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PREDICTION AND EVALUATION OF THE DEPTH OF CARBONATION OF CONCRETE BY THE ACCELERATED TEST

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SYNOPSIS

The accelerated carbonation test is performed to predict the depth of carbonation of concrete under natural exposure condition. The effect of initial curing periods in water, binder content and the replacement ratio of fly ash on the depth of carbonation of concrete under the accelerated carbonation condition is evaluated. The test results of the accelerated carbonation test are compared with those of the natural exposure test.

The depth of carbonation under the accelerated carbonation condition depends on these factors and it can be predicted by the effective water/binder or compressive strength of concrete cured in water for 28 days. The depth of carbonation of concrete exposed indoors for 15 years has a good correlation with the calculated value by the proposed equations using the accelerated test results. The depth of carbonation of concrete under the natural indoor condition can therefore be predicted by the accelerated carbonation test.

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1. INTRODUCTION

In Japan, chloride-induced damage in concrete becomes a matter of concern recently. Corrosion of reinforcement embedded in concrete are accelerated by chloride introduced in concrete from the initial stage due to the use of sea sand, and by intrusion of chloride into concrete. However, there is little possibility of corrosion on reinforcement in the case of no chloride in concrete because the reinforcement in concrete is passivated by alkali environment. On the other hand, carbon dioxide in the air diffuses into concrete and hydrates with calcium hydroxide. This leads to decrease of alkali in concrete and then there is a possibility of corrosion on reinforcement. It is therefore necessary to predict the depth of carbonation of concrete from a viewpoint of durability of concrete structure.

It takes a long time to measure the depth of carbonation of concrete in the natural exposure test because of a low concentration of carbon dioxide in the air. Therefore, the accelerated carbonation test with high concentration of carbon dioxide and the diffusion equation are used for predicting the depth of carbonation in a long term. However, it is necessary to evaluate the correlation between these predicted values and the depths of carbonation of actual concrete structures. Furthermore, carbonation of concrete depends on not only mix proportion such as water-to-cement ratio, cement content and replacement ratio of fly ash, but also environmental conditions such as initial curing conditions, temperature, relative humidity and concentration of carbon dioxide[1-6].

In this study, the accelerated carbonation test was performed to predict the depth of carbonation of concrete in a long term and the effect of initial curing period in water and mix proportion such as binder content and replacement ratio of fly ash on the depth of carbonation was studied. Furthermore, the way to predict the depth of carbonation using the accelerated carbonation test was evaluated by the comparison of the accelerated test results with the depth of carbonation of concrete exposed indoors for 15 years.

2. EXPERIMENTS

2.1 Materials

Three ordinary portland cements blended in equal amounts and a class F fly ash were used. River sand and crashed gravel were used as aggregates. Air-entraining/water reducing agent and air-entraining agent were used.

2.2 Mix Proportions

Mix proportions were divided into two series shown below. In both series, binder contents were changed from 250 to 370 kg/m^3 and a replacement ratio of fly ash was 0 and 30 %.

Series I(nonAE concrete) : Water content was controlled to make the slump 80 mm using no chemical admixture.

Series II (AE concrete) : Air-entraining/water reducing agent was added at a dosage of 250 cc per 100 kg of binder content. Water content and a dosage of air-entraining agent were controlled to make the slump 80 mm and air content 4 % of concrete.

Mix proportions of concrete are shown in Table 1.

Table 1 Mix Proportion of Concrete

	C+F (kg/m^3)	F/(C+F) (%)	W/(C+F) (%)	W (kg/m^3)	Slump (mm)	Air (%)
Series I	250	0	74.0	185	72	1.5
		30	71.2	178	88	0.9
	290	0	63.8	185	82	1.3
		30	61.0	177	82	1.0
	330	0	56.1	185	80	1.3
		30	53.6	177	88	1.2
	370	0	51.4	190	75	1.8
Series II	250	0	66.0	165	90	3.8
		30	63.6	159	100	4.0
	290	0	56.9	165	70	3.2
		30	54.8	159	90	4.7
	330	0	50.3	166	75	3.7
		30	47.9	158	86	4.5
	370	0	45.9	170	70	3.3

2.3 Test Procedures

100×100×300 mm rectangular column specimens were used for the carbonation test. Specimens were transferred to the accelerated carbonation chamber after water curing for 7, 28 and 91 days at 20 c. The accelerated carbonation chamber was controlled at the condition of temperature 40 c, the relative humidity 50 % and the concentration of carbon dioxide 7 %. Specimens were split at the cross section perpendicular to the axis of the specimen at 1, 2, 4, 7 and 9 weeks (in some cases, at 3 and 5 weeks added) after transferring to the chamber. 1 % phenolphthalein ethyl alcohol solution was used as an indicator. The mean depth of carbonation at the cross section was calculated by the following equation and it is defined as the depth of carbonation in the following discussion.

$$x_c = (\sqrt{A} - \sqrt{a})/2$$

where, x_c : depth of carbonation (mm)
A : area of cross section (mm^2)
a : area of colored portion (mm^2)

Compressive strength test of concrete was performed at the age of 7, 28 and 91 days using ϕ100×200 mm cylinder.

3. DISCUSSION

3.1 Depth of Carbonation with Time

Fig. 1 and 2 show relationship between the depth of carbonation in mm of nonAE and AE concrete and the exposure duration in week in the chamber. The depth of carbonation depended on the replacement ratio of fly ash and binder content[7].

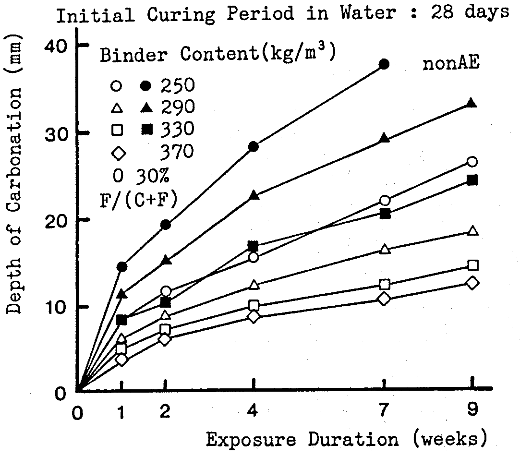

Fig. 1 Depth of Carbonation with Time (nonAE concrete)

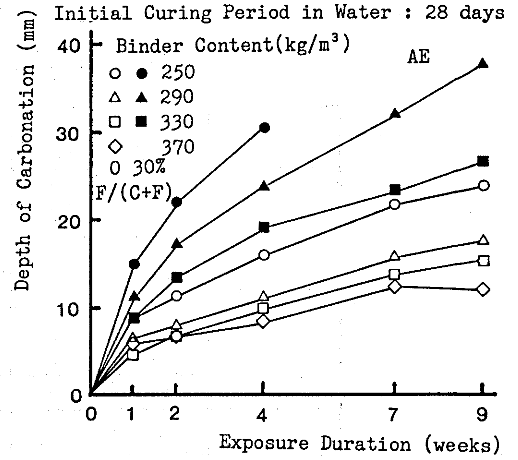

Fig. 2 Depth of Carbonation with Time (AE concrete)

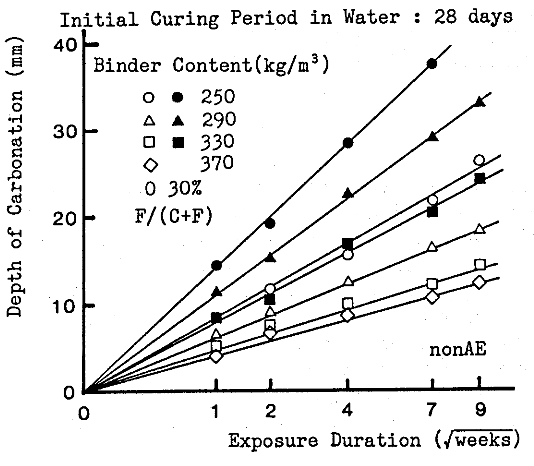

Fig. 3 Depth of Carbonation with Time (nonAE concrete)

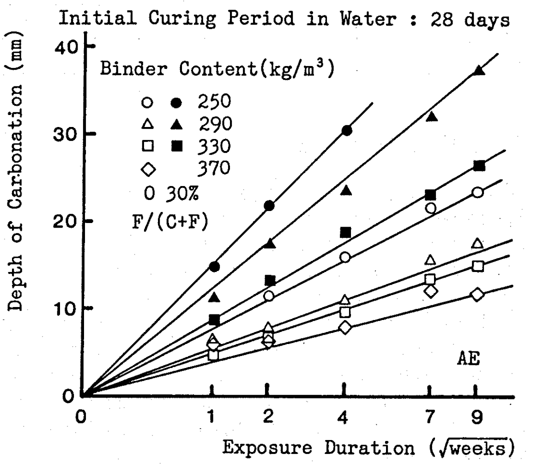

Fig. 4 Depth of Carbonation with Time (AE concrete)

As carbonation of concrete is a phenomenon of diffusion of carbon dioxide into concrete, the depth of carbonation will be in proportion to the square root of exposure duration. The relationship between the depth of carbonation and the square root of exposure duration was therefore evaluated in Fig. 3 and 4 for nonAE and AE concrete. As both had a good correlation independent of mix proportions, the depth of carbonation under the accelerated carbonation condition was dominated by the diffusion of carbon dioxide into concrete. This trend was observed for the concrete with another initial curing period in water. The ratio of the depth of carbonation to the square root of exposure duration was calculated by the regression analysis using test results and was defined as the carbonation coefficient.

3.2 Effect of Initial Curing Period in Water

The effect of initial curing period in water on the carbonation coefficient of concrete is shown in Fig. 5 and 6. In case of nonAE concrete, the carbonation coefficient of concrete initially cured in water for 7 days was slightly larger than that of concrete with another initial curing, independent of replacement ratio of fly ash. As the carbonation coefficients were almost the same in the case of concrete initially cured in water for more than 28 days, there was little effect of initial curing period in water on the carbonation coefficient of concrete if the concrete was initially cured in water for 28 days at least.

In the case of AE concrete, the carbonation coefficient of concrete with fly ash initially cured in water for 28 days was slightly larger than that for 91 days. This difference increased with decrease in binder content.

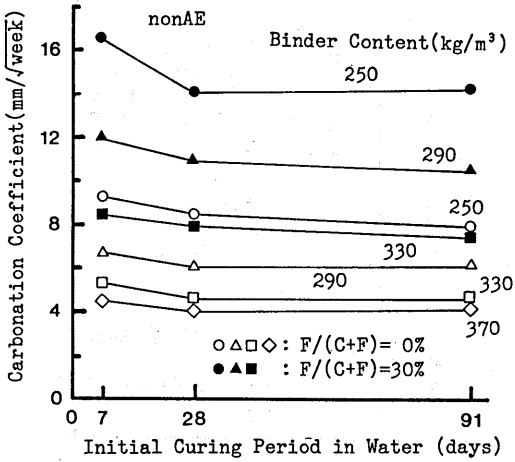

Fig. 5 Effect of Initial Curing Period in Water (nonAE concrete)

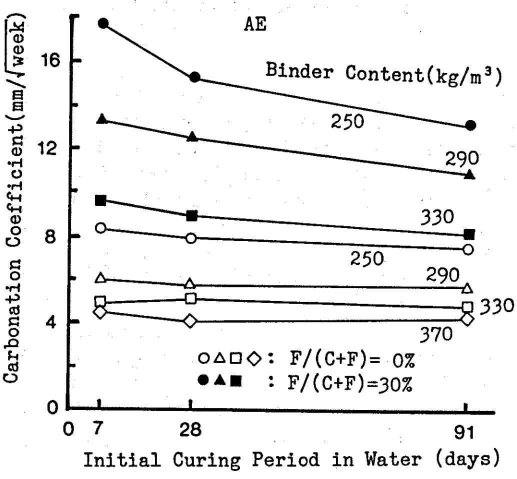

Fig. 6 Effect of Initial Curing Period in Water (AE concrete)

3.3 Effect of Mix Proportions

Effect of binder content on the carbonation coefficient of concrete initially cured in water for 7 and 91 days is shown in Fig. 7. The carbonation coefficient decreased with increase in binder content independent of air content, initial curing period in water and replacement ratio of fly ash. This is due to the improvement of denseness of concrete by reduction of water/binder with increase in binder content. The effect of initial curing period in water on the carbonation coefficient of concrete became less with increase in binder content.

Fig. 8 shows relationship between the carbonation coefficient of concrete and replacement ratio of fly ash. Though water/binder decreased with increase in replacement ratio of fly ash, the carbonation coefficient increased. However, the effect of fly ash addition on the carbonation coefficient became less with increase in binder content and especially in the case of AE concrete with fly ash, the effect of initial curing period in water became less with increase in binder content.

Replacement of part of cement by fly ash has a possibility to reduce calcium hydroxide induced by hydration of cement, due to both the reduction of cement content and the pozzolanic reaction. On the other hand, as fly ash possesses

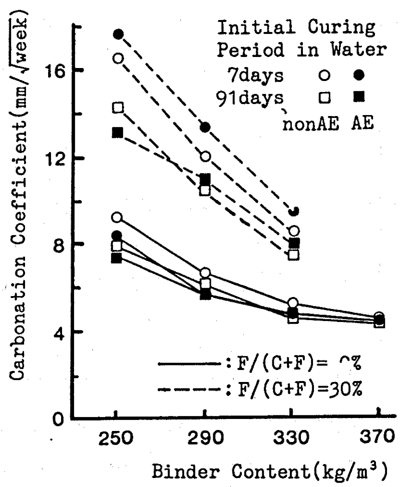

Fig. 7 Effect of Binder Content

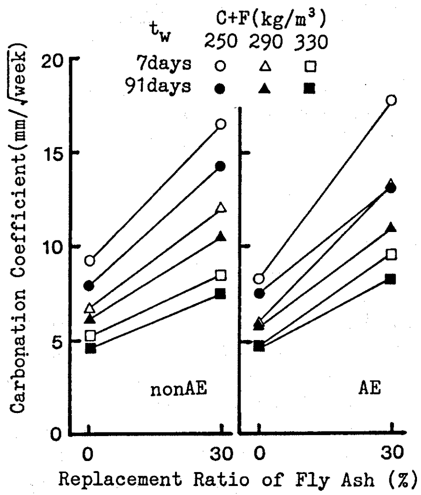

Fig. 8 Replacement Ratio of Fly Ash and Carbonation Coefficient

the reduction effect of water/binder, it is necessary to evaluate the effect of water/binder and compressive strength relating to structure of concrete on carbonation. Relationship between the effective water/binder [W/(C+kF), W:water content, C:cement content, F:fly ash content] and the carbonation coefficient is shown in Fig. 9. The k in W/(C+kF) means contribution of fly ash to cement as a binding material. In the case of nonAE concrete, the relationship depended on replacement ratio of fly ash like the case of natural exposure test[6] and concrete with fly ash had smaller carbonation coefficient than that without fly ash at the same effective water/binder with k=0, that is water-to-cement ratio. Fly ash will therefore contribute to the carbonation coefficient as a binding material. As the carbonation coefficient had a good correlation with the effective water/binder with k=0.2, fly ash will contribute to the carbonation coefficient in 20% of weight of fly ash content as cement. However, in the case of AE concrete, the carbonation coefficient showed a good correlation with the effective water/binder with k=0 (water-to-cement ratio) independent of addition of fly ash and hence there was little contribution of fly ash as a binding material for the carbonation coefficient.

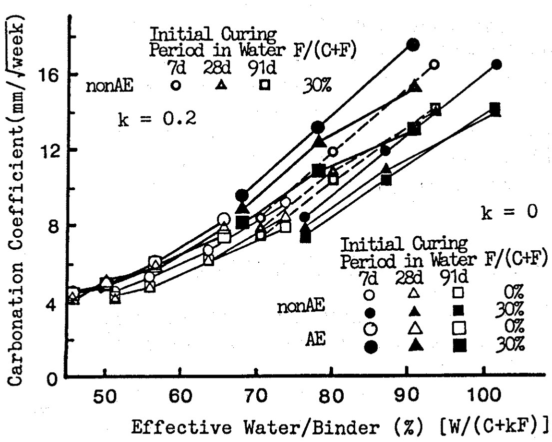

Fig. 9 Effective Water/Binder and Carbonation Coefficient

3.4 Carbonation Coefficient and Compressive Strength

Thick line in Fig. 10 and 11 show the relationship between the square root of

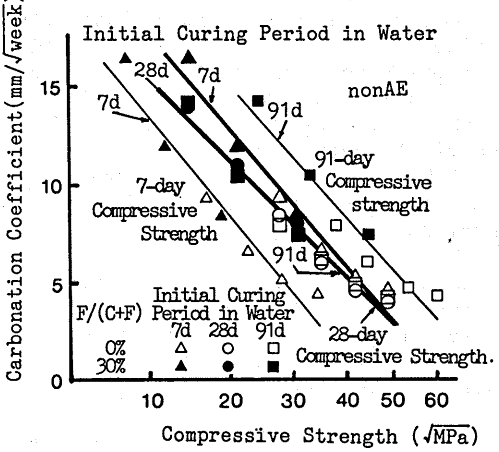

Fig. 10 Compressive Strength and Carbonation Coefficient (nonAE concrete)

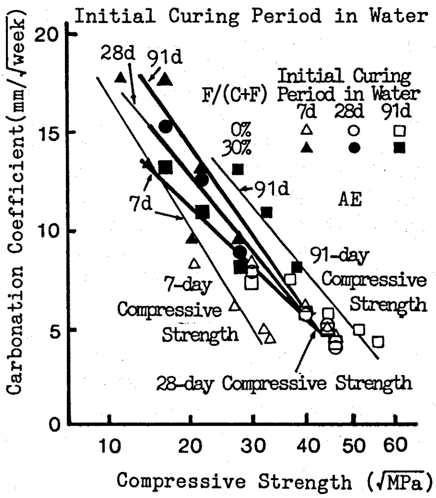

Fig. 11 Compressive Strength and Carbonation Coefficient (AE concrete)

the 28-day compressive strength and the carbonation coefficient of concrete initially cured in water for 7, 28 and 91 days. These relationships had good correlations independent of addition of fly ash, and depended on air content and initial curing period in water. Although the relationship was described in a line for nonAE concrete initially cured in water for more than 28 days, the carbonation coefficient of concrete initially cured in water for 7 days was larger than that with another curing period as discussed in 3.2. However, in the case of AE concrete, the relationships between the 28-day compressive strength and the carbonation coefficient of concrete initially cured in water for 28 and 91 days were different and the effect of initial curing period in water on these relations was significant especially for the concrete with low-strength. Thin line in Fig. 10 and 11 shows correlation between the square root of compressive strength of concrete at the age for start of the accelerated carbonation test and the carbonation coefficient. The correlations for the 7-day and 91-day compressive strength show a good correlation like the case for the 28-day compressive strength. At the same compressive strength, the shorter initial curing period in water, the less is the carbonation coefficient because water/binder was less for the shorter initial curing. Although the effect of quality of concrete on carbonation depended on curing conditions, the depth of carbonation can be predicted using the 28-day compressive strength at the same curing condition.

3.5 Prediction of Carbonation Depth

From the discussion above, carbonation of concrete depended on mix proportions, curing conditions and environmental conditions. Furthermore, it is important to predict the depth of carbonation from a viewpoint of durability of concrete structures. Based on the test results of concrete under the accelerated carbonation condition, the prediction of carbonation depth of concrete was attempted using mix proportions and compressive strength.

There were many equations proposed for predicting the depth of carbonation of concrete, and the depth of carbonation of concrete exposed indoors or outdoors but sheltered from rain was in proportion to the square root of duration[4,8]. On the other hand, although the depth of carbonation of concrete exposed outdoors and not sheltered from rain was smaller than that exposed indoors[9], the mechanism of this phenomenon was not understood. There were many equations proposed using water-to-cement ratio and compressive strength for the ratio of the depth of carbonation to the square root of duration, that is the carbonation coefficient[10-12]. However, although water-to-cement ratio could be decreased by addition of fly ash, compressive strength of concrete with fly ash decreased at the early age due to low reactivity of fly ash with cement. The depth of carbonation of concrete with and without fly ash could not therefore be predicted by a equation using water-to-cement ratio.

The carbonation coefficient depended on the effective water/binder and compressive strength from the discussion above. As the depth of carbonation was in proportion to the square root of exposure duration and the carbonation coefficient was in proportion to the effective water/binder or the square root of compressive strength, the following equations were proposed.

$$x_c = \alpha[W/(C+kF)-\beta] \sqrt{t} \quad \text{------------------------}(1)$$
$$x_c = \lambda(\mu - f'_{28}) \sqrt{t} \quad \text{------------------------}(2)$$

where, x_c : depth of carbonation(mm)
t : exposure duration(week)
$W/(C+kF)$: effective water/binder(%)
f'_{28} : 28-day compressive strength(MPa)
α,β,λ,μ : coefficient

These coefficients in equation 1 and 2 obtained by the regression analysis using test results depended on initial curing period in water as shown in Table 2, because the carbonation coefficient depended on initial curing period in water as discussed in 3.2. The k in equation 1 was 0.2 for nonAE concrete and 0 for AE concrete from the discussion in 3.3.

Table 2 Coefficients in Equation for Prediction of Carbonation Depth(Accelerated Test)

Initial Curing Period in Water		α	β	λ	μ	η	θ
Series I	7d	0.284	37.3	3.77	7.92	3.30	0.0118
	28d	0.244		3.26		3.18	
	91d	0.236		3.14		3.10	
Series II	7d	0.299	31.1	4.53	7.80	3.53	0.0122
	28d	0.256		3.90		3.38	
	91d	0.203		3.09		3.13	

On the other hand, the diffusion coefficient of concrete was expressed empirically as follows[13].

$$D = D_0 \exp(-Q/RT) \quad \text{------------------------}(3)$$

where, D : diffusion coefficient
D_0, Q : coefficient dependent on structure of concrete and independent of temperature
R : gas constant
T : absolute temperature

The following equation was obtained, suppose x_c was described as $b\sqrt{t}$ (b : constant)[14].

$$b^2 = a\,D$$
$$= D_0' \exp(-Q/RT) \quad \text{------------------------}(4)$$

where, a, Do' : constant

Using compressive strength as a parameter representing the structure of concrete, the following equation was proposed from equation 4.

$$b = \exp[\eta(1-\theta f'_{28})] \qquad (5)$$

Therefore, the depth of carbonation was expressed as follows.

$$x_c = \exp[\eta(1-\theta f'_{28})]\sqrt{t} \qquad (6)$$

where, η, θ : coefficient

Coefficients η, θ calculated by the regression analysis using test results are shown in Table 2. These coefficients were valid for concrete with 0 and 30 % fly ash replacement under the condition of 40 c temperature, 50 % relative humidity and 7 % concentration of carbon dioxide. From Table 2, the depth of carbonation under the accelerated carbonation condition was approximately 20 % and 50 % greater for nonAE concrete and AE concrete initially cured in water for 7 days than that for 91 days.

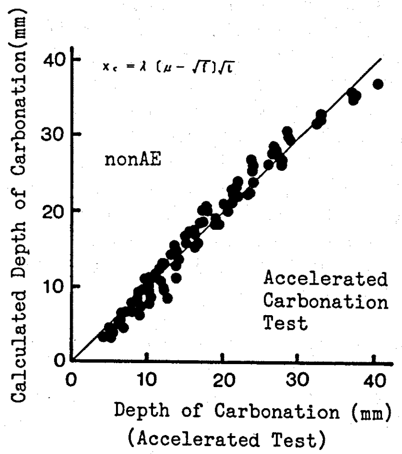

Fig. 12 Test Results and Calculated Values (Accelerated Test)

Fig. 12 and 13 show relationship between the test results of nonAE concrete under the accelerated carbonation condition and the calculated values by these equations. As they had a good correlation and the same trend was observed for AE concrete, the depth of carbonation of concrete under the accelerated carbonation condition can be predicted by equations 1, 2 and 6, using the effective water/binder or the 28-day compressive strength as a parameter for mix proportion.

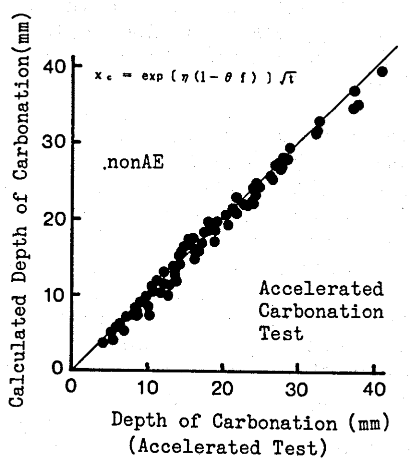

Fig. 13 Test Results and Calculated Values (Accelerated Test)

In the case of natural exposure test[6], mix proportion of concrete was binder content 250, 290 and 330 kg/m^3 and replacement ratio of fly ash 0 and 30 % containing no chemical admixture like the case of the accelerated carbonation test and initial curing periods in water were 1, 7, 28 and 91 days (only 7 and 91 days for indoor condition). Specimens were set outdoors (not sheltered from rain) and indoors. The depth of carbonation was measured at the age of 2, 5, 10 and 15 years.

The rate of carbonation depth of concrete exposed outdoors was delayed compared with that under indoor condition due to both the disturbance of diffusion of carbon dioxide into concrete by rain and the progress of hydration, and the depth of carbonation was in proportion to the fourth root of exposure duration. As temperature, relative humidity and concentration of carbon dioxide in the accelerated carbonation chamber were kept constant, the accelerated carbonation test would simulate the indoor condition. The depth of carbonation of concrete exposed indoors was in proportion to the square root of duration. Therefore, equation 1, 2 and 6 were used like the accelerated carbonation test and coefficients of the equations were determined by the regression analysis using test results of concrete exposed indoors as shown in Table 3. However, the k was determined to be 0.3 from the same evaluation as in 3.3.

Table 3 Coefficients in Equation for Prediction of Carbonation Depth(Natural Exposure Test)

Initial Curing Period in Water		α	β	λ	μ	η	θ
Indoor Exposure Condition	7d	0.0376	37.8	0.370	7.48	1.07	0.0519
	91d	0.0287		0.280		0.804	

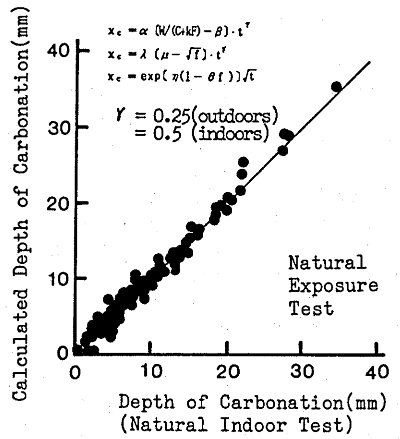

Fig. 14 Test Results and Calculated Values (Natural Exposure Test)

Relationship between the test results of concrete exposed indoors and the calculated values by these equations is shown in Fig. 14. In the case of concrete exposed outdoors, the carbonation coefficient, b in $x_c = b\cdot t^{\frac{1}{4}}$, is expressed using the effective water/binder and the 28-day compressive strength like the case of indoor exposed concrete and the relationship is also shown in Fig. 14. These calculated values had a good correlation with test results in Fig. 14. The depth of carbonation of concrete even under long-term natural exposure condition could therefore be predicted by the equations using the effective water/binder or compressive strength like the accelerated condition.

The carbonation coefficient, calculated by equation 2 using λ and μ obtained by the accelerated test for nonAE concrete and the 28-day compressive strength of concrete used in natural exposure test, was compared with the carbonation coefficient, calculated by the regression analysis using test results of concrete exposed indoors. As a result of the comparison, 2, 5, 10 and 15 years in natural indoor exposure test were corresponded to 0.56, 1.40, 2.81 and 4.21 weeks respectively.

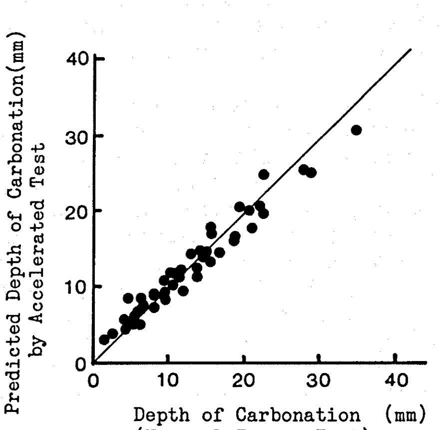

Fig. 15 Test Results and Predicted Values

Fig. 15 shows relationship between test results under natural indoor condition and the predicted depth of carbonation using equation 2 with λ and μ obtained by the accelerated test and the 28-day compressive strength of concrete used in natural exposure test. As both show a good correlation, the depth of carbonation of concrete in natural indoor exposure condition can be predicted by the accelerated carbonation test.

3.6 Evaluation from the Viewpoint of Micro-Structure

Total pore volume, measured by mercury pressure porosimeter, in paste of concrete exposed indoors for 15 years is shown in Fig. 16. Total pore volume decreased with increase in binder content and showed the same trend as the depth of carbonation. Although total pore volume in uncarbonated portion of concrete with fly ash initially cured in water for 91 days was less than that of concrete without fly ash by the pozzolanic reaction, there was little effect of fly ash addition on total pore volume in uncarbonated portion of concrete with 7-day initial curing.

In the case of concrete without fly ash, total pore volume was decreased by carbonation. This is due to the increase of volume of calcium hydroxide reacted with carbon dioxide to be calcium carbonate. Though total pore volume was thought to be decreased due to the production of calcium carbonate by carbonation even in the case of concrete with fly ash, it was increased by carbonation like the case of concrete with blast furnace slag powder[15]. The reason would be the restraint of pozzolanic reaction due to the consumption of calcium hydroxide by carbonation and the loss of water by drying. This was confirmed by the observation of hydration layer around fly ash particles using scanning electron microscope. Although there was thick hydration layer on the surface of fly ash by the pozzolanic reaction in uncarbonated portion, there were more fly ash particles with smooth surface in carbonated portion than in uncarbonated portion and the pozzolanic reaction was little confirmed.

Therefore, total pore volume depended on environmental condition and initial curing period in water, and total pore volume in carbonated portion increased by 30 % replacement of cement by fly ash correspondent to the depth of carbonation. On the other hand, as total pore volume in the uncarbonated portion of concrete with fly ash was less than that without fly ash, fly ash replacement was thought to be effective for restraint of carbonation. However, as the amount of calcium hydroxide was decreased by the reduction of cement content and the pozzolanic reaction, the depth of carbonation increased with the addition of fly ash.

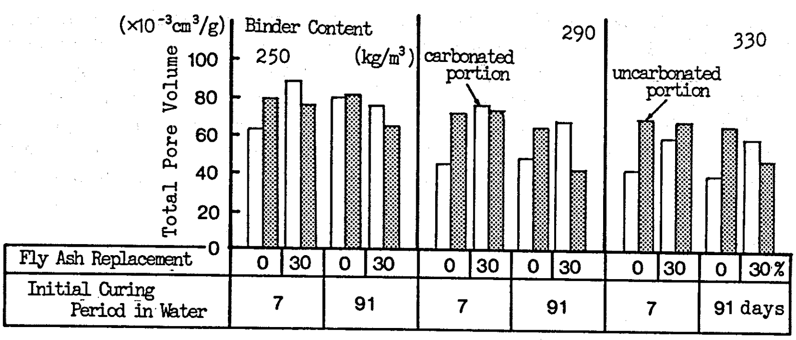

Fig. 16 Total Pore Volume(Natural Indoor Exposure Test)

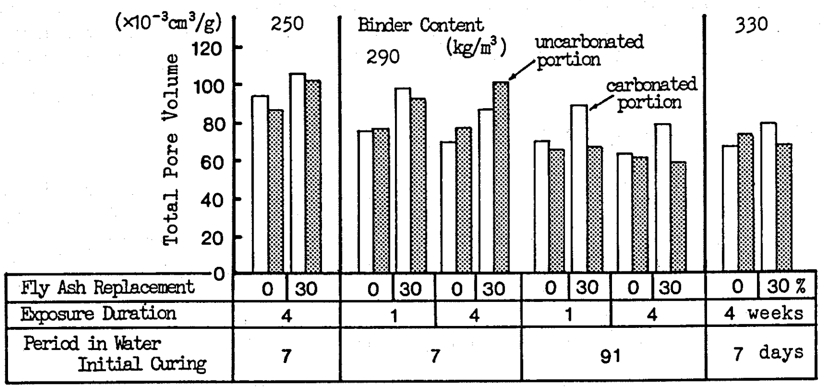

Fig. 17 Total Pore Volume(Accelerated Carbonation Test)

Fig. 17 shows total pore volume in paste of concrete under the accelerated carbonation condition. Total pore volume also decreased with increase in binder content and initial curing period in water, but it was larger than that under natural exposure condition. At the duration of 4 weeks in the accelerated carbonation test, which was approximately corresponded to the age of 15 years under natural exposure test, total pore volume in uncarbonated portion of concrete initially cured in water for 7 days increased with the addition of fly ash, and there was little difference of total pore volume in uncarbonated portion of concrete with and without fly ash initially cured in water for 91 days unlike the case under natural exposure condition. This difference is due to little pozzolanic reaction in the case of the accelerated test by both the severeness of environmental condition such as high temperature, low relative humidity and high concentration of carbon dioxide compared with natural exposure condition and the lack of exposure duration, 4 weeks.

Total pore volume in carbonated portion of concrete with fly ash was larger than that without fly ash like the case under natural exposure condition. However, as total pore volume in carbonated portion of concrete without fly ash was not always decreased by carbonation unlike the case under natural exposure condition, structure of concrete became loose due to the lack of curing under severe environmental conditions.

Although the depth of carbonation of concrete under natural exposure condition could be predicted by the accelerated carbonation test as described in 3.5, micro-structure of concrete under the accelerated condition was not always corresponded to that under the natural exposure condition. However, as micro-structure in the carbonated portion into which carbon dioxide diffused showed the same trend for both condition, the depth of carbonation of concrete under natural exposure condition could be predicted by the accelerated carbonation test.

4. CONCLUSIONS

The accelerated carbonation test was performed to study the effect of initial curing period in water, binder content and replacement ratio of fly ash on the depth of carbonation of concrete and the way to predict the depth of carbonation of concrete under the natural exposure condition was evaluated by the accelerated carbonation test in this study.

The following conclusions may be drawn from this study.

(1) The depth of carbonation of concrete under the accelerated carbonation condition is in proportion to the square root of exposure duration.

(2) The depth of carbonation depends on initial curing period in water. Sufficient initial curing period in water is necessary especially for concrete with fly ash.

(3) The carbonation depth of concrete with replacement of part of cement by fly ash is greater than that of concrete without fly ash, but this disadvantage decreases with increase in binder content and initial curing period in water.

(4) As the depth of carbonation depends on structure of concrete, it can be predicted by the equation using the effective water/binder or the 28-day compressive strength independent of fly ash replacement.

(5) The depth of carbonation of concrete under the natural indoor exposure condition can be predicted by the accelerated carbonation test.

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