.

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1. INTRODUCTION

Recently, the structures required the airtightness such as nuclear reactor containment, evaporating tank of seawater desalinization apparatus and fumigation silo are increasingly constructed with reinforced concrete or prestressed concrete due to the technological advancement of material, construction work and design method. It is necessary to use the concrete with fine airtightness for such concrete structures. The airtightness of concrete is property which can not be disregarded in accodance with the functions of structures.

The transfer of materials which corrode concrete or deteriorate of concrete has to be lessened as much as possible, in order to keep durable. This transfer is induced by the differences of pressure, concentration, temperature, voltage and so on arising between the inside and the outside of concrete. The transfer velocity of materials depends on the permeability of concrete in addition to the degree of those differences. Therefore, in the case that the material is gas such as carbon dioxide which induces carbonation or oxygen which is a cause for corrosion of reinforcing steel, it has been reported that air permeability of concrete is an important property as one of indexes for the deterioration of durability of concrete[1],[2].

When making a survey of the reports on air permeability of concrete, in the majority of cases, the Darcy's law is applied to the air flow through concrete as well as to water flow through concrete. And, air permeability of concrete is evaluated by the air permeability coefficient corresponding to the water permeability coefficient[3],[4],[5]. The concrete having a excellent watertightness also exhibits a excellent airtightness. Therefore, it has been said that the method of improvement for the airtightness of concrete is made in the same manner as the case of watertightness, namely, it is necessary to make the concrete with low water cement ratio and less unit water content and sufficiently compacted[6]. As is obvious from an example that the concrete saturated with water is almost airtight actually, there is difference between liquid and gas for the permeability of concrete. However, the studies on air permeability of concrete are limited compared with those on water permeability. Therefore, the air permeability test method has not been established, and satisfactory investigations and unified evaluation may not be performed on the air permeability of concrete.

As mentioned above, considering the increase of concrete structures requiring airtightness in the future, in order to satisfy the function of concrete structures over a long time and maintain the durability of concrete against the penetration of gas, it is important to clarify the mechanism of air permeability of concrete and to establish the prediction method of air permeability. The objectives of this study is to investigate the behavior of air flow through concrete due to a pressure difference and the applicability of Darcy's law to air permeability of concrete, to clarify the several factors affecting air permeability and to evaluate the air permeability coefficient quantitatively in connection with those factors as wll as pore structure in concrete.

2. EXPERIMENTAL PROCEDURES

Ordinary portland cement was used. River sand and crushed gravel were used as fine and coarse aggregates, respectively. The properties of cement and aggregates are given in Table 1 and 2. Fly ash and silica fume were used in this test. Table 3 shows physical and chemical properties of fly ash and silica fume.

This study took up water cement ratio, kinds of admixture and drying condition as factors affecting the air permeability of concrete. The mix proportions of concrete are tabulated in Table 4. Because the unit water content has significant effects upon the air permeability of concrete, the unit water content of each mix proportion was kept constant at 187kg/m^3. The slump was corrected by sand coarse aggregate ratio for mixtures incorporating fly ash and by a naphthalene sulfonate high condensate superplasticizer for the mixtures incorporating silica fume, respectively. For drying condition, the humidity conditions were varied in three ways, 85±5%R.H.(High), 60±5%R.H.(Medium) and 35±5%R.H.(Low), and temperature was kept at 20±1°C.

15x15x53cm in length prisms were manufactured for each mixture. After curing in water at 20±1°C for the period of 28 days and 91 days, these prisms were cut to prescribed length. Follwing this, four sides of specimens in parallel to the direction of air flow were sealed and the specimens were placed under each drying condition until the air permeability test. The air permeability test equipment is shown in Fig.1. The surfaces of specimen were grinded and was removed oil, dust and so on by acetone. After the steel plate with aperture of 14x14cm was attached to the bottom surface of specimen, the four sides were applied with epoxy

Table 1 Physical and Chemical Properties of Cement

Specific Gravity	Specific Surface (cm²/g)	Setting Time: Mixing Water (%)	Setting Time: Initial Set (hr-min)	Setting Time: Final Set (hr-min)	Flexural Strength (MPa): 3 days	Flexural Strength (MPa): 7 days	Flexural Strength (MPa): 28 days
3.15	3350	28.3	2-47	3-59	3.43	4.90	6.66

Compressive Strength (MPa): 3 days	7 days	28 days	Chemical Composition (%): ig. loss	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3
14.7	25.1	40.0	0.6	21.6	5.3	3.0	64.9	1.3	2.2

Table 2 Physical Properties of Aggregates

Aggregate	Specific Gravity	Absorption (%)	Fineness Modulus
Fine	2.63	1.56	2.21
Coarse[1)]	2.66	0.60	6.64

1)maximum size:20mm

Table 4 Mix Proportions and Properties of Fresh Concrete

Kinds of Pozzolan <P>	W/(C+P) (%)	s/a (%)	Water Content (kg/m³)	C/(C+P) %[1)]	Admixture AEA[2)]	Admixture SP[3)]	Slump (cm)	Air Content (%)
----	40	42	187	0	0.028	0	8.2	4.3
	50	46	187	0	0.028	0	9.6	4.0
	60	48	187	0	0.018	0	7.0	3.9
	70	48	187	0	0.017	0	7.5	3.9
Fly Ash	40	44	187	10	0.050	0	8.4	3.8
	40	47	187	20	0.078	0	8.9	3.7
	40	49	187	30	0.114	0	11.0	3.8
	40	53	187	50	0.154	0	12.0	3.7
Silica Fume	40	42	187	10	0.038	0.20	7.3	3.9
	40	42	187	20	0.043	0.40	7.2	4.2
	40	42	187	30	0.038	0.50	8.0	3.2

1)Percentage replacement cement by weight
2)Air-entraining agent : wt% of cement
3)Superplasticizer : wt% of cement

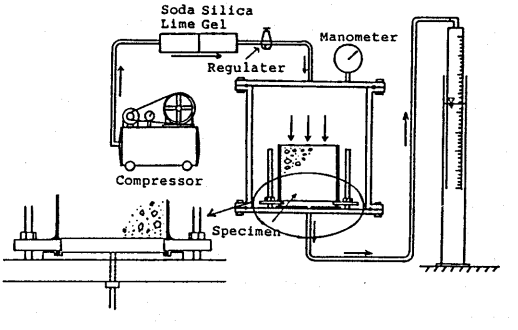

Fig.1 Air Permeability Testing Equipment

Table 3 Physical and Chemical Properties of Fly Ash and Silica Fume

Kinds of Pozzolan	Specific Gravity	Fineness	ig.loss	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O
			Chemical Composition (%)								
Fly Ash	2.14	Blaine 2950cm²/g	2.0	53.6	23.9	5.0	8.0	1.8	1.4	-	-
Silica Fume	2.27	Particle size 1-2μ	6.4	82.6	1.7	0.6	0.3	2.2	1.0	1.6	2.9

resin adhesives three times to avoid the pin hole. The specimen given airtightness treatment had air permeable face of 15x15cm at inlet and 14x14cm at outlet of specimen, and was set in a pressure vessel through O-ring so as to flow air at a right angles with direction of placing. The carbon dioxide and moisture in air were removed by soda lime and silica gel, respectively. Because it was reported that the air without the above treatment leads easily to scattering in the air permeability test[3], the air having the same condition was used for test. The loading pressure was adjusted by the requlater and was kept at the air pressure considered. The air flow rate through concrete was measured in such a manner that water is replaced with air after the air flow had become a steady state.

3. TEST RESULTS AND DISCUSSION

3.1 Air Permeability Coefficient

In many of previous studies, although the equations of calculation for air permeability coefficient vary with testing method and shape of specimen, the conception of air permeability coeficient is based on Darcy's law[3],[8],[9]. However, it is necessary to confirm whether Darcy's law is applicable to air flow through concrete. As is well known, Darcy's law was experimentally obtained. When the fluids flow through porous media or media filled with fine particles, the apparent velocity (υ) expressed as follows is directly proportional to the pressure gradient ($\Delta P/\Delta x$) [10].

$$\upsilon=-K(\Delta P/\Delta x) \qquad (1)$$

The apparent velocity is obtained by dividing the amount of flow by the cross sectional area of media. Eq.(1) defines the permeability coefficient, which is obviously indicative of the permeability of a certain medium to a particular fluid. K is the air permeability coefficient of concrete in the case of air flow through concrete. Fig.2 shows the relationship between apparent velocity of air flow and loading pressure. The relationships are not linear, namely, the rate of increase in apparent velocity is higher than that in loading pressure. As is also found from the figure, the thinner thickness of specimen becomes, the higher the apparent velosity becomes.

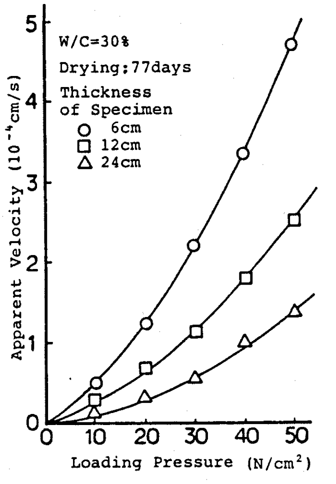

Fig.2 Relationship between Apparent Velocity and Loading Pressure

If air flows through concrete in accordance with Darcy's law, the apparent velocity must be proportional to the pressure gradient. In order to obtain the pressure gradient, it is necessary to know the distribution of pressure in concrete. The distribution of pressure is obtained as follows.;

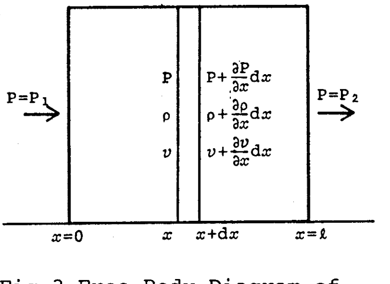

Fig.3 Free Body Diagram of Element of Length dx and Boundary Condition

From the assumption that air in the infinitesimal element of concrete flows steadily in one direction, Eq.(2) is obtained from the continuous equation of compressive fluid with density ρ (see Fig.3).

$$\rho(\partial \upsilon/\partial x)+\upsilon(\partial \rho/\partial x)=0 \qquad (2)$$

The density can also be expressed by the equation of state at constant temperature.

$$\rho=(M/RT)P \qquad (3)$$

Where, P is a pressure, M is a molecular weight of gas, T is an absolute temperature and R is a gas constant. Furthermore Darcy's law is used as the equation of motion.

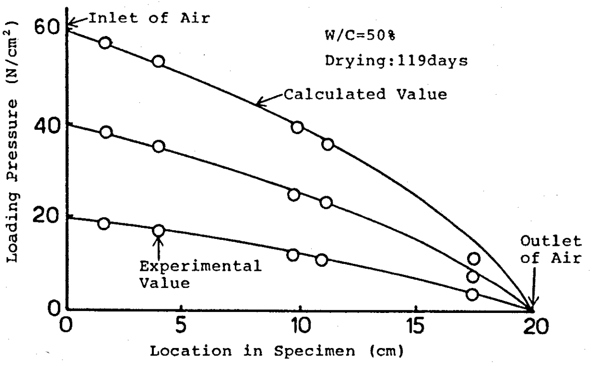

Fig.4 Distribution of Pressure

$$\upsilon=-K(\partial P/\partial x) \qquad (4)$$

Eq.(5) is derived from Eqs.(2),(3) and (4).

$$P\frac{\partial^2 P}{\partial x^2}+\left(\frac{\partial P}{\partial x}\right)^2=0 \qquad (5)$$

Solving Eq(5) under the boundary conditions of $P=P_1$ (loading pressure) at surface of x=0 and $P=P_2$ (atmospheric pressure) at bottum of $x=\ell$, the following equation can be obtained.

$$P=\left(\frac{P_2^2-P_1^2}{\ell}x+P_1^2\right)^{1/2} \qquad (6)$$

Fig.4 shows the distribution of inner pressure measured by the pressure transducer attached to inlet of hole of ϕ1x2cm on a side of specimen. The distribution of pressure which is calculated by Eq.(6) is also drawn in the figure. The experimental values agree well with the calculated value. Therefore, it is found that the distribution of pressure in concrete is not a straight line, but a parabola expressed by Eq.(6).

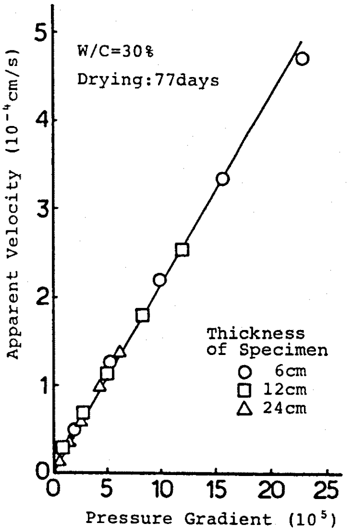

Fig.5 Relationship between Apparent velocity and Pressure gradient

As is evident from Fig.4, the pressure gradient varies with the location in concrete. Because the apparent velocity at outlet of specimen can be measured, the relationship between the apparent velocity and the pressure gradient at outlet of specimen shown in Fig.5 is obtained. The apparent velocity at outlet of specimen has been already shown in Fig.2 and the pressure gradient is given by differentiating Eq.(6) at $x=\ell$. The relationship between the apparent velocity and the pressure gradient is independent of the thickness of specimens and loading pressure, and it is related by a straight line. The slope of this straight line represents the air permeability coefficient. Substituting the pressure gradient obtained by differentiating Eq.(6) into Eq.(4), the air permeability coefficient can be obtained as follows.;

$$K=\frac{2\ell P_2\gamma}{P_1^2-P_2^2}\cdot\frac{Q}{A} \qquad (7)$$

where, K:air permeability coefficient (cm/s), Q:amount of air flow (cm^3/s), . L:thickness of specimen (cm), A:cross-sectional area of specimen (cm^2), P_1:loading pressure (N/cm^2), P_2:atmospheric pressure (N/cm^2), γ:unit weight of air (1.182×10^{-5} N/cm^3). This study uses the unit weight of air when the pressure is transformed into head.

Fig.6 shows the effects of loading pressure and thickness of specimen on the air permeability coefficient. Although the air permeability coefficients of concrete have about the same value irrespective of the difference of specimen thickness, air permeability coefficient slightly decreases with the increase of loading pressure. This reason is considered to be due to the fact that the form loss produced in the pipe from the outlet of specimen to the cylinder is neglected in the equation(7) used for the calculation of air permeability coefficient. However, the about 10% of coefficient of variation shows that the air permeability coefficient is approximately independent of loading pressure. In the case of the results shown in Fig.6, it is water cement ratio that determines air permeability coefficient essentially.

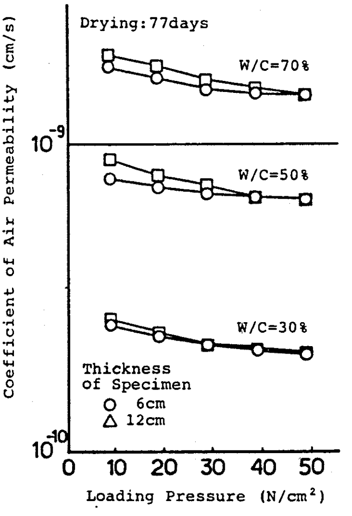

Fig.6 Relationship between Air Permeability Coefficient and Loading Pressure

From the dimensional analysis, it is generally said that the coefficient K in Darcy's law (water permeability coefficient or air permeability coefficient) is related to density and viscosity of fluid as well as quantity, size, shape, distribution and continuity of pores in porous media[10]. Because air permeability test is carried out under the same condition for air, air permeability coefficient obtained from this test depends only on the internal structure of concrete. In general, the applicability of Darcy's law, which needs the negligibility of the inertia force as compared with the viscous force, can be judged from Reynolds number. Many experiments on seepage of soil have been reported that Darcy's law is applicable in the range below Reynolds number from 1 to 10 [10],[11]. However, in the case of concrete, the relationship between the applicability of Darcy's law and Reynolds number has not been clear due to the limited experiment on air permeability of concrete. But the Reynolds number of 10^{-4} in the order of magnitude calculated by using the kinematic viscosity of air, maxmum apparent velosity in this test and the mean radius of capillary pore is sufficiently samll, which means the inertia force to be negligible. Furthermore, judging from the results of Figs.4, 5 and 6, it is concluded that Darcy's law can be applied to the air flow through concrete in this study, and air permeability coefficient defined by equation(7) is available as one of the indexes indispensable to evaluate the air permeability of concrete itself.

3.2 Effects of Mixture on Air Permeability of Concrete

Firstly, the effect of water cement ratio on air permeability of concrete is examined. The all specimens were tested under the drying condition with temperature of 20±1°C and relative humidity of 60±5%, and three kinds of drying duration of 21, 84 and 117 days are selected. Fig.7 shows the relationship between the air permeability coefficient and water cement ratio. The air permeability coefficient of concrete increases remarkably with the increase of water cement ratio. This relationship has been reported in the studies on the air permeability of concrete and mortar[3],[12],[13]. This can be expained by the fact that air as well as water flows mainly in capillary pore of concrete. It is said that the pore structure in concrete is built up in closely connection with both water cement ratio and degree of hydration. That is, the lower the water cement ratio becomes and the more the hydration goes on, the more the capillary pore volume decreases. And the lower the water cement ratio becomes, the earlier the capillary pore forms discontinuous structure in the prosess of hydration[14]. The airtightness with low water cement ratio shown in Fig.7 must be brought about by the decrease of capillary pore volume and the formation of discontinuous structure of capillary pore.

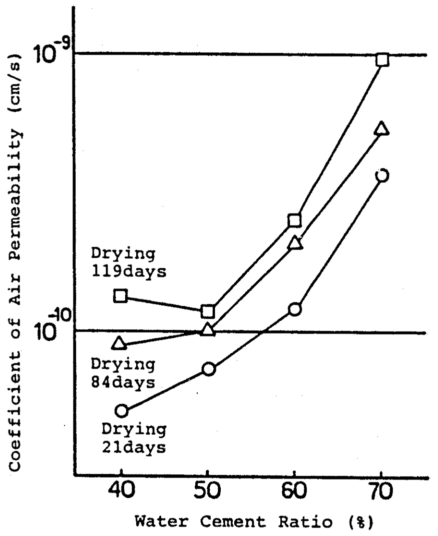

Fig.7 Effects of Water Cement Ratio on Air Permeability

Secondly, the air permeability coefficient of concrete, in which the capillary pore structure is changed by the replacement of admixtures, is discussed. Fig.8 shows effects of replacement of fly ash on air permeability coefficient. In the case of curing in water for the period of 28 days, the air permeability coefficient of concrete with the raplacement ratio of fly ash below 20% is not more than that of concrete without fly ash. However, when fly ash more than 30% is replaced, the air permeability coefficient of concrete with fly ash is larger than that of concrete without fly ash. On the other hand, air permeability coefficients of concrete with fly ash and without fly ash cured in water for 91 days are lower than those of concrete cured in water for 28 days. While, the decreasing degree of air permeability coefficient of concrete with fly ash is larger than that of concrete without fly ash. Therefore, in the case of curing in water for period of 91 days, the air permeability coefficient of concrete with fly ash is below that of concrete without fly ash notwithstanding replacement ratio of fly ash. It is said that the proper replacement ratio of pozzolan has the effect of improvement on airtightness of concrete[8]. In this experiment, the optimum replaceemnt

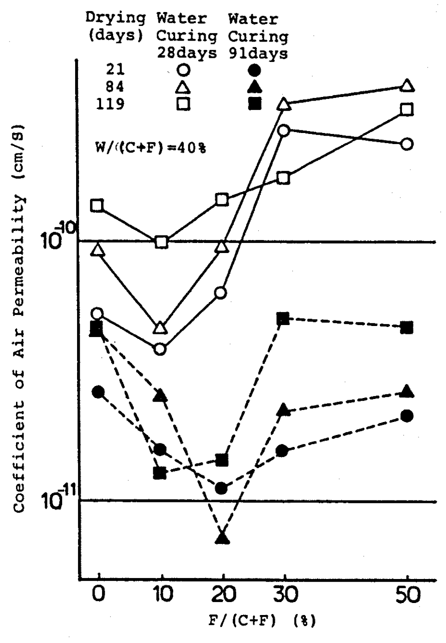

Fig.8 Effects of Replacement of Fly Ash on Air Permeability

ratio of fly ash is 20% for the concrete cured in water for 91 days. The probable expranation for the above reason may be that volume of capillary pore is reduced by the hydrated compounds due to the pozzolanic reaction of fly ash.

Fig.9 shows relationship between compressive strength and the air permeability coefficient. The compressive strength test was carried out immediately after the end of curing in water for 28 and 91 days. The air permeability coefficient decreases with the increase of compressive strength. The air permeability coefficient of concrete with fly ash cured in water for 28 days is almost equal to that of concrete without fly ash at the same compressive strength. The concrete, which is replaced by the fly ash and is cured in water for 91 days, becomes more airtight than that cured in water for 28 days even at the same of compressive strength.

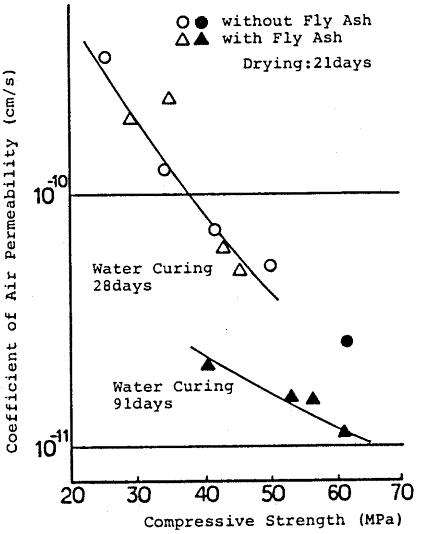

Fig.9 Relationship between Compressive Strength and Air Permeability Coefficient

Fig.10 shows the effects of replacement of silica fume on the air permeability. The air permeability coefficient of concrete with silica fume decreases generally with the increase of replacement ratio of silica fume regardless of the curing period in water. As the excellent property of silica fume compared with other pozzolanic materials, it is pointed out that silica fume has not only higher pozzolanic reactivity but also extremely finer particle size[15]. The cause that air permeability coefficient of concrete with silica fume becomes low regardless of the curing period in water is due to the invation of fine particles among the cement particles followed by the production of hydrated compounds of pozzolanic reaction at relatively early ages.

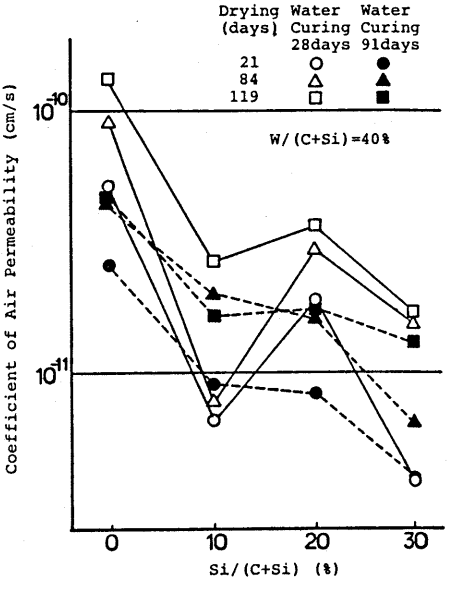

Fig.10 Effects of Replacement of Silica Fume on Air Permeability

Fig.11 shows the air permeability coefficient and compressive strength of concrete with silica fume and without superplasticizer. Although the compressive strength of concrete with silica fume is higher than that of concrete without silica fume, the air permeability coefficient of concrete with silica fume is higher than that of concrete without silica fume. This may be due to the fact that the cohesion restrains its invation into the gap among the cement particles. The improvement of air tightness of concrete with silica fume needs the sufficient dispersion of the silica fume.

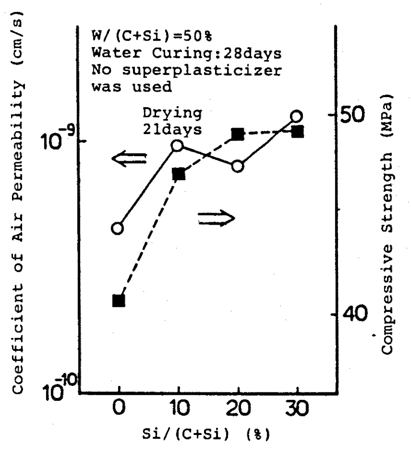

Fig.11 Air Permeability and Compressive Strength of Concrete with Silica Fume without Superplasticizer

3.3 Effect of Drying on Air Permeability of Concrete

In the air permeability test described above, the air flow through concrete was not observed in the early stage after the start of air curing. However, the air permeability coeficient increased in the course of time after drying. This means that the valuse of air permeability coefficient depends upon the amount of water evaporated from concrete. Furthermore, it is reported that the distribution of water which is formed in the process of drying in concrete has the influence on the air permeability coefficient[16]. In the case of concrete with uniformless distribution of water, as the air permeability coefficient distributes corresponding to the distribution of the amount of evaporated water, the air permeability coefficient obtained by Eq.(7) represents air permeability coefficient averaged through the depth. Therefore, the effect of the difference of the amount of evaporated water on air permeability is discussed in this study as follows.

Considering that the air permeability coefficient is closely connected with evaporated water, air must flow through capillary pores in which water has evaporated due to drying. Therefore, the volume of capillary pores through which air is possible to flow can be considered to be equal to the amount of water evaporated from concrete. This amount of evaporated water is obtained from the measurment of weight reduction of concrete owing to drying. Fig.12 shows the internal humidity distribution in concrete with four sides sealed. The humidity in concrete is measured by inserting the electric resistance type hygrometer into the hole with ϕ1x7cm which is prepared at prescribed position. From the results measured the humidity shown in Fig.12 and the previous studies on the moisture distribution in concrete[17], it may be appropriate to assumed that moisture is uniformly distributed along the depth of concrete having four sides sealed with epoxy resin, because the difference between relative humidity at the depth of 1cm apart from surface and that at center depth dose not exceed 5%, furthermore, the volume from the depth of 1cm apart from surface to that apart from bottom accounts for 80% of total volume. Therefore, the specimen, four sides of

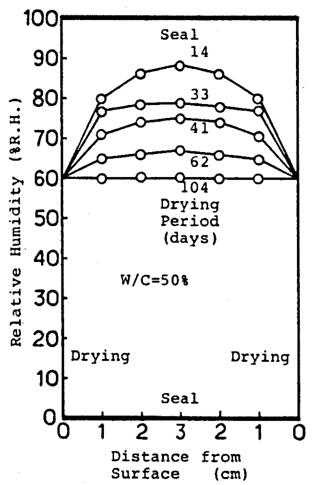

Fig.12 Humidity Distribution in Concrete

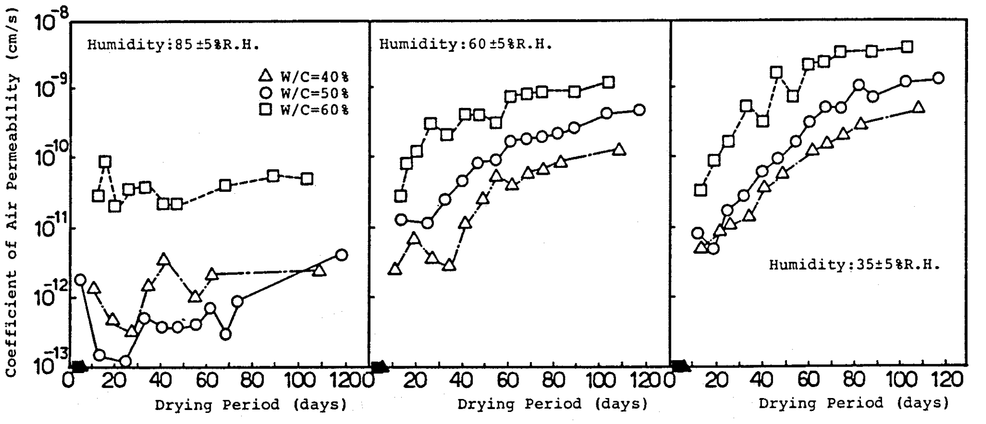

Fig.13 Time-Dependent Change of Air Permeability Coefficient

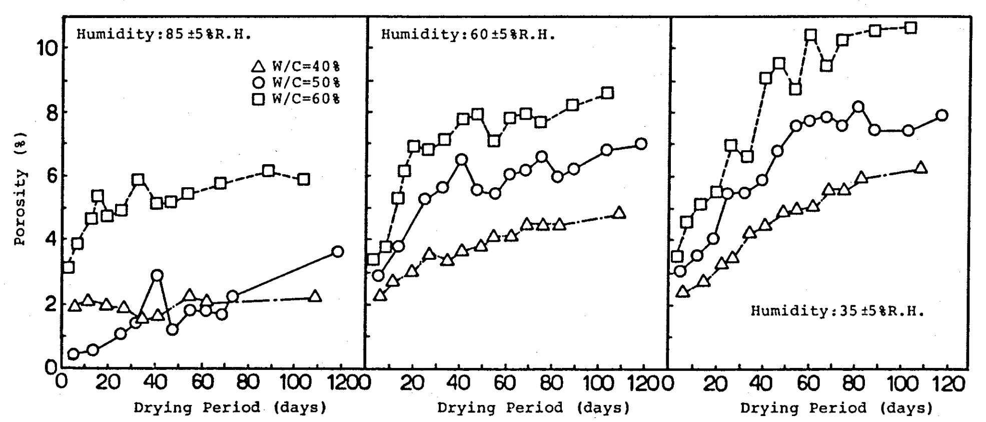

Fig.14 Time-Dependent Change of Porosity

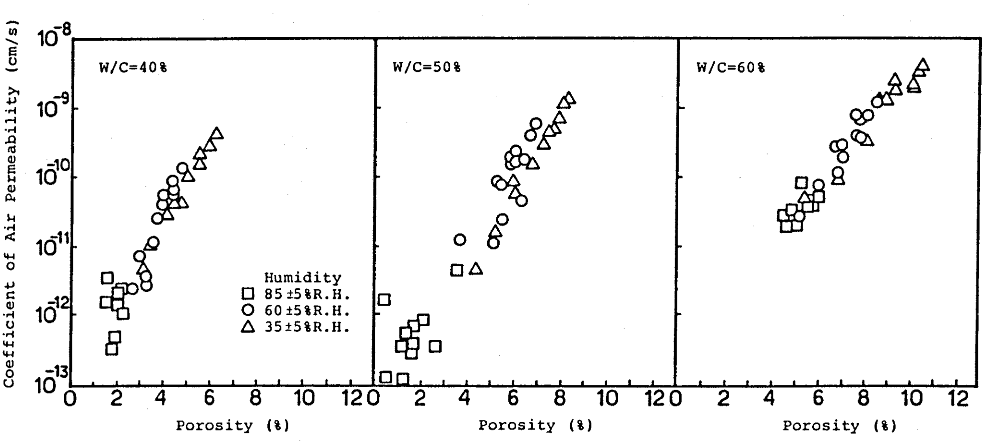

Fig.15 Ralation Ship between Air Permeability Coefficient and Porosity

which are sealed in parallel to the air flow, is used in this test.

Fig.13 shows the time-depemdent change of air permeability coefficient under three kinds of humidity condition. The specimen were placed under high, medium and low humidity conditions after curing in air of 20±1°C and 60±5%R.H. for 7 days. The marks painted black indicate that concrete has perfect airtightness. In this experiment , the air flow through concrete was not observed until the age of 10 days after the start of drying excluding one specimen. For the results after the age of 10 days under drying, the air permeability coefficient of concrete placed under high humidity condition were almost constant. On the contrary, the air permeability coefficients of concrete placed under medium and low humidity conditions increase in all cases of three kinds of water cement ratio in the course of time under drying. However, each increasing rate decreases with the lapse of drying days and the air permeability coefficient has a tendency to converge to the almost constant value. The air permeability coefficient of concrete with higher water cement ratio increases faster in early ages after the start of drying, and moreover, the converged value becomes larger. Compared at the same age after the start of drying, as is shown in Fig.7, the concrete with higher water cement ratio under the constant humidity condition showed larger air permeability coefficient. The air permeability coefficient of concrete made by the same mix proportion has also larger value as environmental relative humidity decreases.

Fig.14 shows the time-dependent change of the amount of water evaporated from concrete. Where, in this figuer, the porosity in ordinate is difined as the ratio of volume of evaporated water to that of specimen. The time-dependent change of porosity indicated the same tendency as that of air permeability coefficient shown in Fig.13. Therefore, the relationship between air permeability coefficient and porosity is illustlated in Fig.15. It is found that, in any case of water cement ratio, there is a near connection between the air permeability coefficient and porosity regardless of humidity condition surrounding concrete. However, because water cement ratio varies the increasing rate of air permeability coefficient to the porosity, evaluation of air permeability coefficient of concrete with different mix proportions can not be perfromed only by the porosity.

3.4 Quantitative Evaluation of Air Permeability Coefficient of Concrete

The internal structure of cement paste includes gel pores and capillary pores. The size of these pores ranges from about 10 Å to several micrometeres. Furthermore, the pore structure in concrete is not uniform in size as well as in distribution due to the presence of various kinds of pore such as pores under the aggregates, entrapped and entrained air voids and microcracking. The air permeability coefficient of concrete is not a simple function of the porosity, but depends also on the size, the distribution and the continuity of the pores. For the purpose of quantitative evaluation for the air permeability coefficient of concrete with different mix proportions, the porous medium with a bundle of straight, parallel capillaries of uniform radius shown in Fig.16 is assumed in this study. This model aims at correlating the air permeability coefficient of concrete with the quantity and the size of pores. The model is available to deal with fluid flow in porous media [11],[18],[19]. As the

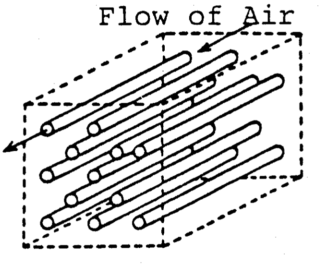

Fig.16 Model Based on Linear Capillaries

size of pores is small and the velocity of air flow is not high so much, the air flow in pores is assumed to be a laminar flow. According the discussion, the apparent velocity of porous media is proportional to the pressure gradient as well as the product of porosity and radius of capillary squared. Therefore, comparing with the Darcy's law, the permeability of this model is given as follows.

$$K' = C\varepsilon d^2 \qquad (8)$$

where, K' is the permeability of porous media, ε is the porosity of the porous media, d is radius of capillaries in porous media and C is a constant. Although the permeability of porous media K' is influenced by the viscosity of fluid, the constant C contains the effects of viscosity of fluid. εd^2 with the dimension of length squared is controlled by the pore structure of porous media and is independent of properties of fluid.

The above approach is applied to the air permeability of concrete. Because capillary pores without water due to drying become the path of air flow as is shown in Fig.15, the porosity ε is calculated from evaporated water. The time-dependent increase of air permeability coefficient due to drying can be explained by the increase of porosity shown in Fig.14.

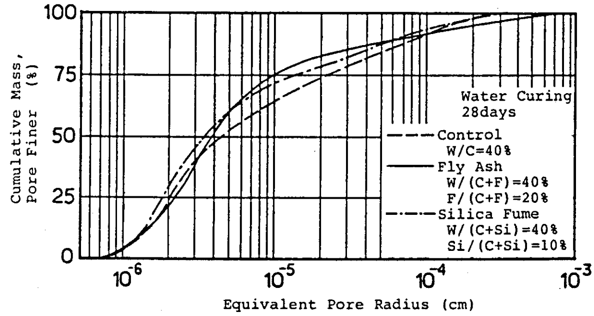

Fig.17 Pore Size Distribution

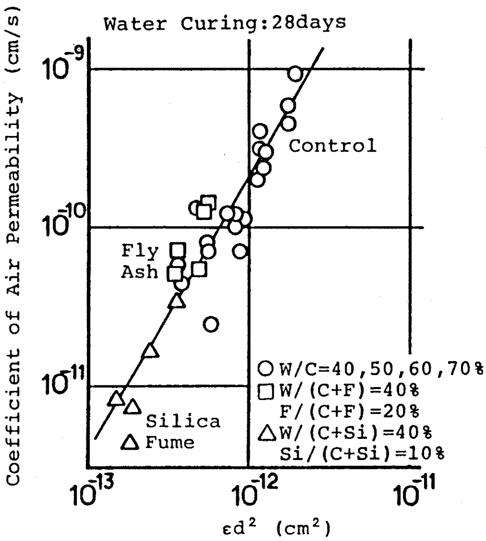

Fig.18 Relationship between εd^2 and Air Permeability Coefficient

The mean radius of capillary pores is used as radius of capillaies d, because the path of air flow is capillary pore in concrete. Fig.17 is an example of pore size distribution curve. The mean radius of capillary pores used in this study is the radius at the value of 50% of pore size distribution curve measured by the marcury penetration method. Both mean radii of concrete with fly ash and that with silica fume are smaller than that of concrete without the admixtures. The effects of water cement ratio and replacement of admixture on air permeability coefficient can be evaluated by the size of mean radius of capillary pores in addition to the increasing rate of porosity.

Fig.18 shows the relationship between the air permeability coefficient of concrete and εd^2. Though the air permeability coefficient of concrete fixed mix proportion can be evaluated only by the porosity calculated from the evaporated water, in case of concrete with different water cement ratio, different replacement ratio of fly ash and that of silica fume, Fig.18 indicates that relationship between the air permeability coefficient of concrete and εd^2 is linear. This fact means that the air permeability coefficient can be determined by both the porosity and the mean radius of capillary pores. However, the ralationship between air permeability coefficient and εd^2 is represented by $K=(\varepsilon d^2)^n$, and this relationship differs from equation(8). This reason is due to the application of model with straight capillaries, that is, the capillary pores in actual concrete are not connected in a straght line. As the problem to be investigated, in order to evaluate the air permeability coeficient of concrete more strictly, taking the geometrical properties of pore structure into account is needed. However, based on the model that concrete is porous media with a bundle of straight parallel capillaries of unifrom radius, as is expressed in Fig.18, it is clear that the air permeability coefficient of concrete with different mix proportions could be quantitatively estimated by incorporating the mean radius of capillary pores and the porosity due to the evaporated water.

4. CONCLUSIONS

The air permeability test was carried out in this study to catch the air permeability of concrete. The air permeability coefficient as the index of air permeability of concrete was examined. Furthermore, this study discussed the mechanism of air permeability of concrete. The main results obtained from this study are summarized as follows.

(1) When air pressure is applied to concrete surface, the pressure distribution through the depth of concrete is not straight but parabolic expressed by the equation (6). The rate of increase in apparent velocity is higher than that in loading pressure.

(2) Darcy's law can be applied to estimate the air flow through concrete. The air permeability coefficient of concrete has almost constant value regardless of thickness of specimen, and depends on pore structure in concrete. Therefore, it is possible to apply the air permeability coefficient as the index of air permeability of concrete.

(3) Although the concrete with fly ash cured in water for period of 28 days has almost the same value as concrete without fly ash at the same compressive strength, the concrete with fly ash cured in water for period of 91 days has a lower air permeability coefficient than concrete without fly ash due to the pozzolanic reaction.

(4) The silica fume makes the internal structure of concrete finer because of the high pozzolanic reactivity and its very fine particle size. As the result, the use of silica fume makes the air permeability coefficient of concrete decrease regardless of curing period in water and the degree of decrease becomes large with the increase of replacement ratio of silica fume.

(5) Because the path of air flow is capillary pores without water, not all capillary pores, the air permeability coefficient of concrete from which water evaporates easily or which is placed under evaporable environment increases rapidly and reaches a large value.

(6) The air permeability coefficient of concrete is expressed by the single straight line as the function of the porosity obtained from the evaporated water

as well as the mean radius of capillary pores measured by the murcury penetration method.

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