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EVALUATION OF SURFACE TREATMENT EFFECTS FOR REINFORCED CONCRETE MEMBERS BASED ON DURABILITY DESIGN APPROACH

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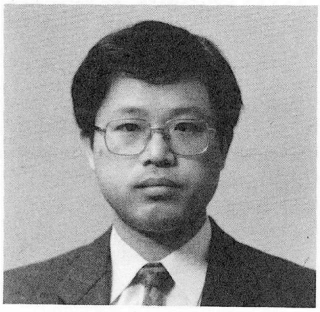

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SYNOPSIS

Permeability performance of surface treated concrete using synthetic resin is examined experimentally. Transmission rates of oxygen, liquid phase water and vapour phase water through surface treatment-concrete system are measured. And fundamental concept of durability design against reinforcement corrosion is discussed. The conclusions in this paper are summarized as follows; (1) Transmission abilities decrease with increasing surface treatment thickness and decreasing water cement ratio. (2) While, epoxy lining or MMA impregnation is a water proofing system, silan impregnation, silan with polymer cement mortar coating or urethane lining is a water phobic system. (3) Concrete surface treatment can't elongate the service life of chloride damaged reinforced concrete member, unless chloride contaminated cover concrete is removed.

Keywords: surface treatment, reinforced concrete member, durability design, diffusion of oxygen, diffusion of water, chloride corrosion, synthetic resin, repair

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1. INTRODUCTION

Since the period of high economy growth during 1955∿1965 in our country, a number of enormous concrete structures such as high rising buildings, express ways and dams for hydraulic power generation etc. have been constructed. And, as supply of river sand and gravel has become insufficient, marine sand and crushed stone have increasingly been employed as aggregate for concrete. On the other hand, many kinds of concrete structures have been constructed in the marine environment such as along the seashore or water front of the bays. As a result, a number of examples of early deterioration caused by reinforcement corrosion and alkali-aggregate reaction have been reported. Consequently, the cases that require the repairing and strengthening for the damaged existing structures are increasing rapidly.

Under these circumstances, the concept of durability design that consideration should be paid for the durability as much as to the strength in the stages of designing was generated. The purpose of durability design can be considered to guarantee the function of a structure with a certain reliability by means of a comprehensive system that consists of design, construction, maintenance, repairing, strengthening and dissolution, taking into account the time-dependent properties of constitutive materials and their effects on the performance of the structure.

Generally, the durability design may be divided into two categories, namely, the one that is executed at the time of construction and the other done at the time of repairing to elongate the life of the struction. For instance, the process of reinforcement corrosion can generally be illustrated as shown in Fig.1[1] in which t_1 denotes the time until corrosion begins after constructed and t_2 does the time until the critical amount of corrosion causing the cracks in the cover concrete is reached. In this case, estimating the values of t_1 and t_2 or designing the structure for the required values of t_1 and t_2 represents the durability design at the time of construction. On the other hand, the another one corresponds to specifying the time and method of repairing to be done in order to elongate the service life of the deteriorated structure for a required length[2], as shown in Fig.2 where t_r denotes the life expectancy after repairing.

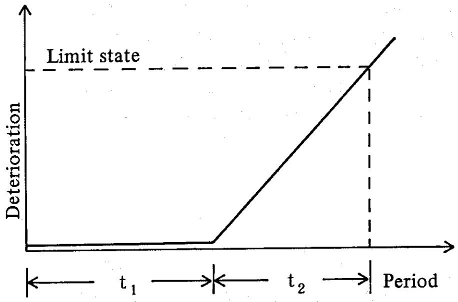

Fig. 1 Deterioration due to reinforcement corrosion

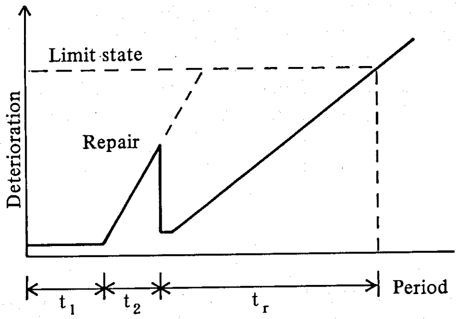

Fig. 2 Concept of repair

In the durability design, it is essential to determine exactly the characteristics of the concrete structure and the method of repair as well as the macroscopic or microscopic environmental conditions. However, in addition to the fact that concrete itself is a composite material, there are numerous factors that affect the durability. It, therefore, will take a long period for the exact evaluation of durability. For this purpose, firstly resolution of the required performance into the fundamental units should be done and the principal factors affecting the durability should be confirmed. Then sistematizing these results, a comprehensive model for analysis of the durability should be developed to represent the durability performances quantitatively.

In this study, the surface treatment with the synthetic resins for repairing of the concrete structures is examined. And, the it is intended to clarify the effect of the properties of resins and concretes, the film thickness of treatment and the ambient humidity etc. on the permeability of oxygen and water. The fundamental approach for the durability design of the concrete structure is also proposed, taking reinforcement corrosion as an example.

2. Permeability in Surface Treatment-Concrete System

As the permeability of oxygen, water or chloride into concrete varies significantly depending upon the types of surface treatment, a system of low permeability against a substance related closely to an anticipated deterioration should be chosen when surface treatment is adopted in the durability design. It is generally recognized that the rate of reinforcement corrosion is controlled by permeability of oxygen and that the alkali aggregate reaction is affected significantly by the existence of water. Some types of surface treatment which have an ability of dissipating moisture included within concrete have been developed. The following three factors relating to the surface treatment are chosen.

i) Water cement ratio W/C of concrete: In order to examine the influence of the quality of concrete, four levels of W/C of 30%, 40%, 50% and 60% are used. Their mix proportions are shown in Table 1, in which a high early strength portland cement is used for all mixes.

ii) Types of surface treatment: Following five kinds of surface treatment in practical use are adopted.

a) epoxy system (β is phenol A type: elongation 10%),
b) urethane system which is expected for its high crack bridging ability (poly-buthadiene type: elongation 400%),
c) MMA system which has abundant experience as impregnating agent in the U.S.,
d) silan system which is expected for its controlling effect against alkali aggregate expansion (oligomer) and
e) the PCM system (polymer cement mortar of acryl type: water/cement ratio: 63%, polymer cement ratio 113%, cement/silica sand ratio: 1 : 1.5) in combination with d) for improving weather resistant and preventing carbonation of concrete.

Generally, the former three can be classified into a water proofing system: suppressing both of intrusion and diffusion of water through the treated surface layer, and the remaining two to a water repellent system: dissipating water out of concrete in addition to preventing its intrusion into concrete.

iii) Degree of surface treatment: With regard to the epoxy and urethane systems, four different thickness of 120 μm, 240 μm, 500 μm and 1000 μm are taken based upon "Guidline of Counter-Measure against Salt Attack in Road Bridges (draft) and its Commentary" together with experiences of practical repair works. On the other hand, two different amount of 500 g/m^2 and 1000 g/m^2 for MMA a single amount of 100 g/m^2 for silan, and two different thickness of 0.5 mm and 1.2 mm for PCM are used.

Table 1. Specified mixproportion of concrete

W/C (%)	Slump (cm)	Air content (%)	S/A (%)	Maximum size of coarse aggregate(%)	Unit content (kg/m^3)				Admixture (g/m^3)
					Cement	Water	Fine aggregate	Coarse aggregate	
30	7~10	4 ±1	35	15	600	180	531	1024	5800 (Superplasticizer)
40			35		360	144	992	843	7000 (Superplasticizer) 1440 (Air entraining agent)
50			55		360	180	942	799	1800 (AE water reducing agent)
60			55		360	216	890	757	1440 (Air entraining agent)

(1) Permeability of oxygen

a) Diffusion of oxygen

When intrusion and diffusion of oxygen within concrete is discussed it should be noted that the process of reinforcement corrosion is to be an electro-chemical reaction. In the reaction process accompanied by the flow of electrons in an electrodes/electrolyte system two processes of, i) electric charge transfer and ii) substance mass transfer are considered to take place as shown in Fig.3. In the case of reinforcement corrosion, reactions at the anode and cathode correspond to the process i), white intrusion and diffusion of water and oxygen to ii). The process of diffusion during the mass transfer is indispensable for the progress of the electro-chemical reaction and constitutes the rate controling process. In the corrosion process of steel in concrete, diffusion of oxygen is supposed to be the rate controlling process.

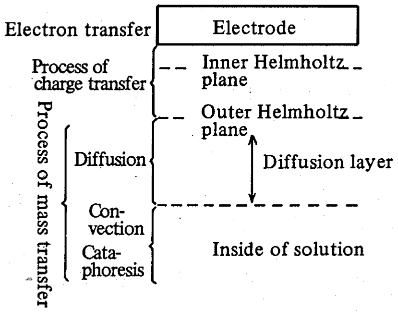

Fig. 3 Reaction of electrode

As the fundamental formula of diffusion, Fick's low has been well known. According to the law, as shown in the formula(1), dQ/dt, the quantity of substance that passes through an unit area of the plane at position x is proportional to dC/dX, the gradient of concentration at this plane.

$$-dQ/dt = d(dC/dX) \quad \ldots\ldots\ldots\ldots (1)$$

Where, D: Coefficient of diffusion
The value of dC/dX can be approximately represented by the following formula:

$$-dC/dX = (C_b - C_o)/\delta \quad \ldots\ldots\ldots\ldots (2)$$

Where, C_b: Concentration of substance within the solution
C_o: Reaction surface of the electrodes (Concentration at the outer Helmholtz surface)
δ : Thickness of the diffusion layer

If diffusion of oxygen is assumed to be in the stage of controlling the rate of corrosion reaction, oxygen that reaches the steel surface is wholly consumed there, thus $C_o = 0$. Accordingly, the formula(1) can be transformed into

$$-dQ/dt = D(C_b/\delta) \quad \ldots\ldots\ldots\ldots (3)$$

The thickness of the diffusion layer changes with time t and it is represented by[3]

$$\delta(t) = \sqrt{xDt} \quad \ldots\ldots\ldots\ldots (4).$$

The thickness, δ, is found to be affected by the convection within the solution and to grow only up to around 0.5 mm[3]. Therefore, the true diffusion layer for reinforcement corrosion can be considered to be not the whole of cover concrete but the thin layer close to the reinforcing bar.

However, according to this concept, the gradient of oxygen concentration within the cover concrete is not taken into account, and then the distinction between oxygen in dissolved state within water and oxygen in the gaseous phase, which is the most important item to be considered in the corrosion reaction, is not made clear. Therefore, it results in a model where the thickness of concrete cover does not influence the diffusion of oxygen.

It is reported by Kobayashi[4] and Miyagawa et al.[5] that the water content of concrete has great influence on the permeability of air. And, it is presumed that there could be a gradient of concentration, due to the existence of pores and the condition of water content, in the concrete cover. When the surface of concrete is not wet and subject to sufficient supply of oxygen, even if the distribution of pores is uniform within concrete, the water content decreases with reducing distance from the concrete surface due to evaporation of water. In addition, extension of the diffusion layer due to the convection within solution and variation in the water content should be taken into account. However, since the distance of diffusion is difficult to be determined experimentally, it is roughly assumed that the apparent gradient of concentration is linear throughout the cover concrete. By using the apparent gradient of concentration, the phenomenon of oxygen diffusion can be dealt with in a simplified way.

b) Method of measurement

The pressuring method, equi-pressure method and electro-chemical method etc. have been used for measuring the permeability of oxygen. However, according to Feldman[6], the pores within concrete are enlarged and connected together in the pressurized condition, resulting in a quite different state from the original one. Therefore, this method is not proper for the test of corrosion. The equi-pressure method, although not changing the pores-structure, is not suitable to examine whether the pores really participates in the corrosion of steel and also to make clear the behavior of oxygen in the dissolved states as the measurement is done in the air. On the other hand, since the electro-chemical method makes use of the reaction of oxygen reduction, the measured value in the case reinforcement corrosion is to be equivalent to the amount of oxygen transmission. And, the third method adopted in this study.

The specimens as shown in Fig.4 are prepared. The steel plate is bonded to the bottom of the vessel by using epoxy resin and the same kind of resin is applied on the inside surface of the vessel immediately before placing concrete in order to prevent the intrusion of air or water through the aperture between the vessel and concrete. Concrete is cured in the sealed condition for more than four weeks. As, in the case of the surface treatment agent of impregnating type such as MMA and silan, the agent may stick on the platinum wire and affect its function as the reference electrode, a small quantity of epoxy resin is applied on the joint portion of concrete surface with the platinum wire prior to the surface treatment.

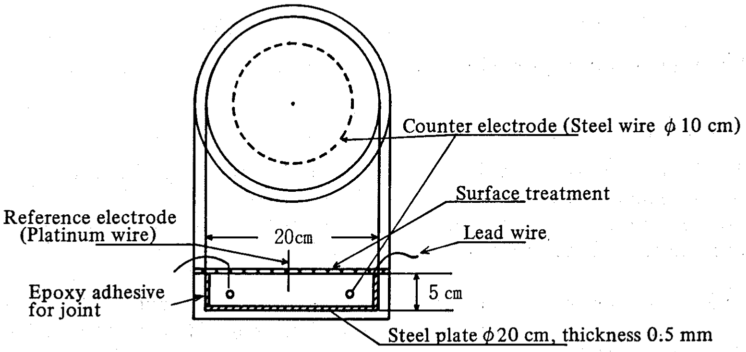

Fig. 4 Specimen for oxygen permeability test

Two specimens are prepared for each one test variable and kept in the thermostatic chamber of 20°C and RH 85 ± 5%. In case oxygen in dissolved state within the specimen is reduced at the cathode by the corrosion reaction, the cathodic reaction shows a nature of controlling the diffusion rate and the polarization curve indicates the critical current parallel to the electric potential axis.

First, the polarization test is conducted at the rate of -0.08 mV/s in the range of -500 mV $\sim$ 1,500 mV by means of the automatic polarization apparatus and the potential E_{llm} that gives the critical current density i_{llm} is obtained. And then, the sampling electrodes within the specimen is kept at the potential E_{llm} using the potentiostat. The current between the counter electrode and the potentiostat is measured with the resistanceless ammeter. The stationary value obtained during the test period of 7 days is taken as the critical current. When the stationary current is not reached during 7 days, the minimum value of the current is set to be the critical current.

The relation between the amount of oxygen transmission and the density of electric current (i/A) is given by the formula(5) according to Faraday's law, assuming that the amount of oxygen consumed at the electrode is transmitted.

$$-dQ/dt = i/(nAF) \qquad \dots\dots\dots\dots (5)$$

From the formulas(1) $\sim$ (5), the formula(6) can be obtained.

$$J_4 = i/(nAF),\ D_4 = J_4 \delta / C_b \qquad \dots\dots\dots\dots (6)$$

where J_4 : Apparent oxygen flux
D_4 : Apparent coefficient of oxygen diffusion
i : Critical current
A ; Area of electrode
n : Atomicity (n=4)
F : Faraday's constant (96,500)
δ : Thickness of cover concrete (5 cm)
C_b : Concentration of oxygen in air in contact with surface of cover concrete (8.93×10^{-4} mol O_2/cm^3)

c) Result of tests

The values of J_4 and D_4 gained as an average value for two specimens are shown in Table 2. The values of D_4 for the non-treated specimens lie in the range of $10^{-5} \sim 10^{-4}$ cm^2/s, in which the measured water content of each corresponding specimen is $70 \sim 80\%$. The value of D_4 is found to be slightly smaller than that obtained by Kobayashi et al.[4] using the equi-pressure method.

Table 2 Oxygen permeability

W/C (%)	Specifications for treatment	Amount of treatment	Oxygen flux $J_o \times 10^{-12}$ (mol O_2/cm^2·sec)	Apparent coefficient diffusion $D_o \times 10^{-6}$ (cm^2/sec)
50	Epoxy	120 μm	6.4	0.4
		240 μm	20.6	1.2
		500 μm	10.6	0.6
		1000 μm	9.7	0.6
	Urethane	120 μm	90.9	5.1
		240 μm	122	6.9
		500 μm	70.1	3.9
		1000 μm	52.9	3.0
	MMA	500 g/m^2	54.2	3.0
		1000 g/m^2	31.7	1.8
	Silan	130 g/m^2	12.2	0.7
	Silan +PCM	130g/m^2 +0.5mm	150	8.4
		130g/m^2 +1.2mm	114	6.4
	No treatment		194	10.9
30	Epoxy	240 μm	7.4	0.4
	Urethane	240 μm	27.1	1.5
	MMA	500 g/m^2	4.2	0.2
	Silan	130 g/m^2	27.5	1.5
	Silan +PCM	130g/m^2 +0.5mm	18.6	1.0
	No treatment		57.4	3.2
40	Epoxy	240 μm	17.2	1.0
	Urethane	240 μm	33.6	1.9
	MMA	500 g/m^2	59.5	3.3
	Silan	130 g/m^2	85.8	4.8
	Silan +PCM	130g/m^2 +0.5mm	67.5	3.8
	No treatment		46.1	2.6
60	Epoxy	240 μm	111	6.2
	Urethane	240 μm	136	7.6
	MMA	500 g/m^2	223	12.5
	Silan	130 g/m^2	149	8.4
	Silan +PCM	130g/m^2 +0.5mm	167	9.4
	No treatment		213	11.9

The relation between the critical current and the resistance of concrete at the end of oxygen transmission test is shown in Fig.5. It is clearly indicated that the higher water/cement ratio results in the lower resistance of concrete and the larger critical current. According to the report by Okada et al.[4], when dried for a very long period, the concrete of high water/cement ratio tends to show a low resistance. This may be due to that once water is thoroughly dispersed from concrete of high water/cement ratio, a large volume of pores can contribute to increase the electric resistance. However, according to the results of this study, the concrete of higher water/cement ratio has lower resistance. The condition of tested specimens is close to that of concrete in the structures which are subject to normal repetition of drying and wetting. Therefore, with regard to the amount of oxygen diffusion, it can be considered to be very close to the actual condition.

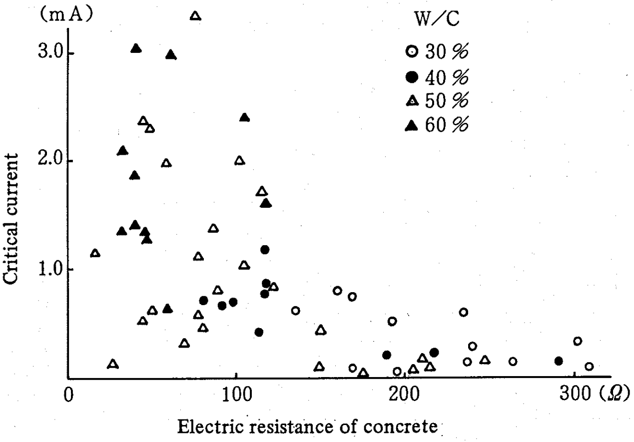

Fig.5 Relation between critical current and electric resistance of concrete

The influence of the water/cement ratio on the apparent coefficient of oxygen diffusion D_4 for the non-treated specimens in comparison with that of treated ones with epoxy is shown in Fig.6. In other systems of the surface treatment, the similar trend can be seen. In the specimens without treatment, the value of D_4 is found to increase with increasing water/cement ratio, and this trend becomes remarkable when the water/cement ratio exceeds 50%. Also, similarly in the specimens with surface treatment, the amount of transmission and diffusion of oxygen increases with increasing water/cement ratio, particularly conspicuous at the water/cement ratio of 60%.

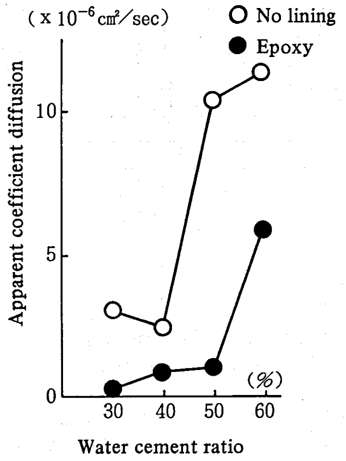

Fig. 6 Influence of water cement ratio on the apparent coefficient of oxygen diffusion

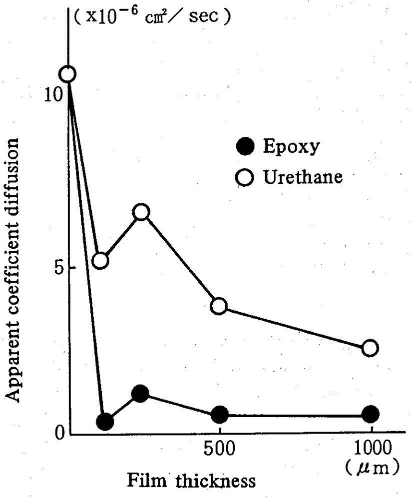

Fig. 7 Influence of film thickness on the apparent coefficient of oxygen diffusion

When surface treatment is applied, it is anticipated that diffusion of oxygen would be controlled at the treatment layer and be scarcely affected by the quality of concrete, but the obtained result is negative. As the test is conducted using the concrete specimen rather than the free film of the treatment agent, pin holes are apt to be generated in the treated layer on concrete that has a high water/cement ratio, that is, large volume of pores, through which diffusion of oxygen takes place. It may difficult to intercept completely the intrusion of oxygen by means of surface treatment in the actual structures. Therefore, it is extremely important to use dense concrete with a low water/cement ratio.

With regard to the lining of epoxy and urethane systems, influence of the film thickness on the diffusion coefficient is shown in Fig.7. Although the diffusion of oxygen can be diminished with increasing film thickness, its effect is not so remarkable.

Among various types of surface treatment tested, the controlling effect against oxygen diffusion is recognized to be higher in the following order: epoxy > urethane > silan ≑ Silan + PCM > no treatment.

(2) Permeability of liquid water

(a) Permeation and diffusion of liquid water

Among the causes of permeation and diffusion of water into concrete, the diffusion accompanied by the difference in water content due to existence of unsaturated pores and the drying due to dispersion of water is considered to be the primary one. Transfer of water accompanied by hydration of unhydrated cement particles and absorption of water by the alkali-aggregate reactive products are considered as the other causes.

First, as the major portion of hydration is finished in the old concrete structure about which durability is to be discussed, the influence of cement hydration on the permeation of water into concrete is to be very small. Next, with regard to the water pressure, unlike hydration of cement, it may affect the permeation of water considerably. However, the concrete structures about which durability is discussed and to which repairing with surface treatment is being applied are not placed in the water subjected to high water pressure, but in the splash zone or in the atmospheric zone.

b) Method of measurement

The plate concrete specimens as shown in Fig.8 are prepared with reference to the permeation test specified by JIS A 6910 "Multi-layer Coating Material" and the cured under the sealed condition for more than 4 weeks. The specimen is placed horizontally with bottom face upward (the surface to be treated) and a funnel is fixed invertly on it with sealing material. After completely displacing air in the funnel by filling distilled water in it, a mess-pipette (ϕ5 ml) is connected to it by a rubber tube. Distilled water is poured into it up to the level 35∿40 cm above the surface of the specimen, and then a small quantity of liquid parafin is added on it to prevent evaporation of water. The environmental condition is set to the same as that for the air permeation test.

The amount of water permeation is measured by reading the change of water head. Measurement is normally conducted at 7 days' interval for 10 weeks, but for the specimens whose change of water head is larger, intervals are shortened to 2 or 3 days. Each one specimen is prepared for a test variable and the reading is done at 3 points of each specimen for taking an average value.

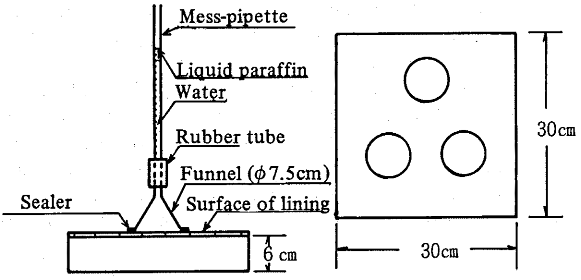

Fig. 8 Specimen for liquid water permeability test

c) Result of tests

The change of the amount of water permeation per unit time is recorded with time. As the water head in the mess-pipette changes during the water permeation test, when the specimens of high permeability, for instance, non-treatment or water repellent type are tested, the fluctuation of the amount of water permeation tends to become larger, being presumably affected by the change of water pressure in the early stage of testing. However, the fluctuation is diminished with an elapsed time and the amount of water permeation shows a trend converging toward a certain value. The amount of water permeation thus settled at a constant value is converted to the value per unit time and per unit area, which is made an indication representing the water permeability. The test result are shown in Table 3.

Presumably, Fick's law would hold good apparently with regard to permeation and diffusion of water into concrete. However, unlike diffusion of oxygen in the case of reinforcement corrosion, as the water permeated into concrete is accumulated gradually the distribution of water concentration changes widely. For the purpose of obtaining the apparent coefficient of water diffusion D_l in a simplified way, it may be possible to find the location where the concentration of water is constant and to estimate D_l from the difference between the concentrations at that point and at the concrete surface. In this test, the locations which can be assumed to have a constant concentration of water are the lower surface of the surface treatment layer and the bottom surface of the concrete specimen. If it is assumed that concrete has been fully dried and that water passing through the surface treatment layer diffuses immediately into concrete and will not remain just below the treated layer, the concentration of water at the lower surface of the treatment is to be almost zero. In this case, the diffusion layer is the thickness of surface treatment. On the other hand, the concentration of water at the bottom surface of the specimen in direct contact with the air may be considered to be zero. In this case, the diffusion layer is the thickness of the specimen in cluding surface treatment. However, while the former is the diffusion coefficient of the coated film only and the influence of the primer and putty is excluded, the latter indicates the apparent value in which concrete is included and corresponds well to the result of air permeation tests. The diffusion coefficients calculated by the latter are presented in Table 3.

Table 3 Liquid water permeability liquid

W/C (%)	Specifications for treatment	Amount of treatment	Liquid water flux x 10^{-2} ($g/m^2 \cdot hour$)	Apparent coefficient diffusion D_l x 10^{-9} (cm^2/sec)
50	Epoxy	120 μm	8.1	1.4
		240 μm	6.5	1.1
		500 μm	5.4	0.9
		1000 μm	4.0	0.7
	Urethane	120 μm	20.6	3.4
		240 μm	14.1	2.4
		500 μm	10.8	1.8
		1000 μm	7.6	1.3
	MMA	500 g/m^2	7.0	1.2
		1000 g/m^2	6.0	1.0
	Silan	130 g/m^2	33.5	5.6
	Silan +PCM	130g/m^2 +0.5mm	32.5	5.4
		130g/m^2 +1.2mm	26.0	4.3
	No treatment		195	32.5
30	Epoxy	240 μm	6.5	1.1
	Urethane	240 μm	10.8	1.8
	MMA	500 g/m^2	10.8	1.8
	Silan	130 g/m^2	13.0	2.2
	Silan +PCM	130g/m^2 +0.5mm	15.2	2.5
	No treatment		27.1	4.5
40	Epoxy	240 μm	7.6	1.3
	Urethane	240 μm	15.2	2.5
	MMA	500 g/m^2	10.8	1.8
	Silan	130 g/m^2	21.1	3.5
	Silan +PCM	130g/m^2 +0.5mm	20.6	3.4
	No treatment		51.9	8.7
60	Epoxy	240 μm	4.9	0.8
	Urethane	240 μm	19.5	3.3
	MMA	500 g/m^2	14.6	2.4
	Silan	130 g/m^2	24.9	4.2
	Silan +PCM	130g/m^2 +0.5mm	28.1	4.7
	No treatment		238	39.7

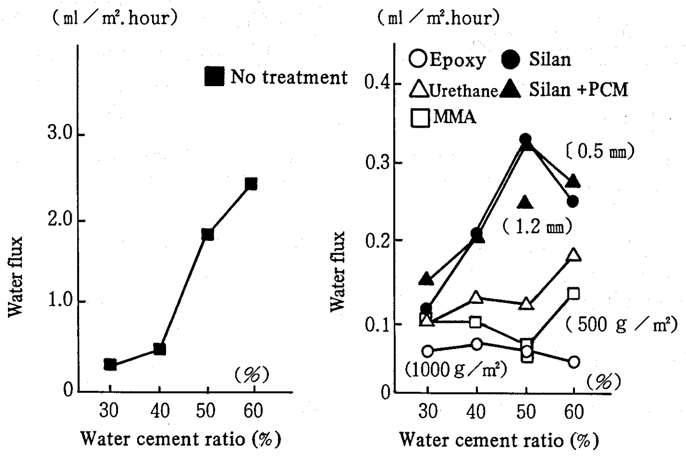

Fig. 9 Influence of the water cement ratio on water permeability

For each surface treatment system, the influence of the water/cement ratio on the permeability of water is shown in Fig.9.

Although the water permeability of surface treatment with epoxy, urethane and MMA group of the water proofing type is scarcely affected by the water/cement ratio, that of water repellent type such as silan and silan plus PCM group depends strongly upon it. In the latter case, the water permeability increases as the water/cement ratio increases, and the similar trend to the case of non-treatment can be seen.

For the lining of epoxy and urethane group, the influence of the film thickness on the water permeability is shown in Fig.10. The water permeability decreases as the thickness of film increases, and have almost a constant value for the thickness exceeding 240 µm. This fact explicitly indicates that when the film thickness exceeds a certain value, its effect on permeability of water is diminished extremely.

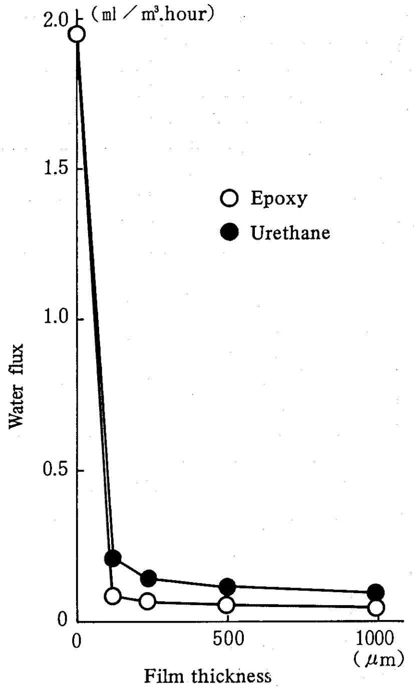

Fig. 10 Influence of film thickness of lining on water permeability

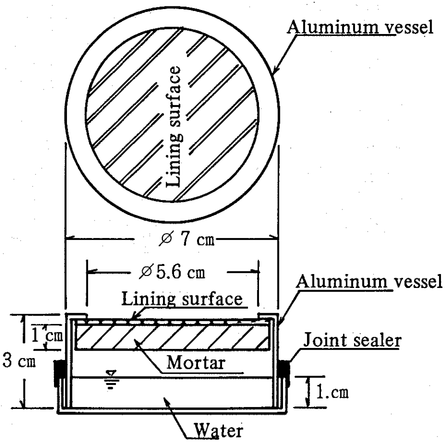

Fig. 11 Specimen for water vapor permeability test

The ability of surface treatments controlling the permeation of water can be presented in the following order:

Epoxy > MMA > Urethane > Silan + PCM > Silan > Non-treatment

(3) Permeability of Water Vapour

a) Dissipation and diffusion of water vapour

While the permeation of liquid phase water takes place when the surface of concrete or surface treatment is wet, dissipation of vapour phase water occurs under the conditions that the surface is dried and concrete has a sufficient water content.

b) Method of measurement

With reference to JIS Z 0208 "Testing Method of Moisture Permeability of Moisture-proof Materials", the specimens as shown in Fig.11 are made of mortar after wet-screening with a sieve of nominal size 5 mm. Those are cured for more than 4 weeks under the sealed condition, and then fixed in a aluminum vessel with epoxy resin adhesive. Clearance between the vessel and the specimen is filled with epoxy resin filling and the vessel is sealed with epoxy resin adhesive. Thereafter, a hole is bored to the vessel and about 20 cc of distilled water is injected. Then, it is sealed again. As the ambient humidity, two conditions of RH 60 ± 5% and RH 85 ± 5% are chosen. Two specimens are prepared for a test variable and the amount of water vapour dissipated from the specimen is measured by weighing the change of weight. Measurement is done at the intervals of 24 hours during the first 28 days and thereafter at 7 days' intervals.

c) Result of tests

Since the room temperature does not fluctuate widely and humidity of the side of the specimen facing the vessel is kept to be always 100%, when the ambient humidity is kept constant, the concentration of water vapour or the amount of moisture transmission, is to be constant. Therefore, in the similar manner done for the liquid water permeability test, firstly the constant value is estimated from the changes of moisture transmission. And, based on this value, the weight of water vapour dissipated within the unit time through the unit area termed as the moisture permeability, as shown in Table 4.

With regard to water vapour within concrete, its transfer is supposed to follow Fick's law apparently as well as oxygen and liquid water. Water vapour within concrete exists in the gaseous portion in the pores. And, when there exist water in the pores, the humidity in the concrete may be assumed to be 100%, similar to the tested specimens, except the portion close to their surface under the influence of atmosphere. Under this assumption, the layer of vapour diffusion may be limited to a very thin portion close to the concrete surface. However, in the case of non-treatment or the case of surface treatment of impregnating type in which coating thickness is almost zero and the impregnating depth of agent is not always uniform, estimation of the coefficient of diffusion is difficult. Therefore, in evaluation of water vapour transmission for these cases, the system including the covering concrete is taken as the apparent layer of diffusion. The apparent coefficient of diffusion D_V estimated in such manner are shown in Table 4.

The influence of the water/cement ratio on the diffusion of water vapour is shown in Fig. 12. Except for epoxy that has considerably low permeability, the diffusion of water vapour is observed to increase as the water/cement ratio increases.

The influence of film thickness of the lining of the epoxy and urethane groups is shown in Fig.13. As seen in the cases of the air and water permeation tests, the larger the film thickness becomes, the diffusion of water vapour is lower. Comparing between epoxy and urethane at the same thickness, the former has a lower permeability, especially, at the thickness above 240 μm. Influence of the ambient humidity for three cases of non-treatment, epoxy and urethane lining is shown in Fig.14. Compared with the specimens with surface treatment, the permeability of the one without treatment is affected heavily by the ambient humidity. Accordingly, considering together with the result of tests for water

Table 4. Water vapour permeability

W/C (%)	Specifications for treatment	Amount of treatment	Ambient humidity (%)	Water vapour flux x 10^{-2} ($g/m^2 \cdot hour$)	$\frac{\text{Water vapour flux}}{\text{Liquid water flux}}$	Apparent coefficient of diffusion of water vapour D_v x 10^{-16} (cm^2/sec)
50	Epoxy	120 μm	60 ± 5	4.1	0.50	1.6
		240 μm		1.6	0.25	0.7
		500 μm		1.3	0.24	0.5
		1000 μm		0.8	0.21	0.3
	Urethane	120 μm		21.2	1.03	8.5
		240 μm		15.7	1.11	6.3
		500 μm		10.6	0.98	4.3
		1000 μm		6.5	0.86	2.6
	MMA	500 g/m^2	85 ± 5	5.9	0.84	2.4
		1000 g/m^2		4.1	0.69	1.6
	Silan	130 g/m^2		40.8	1.22	16.4
	Silan +PCM	130g/m^2 +0.5mm		19.6	0.60	7.9
		130g/m^2 +1.2mm		16.3	0.63	6.6
	No treatment			114	0.59	45.9
	Epoxy	240 μm		0.8		0.3
	Urethane	240 μm		15.5		6.2
	No treatment			21.2		8.5
30	Epoxy	240 μm	60 ± 5	1.6	0.25	0.7
	Urethane	240 μm		7.8	0.72	3.1
	MMA	500 g/m^2		4.4	0.41	1.8
	Silan	130 g/m^2		6.5	0.50	2.6
	Silan +PCM	130g/m^2 +0.5mm		5.7	0.38	2.3
	No treatment			27.8	1.03	11.2
40	Epoxy	240 μm		1.2	0.16	0.5
	Urethane	240 μm		21.2	1.40	8.5
	MMA	500 g/m^2		6.0	0.56	2.4
	Silan	130 g/m^2		18.0	0.85	7.2
	Silan +PCM	130g/m^2 +0.5mm		11.4	0.56	4.6
	No treatment			45.7	0.88	18.4
60	Epoxy	240 μm		2.0	0.40	0.8
	Urethane	240 μm		15.5	0.80	6.2
	MMA	500 g/m^2		14.7	1.01	5.9
	Silan	130 g/m^2		47.4	1.90	19.0
	Silan +PCM	130g/m^2 +0.5mm		21.2	0.75	8.5
	No treatment			57.2	0.24	23.0

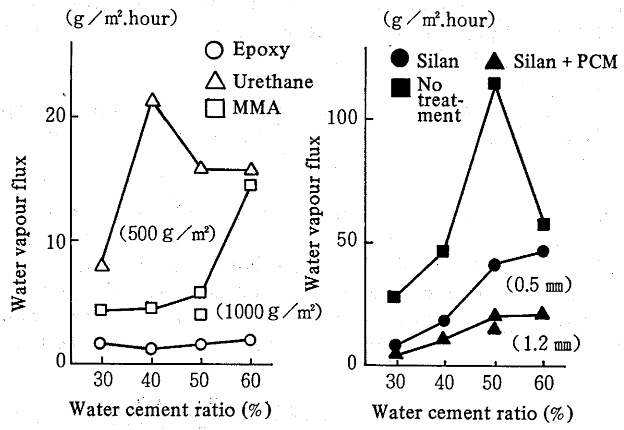

Fig. 12 Influence of water cement ratio on water vapour permeability

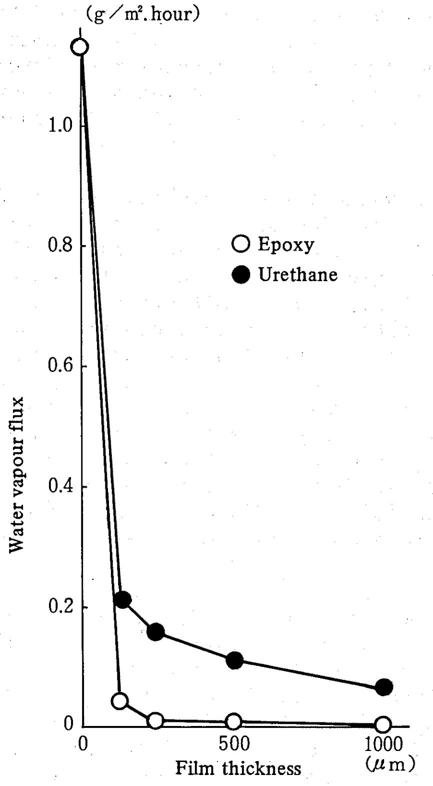

Fig. 13 Influence of film thickness of lining on water vapour permeability

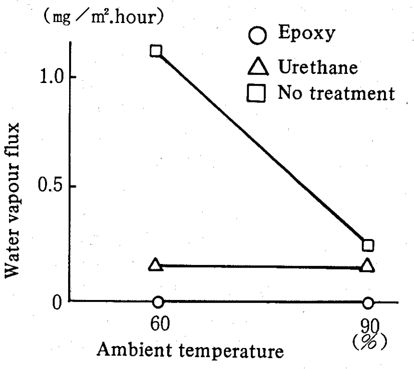

Fig. 14 Relation between ambient humidity and water vapour permeability

permeability, it is possible to diminish the influence of the ambient humidity on the amount of water that penetrates into or diffipates from concrete by applying surface treatment when RH60% ∿ 90%.

Among the different surface treatments, the diffusion of water vapour is found to be low the following order: non-treatment > silan > silan plus PCM > urethane > MMA > epoxy.

The ratio of moisture permeability to water permeability is presented in Table 4. According to Table 4, as easily expected, this ratio is large for silan. And, it should also be noted that urethane has a high ratio comparable to silan and display quite different behavior from that of epoxy. Urethane is primarily of the water proofing type, but it should rather be considered to belong to the water repellent type from the results of this test.

3. Application of durability design for reinforcement corrosion

Based upon the results of these tests on the characteristics of the surface treatment system for concrete, some fundamental considerations on the durability design for controlling the corrosion of steel in concrete are done as follows.

When the durability design is undertaken in the limit state design method for the concrete structures, the durability limit state, as well as other limit states, should be defined explicity corresponding to each machanism of deteriorations anticipated in the structure. Therefore, for application of the durability design the limit state related to the mechanism of deterioration under consideration should be made clear.

As the limit states for salt attack, the following three items may be considered in general: i) occurrence of corrosion, ii) formation of longitudinal crack in concrete cover along reinforcing bar and iii) loss of effective area of bar due to corrosion. Most of the present design practice adopt the concept that treating the occurrence of severe corrosion as the principal limit state, each allowable width of crack is to be set, for instance, in accordance with the environmental conditions. However, occurrence of corrosion corresponds simply to the beginning of the deterioration and this stage can be considered to be too conservative as compared to the limit state in terms of the ultimate strength of structure. Formation of longitudinal crack makes oxygen and chloride ions to be in direct contact with the steel and leads to the loss in strength caused by reduction of the effective steel area due to accelerated corrosion reaction as well as reduction in ductility due to pitting[8]. Therefore, in this study, the formation of longitudinal crack in the concrete cover is treated as the principal limit state.

The time length until cracking of the concrete above the rusting steel can be divided into two stages, namely, the first phase up to occurrence of corrosion and the second phase up to formation of crack after commencement of corrosion. The time length of the first phase t_1 required to initiate corrosion due to destruction of the passive oxide film of steel depends on, in general, the diffusion of chloride ions into concrete. The apparent rate of diffusion of chloride ions can be estimated easily by applying the error function etc.

However, once corrosion has started, the rate of corrosion is to be controlled by the diffusion process of oxygen. When the rate of corrosion is accelerated, the times until formation of cracks and until occurrence of remarkable loss in the strength due to reduction of the effective steel area are shortend so much. For restricting of the rate of oxygen diffusion that controls the rate of corrosion, it is essential to reduce the apparent coefficient of oxygen diffusion as mentioned in the above. Judging from the above test results, the use of high-quality, impermeable concrete with a low water/cement ratio and protective coating with the surface treatment systems of epoxy, MMA and urethane can be very effective measures for providing good resistance to reinforcement corrosion.

If it is assumed that the rate of corrosion of steel embeded in concrete is controlled only by the diffusion of oxygen, the allowable amount of rust required for cracking of the concrete can be determined by estimating theaamount of rust using the monitoring method such as half cell potential measurement of the steel or by means of chipping etc. Furthermore, it is possible to calculate the time length until the limit state is reached (the life expectancy of the structure t_r) from the allowable amount of rust by using the rate of oxygen diffusion. Figure 15 shows a simple flow chart for estimating the life expectancy of structures under salt attack, though it is not yet deterministic.

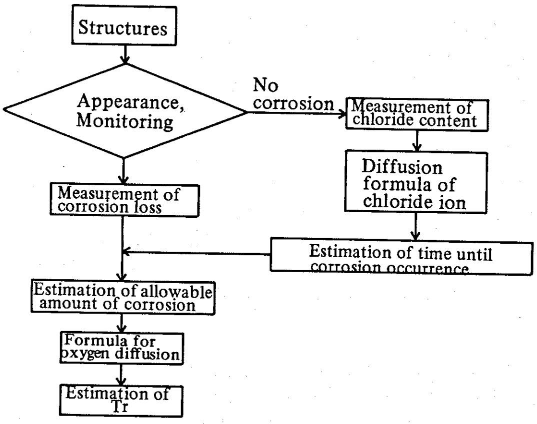

Fig. 15 Flow chart for estimating the life expectancy of structures

Assume based on the previous studies that the allowable amount of rust is set to be 10 mg/cm^2[9] at the time of longitudinal cracking, taking the most safe side for the concrete with a water/cement ratio of 50% and its cover thickness of 5 cm. In repairing the structure, a simple example of calculation for estimating the life expectancy of a structure is presented under the following conditions.

Conditions for calculation:
Relative humidity 80%: in atomosphere
Amount of rust of steel $C_0 = 0\ g/cm^2$
Critical amount of rust of steel $C_1 = 10\ mg/cm^2$
(at formation of longitudinal cracks)
Amount of chloride ions = above the amount of causing corrosion
(say above 1.2 kg/m^3)

Since the amount of chloride ions is sufficient to initiate corrosion, the time length until corrosion starts, as shown in Fig.15, is set to be zero at calculating the life expectancy and then the allowable amount of rust can be obtained by the equation of $C_a = C_1 - C_0 = 10\ mg/cm^2$. If O_2 of 1 mol is supplied, Fe of 2 mols is corroded. The value of t_r can be represented by the following formula using the rate of oxygen diffusion flux J_o and the molecular weight of Fe (M = 55.8):

$$t_r = C_o/(2J_oM) \qquad \text{. . . . .} \ (7)$$

Furthermore, if the distribution of oxygen concentration is assumed to be linear, t_r can be represented by the following formula, using the apparent coefficient of diffusion D_o:

$$t_r = C_o/(2J_4M) \qquad \text{. . . . .} \ (8)$$

Substituting the values obtained from the air permeation test into this formula, the ratio of the life expectancy of each surface treated concrete to that of non-treated concrete is shown in Table 5.

Table 5 Estimation of life expectancy (t_r)

Specification of treatment	Ratio of life expectancy to that of no treatment
No treatment	1.0
Epoxy (240 μm)	9.2
Urethane (240 μm)	1.5
MMA (500 g/m^2)	3.5

It is clearly shown in Table 5 that so far as tested surface treatments are concerned, the diffusion of oxygen is reduced and therefore the elongation of the life expectancy is made possible by applying protective coatings on the concrete even after corrosion of steel has started. However. since it is theoretically indicated that the degree of extension differs so much depending upon the types of treatment, careful attention should be paid to the choice of the specifications of surface treatment.

According to the result of analysis based on the formula(8), the absolute value of the life expectancy is less than 2 years, for instance, even in the case of tested epoxy coating, and therefore the effectiveness of repair can not be expected so much. This conclusion may be reasonable considering the fact that in a number of structures repaired without chipping off concrete cover, corrosion damage occurred again within a short period.

The above simple calculation is done under a rough assumption that the amount of diffused oxygen to the steel surface is a primary controlling process in the corrosion, and also the controlling effect of surface treatment on formation of the crack is not taken into account. And, the life expectancy of the concrete structures is not estimated with a certain reliability. However, the above approach will serve as a criteria for evaluating the effectiveness of a repairing method to be intended.

4. Conclusion

The conclusions obtained in the scope of this study are summarized in the followings:

(1) The analysis of test results, in which consumption of oxygen on the surface of steel caused by corrosion and diffusion of oxygen accompanied by it are simulated with the proposed models, shows that the apparent coefficient of oxygen diffusion within concrete lies within the range of $10^{-5} \sim 10^{-4} cm^2/s$.

(2) Surface treatment system using epoxy, MMA or urethane has a high ability of controlling the transmission and its effectiveness becomes remarkable for the film thickness exceeding a certain value (240 μm for epoxy and urethane).

(3) Silan and combination of silan and polymer cement mortar can be expected have an ability of dissipating moisture out of concrete, though their controlling effect of transmission is smaller than epoxy etc. Urethane is found to have the similar effect to silan.

(4) The controlling effect of surface treatment against transmission is somewhat affected by the water/cement ratio of concrete. However, the influence is less than in the case for non-treated concrete.

(5) In case much amount of chloride ions have already been accumulated within concrete, unless chloride contaminated cover concrete is removed, removing the effect of repair is small even if the conventional surface treatments in practical use are applied. The methods of repair have to be investigated toward improving of the specifications and so forth.

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