STUDY ON CARBONATION OF MORTAR BEAM SUBJECTED TO CRACKING

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Although the most of National Codes of Practices which deal with cracking recommends a limit for crack widths in order to control the risk of corrosion of reinforcement, the research to date has not sufficiently discussed the effect of cracks on carbonation of concrete. Therefore, this study has been carried out to improve the understanding of the effects of cracking on carbonation process. Mortar beams were used to investigate the effect of crack width on carbonation depth under an accelerating neuteralization test. Comparisons were made between the accelerated and exposure test results to evaluate the effect of acceleration on the carbonation depth. Also the influence of various constituents and curing time on carbonation depth was discussed.

Keywords : carbonation, cracking, mortar beam, crack width

1. INTRODUCTION

Concrete deteriorates in many ways. Perhaps the greatest concern nowadays is the corrosion of the reinforcing steel and subsequent spalling and cracking of the cover concrete. The cement compounds such as C_3S and C_2S react with water (hydration) to form their hydrates and calcium hydroxide $Ca(OH)_2$. Calcium hydroxide solution is strongly alkaline with a pH value of about 12.6 under saturated condition. The alkali content of cement (sodium and potassium oxides) is also significant. In the presence of an alkaline environment corrosion of reinforcement is inhibited by the formation of a thin protective film of iron oxides or hydroxides on the metal surface which renders it passive. If the alkaline environment is lost and air and moisture permeate to the reinforcement, the conditions are right for corrosion to take place. The loss of the alkaline environment is caused by a process known as carbonation. Carbonation of concrete has been known for well over 50 years[1] though it is only recently that its significance has received general recognition.

The presence of cracks in concrete provides easy access for carbon dioxide, oxygen and moisture and can significantly influence the durability of concrete. Therefore, in recent years codes and design regulations in various countries have dealt with durability by specifying limits of crack width. A substantial amount of test data which deals with cracking and corrosion of reinforcement is available[2]~[5], while there have been a few numbers of investigations which at least in part, were aimed at finding a relation between cracking and carbonation of concrete[6],[7]. Also, the research to date has not discussed sufficiently the effect of cracks on carbonation of concrete and until now there is still some lack in this subject. The purpose of this research is, therefore, to discuss the effect of presence of crack on carbonation. Since carbonation is a long-term

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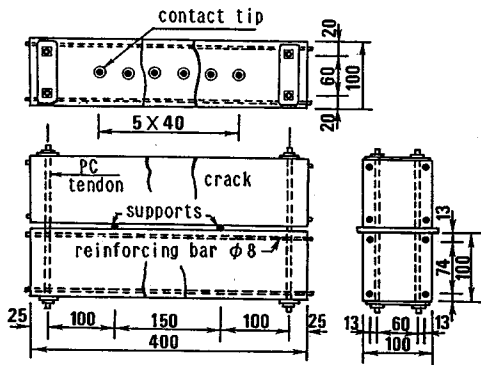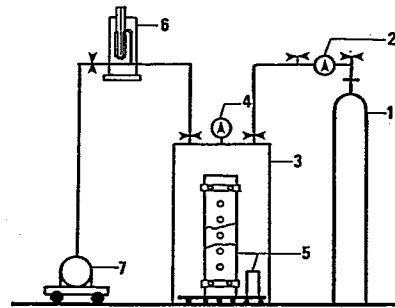
process, an accelerated carbonation test was used to reduce the time required for testing. To evaluate the effects of acceleration on the carbonation depth, an exposure test was carried out. Also, the influence of various constituents including two types of cement and four kinds of blast furnace slag on the carbonation depth were investigated. In addition, the effects of initial curing time on carbonation depth in both accelerating and exposure tests were discussed.

2. EXPERIMENTAL PROCEDURE

(1) Materials and mix proportions

Three kinds of cement were used in this experiment; ordinary portland cement (OPC), high early strength portland cement (HESPC) and blended cement (BC). Blended cement was produced by replacing a part of OPC with blast furnace slag (BFS). Four types of BFS were used in this work. The chemical analyses and physical properties of the materials (cement and blast furnace slag) are shown in Table 1. A pit sand of fineness modulus 3.0 and specific gravity 2.58 was used with ratio $3:1$ (sand : cement). Ordinary portland cement was mixed with W/C ratios 0.4, 0.5 and 0.6. Cement and slag were mixed by the weight ratios $75:25$, $65:35$, $60:40$ and $45:55$ with $W/(C+S)0.5$. The mix proportions of the mortars and their compressive strength are given in Table 2.

(2) Preparation of specimens

Mortar beams $100 \times 100 \times 400$ mm in size reinforced with four reinforcing bars of 8 mm in diameter and with the thickness of cover 1 cm were used in this experiment. After casting, all specimens were stored in moulds for 24 hours in a chamber with about 100 % R.H. at 20°C. After demoulding they were cured in water at 20°C for 7, 14 or 28 days. Then, they were kept in a chamber with 50 % R.H. at 20°C until testing. Fig. 1 shows the summary of carbonation test program. The beams were loaded at middle span by using 4 PC tendons and subjected to flexural cracks as shown in Fig. 2. The crack widths were measured on the surface by contact gauge and they were controlled to be between 0.02 mm and 0.50 mm.

Thirty six prisms $50 \times 50 \times 200$ mm in size were prepared from different mixes and cured for 3, 7 or 28 days, then they were exposed for two years in the laboratory under the normal concentration of CO_2 (about 0.03 %) and with 50 %R. H. at 20°C.

(3) Equipment for accelerated carbonation test

A steel chamber of 350 mm in diameter and 650 mm in height was used for storing and carbonating the specimens. The chamber was connected to an electric vacuum pump to evacuate air in the carbonation chamber

Table 1   Chemical analyses and physical properties of cement and slag.

Type	Specific gravity	Surface Area (cm² /g)	Chemical Compositoin						
			SiO₂	Al₂0	Fe₂0	CaO	MgO	SO₃	Total
OPC	3.16	3220	22.1	5.10	2.90	64.3	1.20	1.70	97.3
HESPC	3.14	4370	21.0	4.90	2.70	65.3	1.30	2.40	97.6
BFS-B25	2.91	2650	34.0	14.0	0.70	42.2	5.70		96.6
BFS-B40	2.91	4000	33.9	14.0	0.50	42.1	5.80		96.3
BFS-B50	2.91	5580	33.9	14.2	0.40	42.0	5.80		96.3
BFS-B80	2.91	7890	33.8	14.8	0.60	41.7	5.80		96.7

B25 : BFS of specific surface area (Blaine) about 2500 cm² /g

Table 2   Mix proportions and compressive strength of mortar.

Mix No.	Type	W/(C+S) (%)	Materials in kg/m³ mortar					f₂₈ (kg/cm²)
			water	cement	slag	sand	admixture	
1	R-0-OPC	40	216	540	---	1620	2.7	528
2	R-0-OPC	50	250	500	---	1500	2.5	493
3	R-0-OPC	60	293	488	---	1464	2.4	444
4	R-0-HESPC	50	250	500	---	1500	2.5	549
5	R-25-B50	50	250	375	125	1535	5.0	469
6	R-40-B50	50	250	300	200	1535	5.0	401
7	R-55-B50	50	250	225	275	1535	5.0	366
8	R-40-B25	50	250	300	200	1535	5.0	334
9	R-35-B40	50	250	325	175	1535	5.0	415
10	R-40-B40	50	250	300	200	1535	5.0	395
11	R-55-B40	50	250	225	275	1535	5.0	380
12	R-55-B80	50	250	225	275	1535	5.0	466

R-25-B50 : Replacing 25% of OPC with BFS (B50)

type of specimen	Age (days)								
	0	7	14	21	28	35	42	49	56	63
I OPC	O----●----------------------◎-----★								
II OPC	O----●--------------------------------◎------★								
III BFS	O----●--------------------------------◎------★								
IV BFS	O------------●------------------------------◎-----★								
V BFS	O--------------------------●----------------------------------◎-----★								

O casting of specimen   ------ curing in water at 20 C (W)
● end of initial curing time   ------ curing in 50% R.H. at 20 C (D)
◎ specimen was subjeted to crack   OPC Ordinary Portland Cement (mix No.2)
★ accelerated carbonation test   BFS Blast Furnace Slag B40 (mix No.10)

Fig. 1   Summary of carbonation test program for cracked beams.

Fig. 2 Arrangement of cracked mortar beams.

(1) pressurized CO_2 cylinder ; (2) pressure meter and anti-freeze flow controller ; (3) carbonation chamber ; (4) pressure meter ; (5) test specimens ; (6) mercury meter ; (7) vacuum pump.

Fig. 3 The setup for accelerated carbonation test.

before supplying CO_2. The CO_2 gas was fed from a pressured steel cylinder continuously into the chamber during the test. The setup for accelerated carbonation test is shown in **Fig. 3**.

(4) **Procedure and testing**

For each set of experimental conditions, three prisms or two beams were used for carbonation test and three cylinders for compressive strength. After curing of the specimens, compressive strength were determined, as well as, the pore volume and pore size distribution of wet-screened mortar specimen was measured by means of mercury porosimetry. The specimens were placed in the carbonation chamber, then, an accelerating carbonation test was carried out with CO_2 (about 100 %)[3]. The specimens were kept in the carbonation chamber for 3 days, after that, the weight gain was determined and carbonation depth was measured as follows. The specimens were split and the split surfaces were sprayed with 1 % phenolphthalein solution (1 g phenolphthalein dissolved in 50 m*l* alcohol and diluted to 100 m*l* water). The depth of rim that showed no colour change after spraying the phenolphthalein solution was measured for each cross section and was regarded as the carbonation depth.

The carbonation depth was measured for both longitudinal and lateral sections at cracked positions. In view of the effect of carbonation area around the crack on destroying the protective layer on the surface of reinforcement steel, carbonation depth which was measured from longitudinal section is named virtual carbonation depth (d_{vc}) to distinct it from the depth that was measured from lateral section (d_c), which gives only an indication of carbonation of cracked surface.

The ratio between carbonation depth measured at cracked position (d_c) and that measured at uncracked position (d_0) of same specimen is named "Carbonation Ratio (C. R.)" and given by the equation below.

$$C. R. = d_c/d_0 \quad\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (1)$$

3. TEST RESULTS AND DISCUSSION

(1) **Results of accelerated test**

a) **Observation of lateral section of cracked beam**

By observing the cross section of the specimens at cracked and uncracked positions, it was found that most surfaces of cracks were carbonated, but at uncracked position only a thin layer was carbonated. **Fig. 4** shows a typical carbonated area at cracked and uncracked positions for specimens made from OPC and BFS which were cured for 7 days in water. From these data the carbonation ratios were calculated from equation 1 and their values were plotted against the crack width as shown in **Fig. 5**. The carbonation ratio is increased by increasing the crack widths and their values are between 1 to 17 for crack width ranging from 0 to 0. 25 mm, but the influence of crack width was less for crack width more than 0. 15 mm. For specimens

made from BFS, a sequence of individual relationships between crack width and carbonation ratio was found for different curing periods. Carbonation ratio was increased with the increase of curing time and the influence of curing time on carbonation ratio was remarkable at wide cracks. This result can be explained as follows. The carbonation depth at cracked position is not affected by curing time, but it is mostly dependent upon crack width and depth as explained later, while the carbonation depth at uncracked position is usually depen-

Fig. 4   An example of carbonated area of lateral section at cracked and uncracked position.

dent upon curing time and their values were decreased with increasing the curing time. At the same curing time, the values of carbonation ratio of specimens which were made from OPC and cured for 7 days are larger than those made from BFS. The same results were obtained from the relation between crack depth and carbonation ratio as shown in **Fig. 6**. This Figure shows that the influence of crack depth on carbonation ratio is remarkable for crack depth more than 60 mm and its effects are dependent upon the curing time.

Fig. 7 & 8 show the relations between the carbonation depth at cracked position (d_c), and crack width, and crack depth respectively. The mean values of carbonation depths are between 30 mm and 80 mm depending on the crack widths. There is a remarkable increase in carbonation depth with increasing crack width up to 0.15 mm, but at crack width more than 0.15 mm the effect of crack width on carbonation depth is somewhat decreased. But, there are no change in these values with different kinds of mortars (i. e. there is no effect of type of cement or curing time on the relation between crack width and carbonation depth). Indeed, the carbonation of mortar at the crack surface is not dependent upon mortar quality, but it is mostly dependent upon both crack widths and crack depths. The most of carbonation depths are less than or equal to the crack depths as shown in **Fig. 8** , except for few results that show larger carbonation depths than crack depths.

b)   Observation of longitudinal section of cracked beam

JCI research and study committee on concrete cracking mentioned that even if all cover concrete is not carbonated the presence of wide crack can develop the carbonated area around reinforcing steel[7]. Therefore, crack width must be controlled. Carbonated area around the crack observed from longitudinal section, was dependent upon mortar quality and both crack width and depth. **Fig. 9** shows a typical carbonated area around the crack and virtual carbonation depth measured from longitudinal section. The
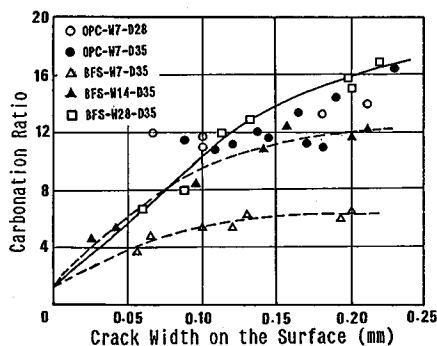
Fig. 5   The relationship between carbonation ratio and crack width on the surface.
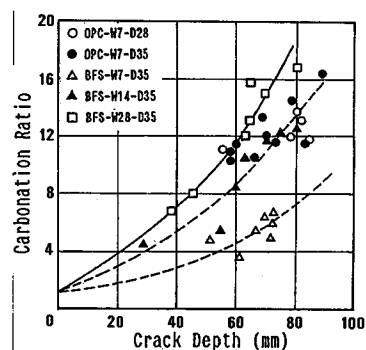
Fig. 6   The relationship between carbonation ratio and crack depth.
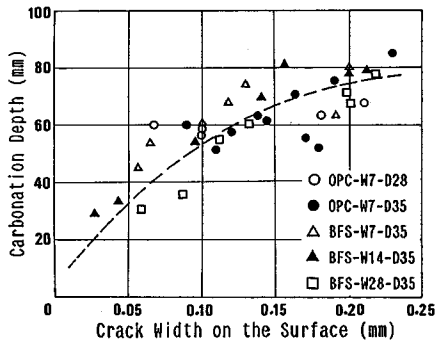
Fig. 7 The relation between carbonation depth (d_c) measured from lateral section and crack width.
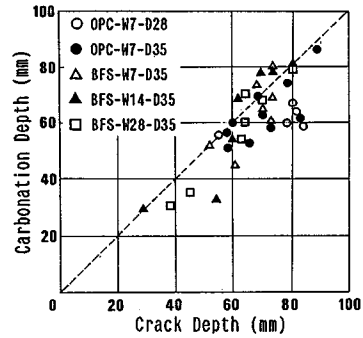
Fig. 8 The relation between carbonation depth and crack depth.
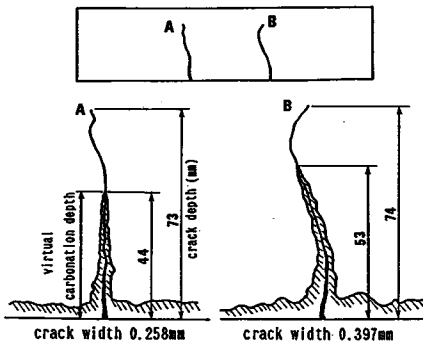
Fig. 9 Typical virtual carbonation depth measured from longitudinal section.
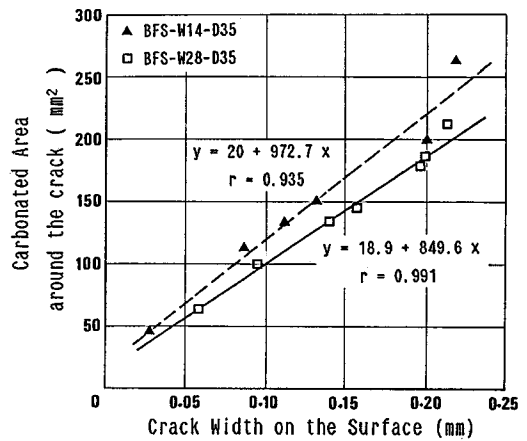

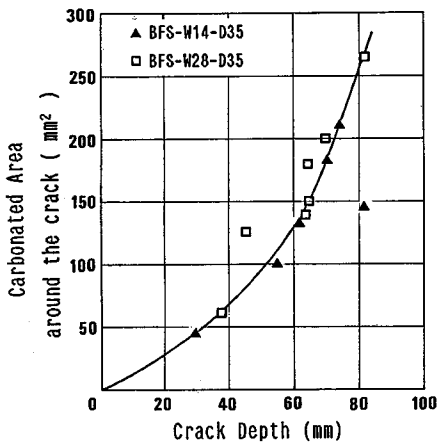Fig. 10 The relation between carbonated area around the crack and crack width.

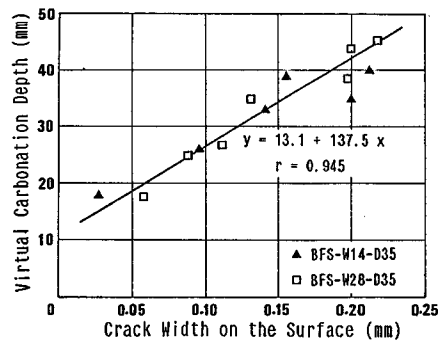Fig. 11 The relation between carbonated area around the crack and crack depth.

Fig. 12 The relation between the virtual carbonation depth and crack width.

carbonated areas around the crack were measured and their values were plotted against the crack width and crack depth as shown in Fig. 10 and 11 respectively. It was found that carbonated area around the crack was related to both the crack width and depth. The carbonated area is proportional with the crack width.

It can be said that the carbonation speed is increased with the increase in crack width and this result was coincided with that obtained by Izumi et al.[6]. Also, the relation between carbonated area and crack width is affected by curing time. Equations (2) and (3) give the relation between carbonated area (A_c) and crack width (W) for the specimens which were cured for 14 and 28 days respectively.

$$A_c = 20 + 972.7 \ W \qquad \text{(for curing time 14 days)} \quad\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (2)$$
$$A_c = 18.9 + 849.6 \ W \qquad \text{(for curing time 28 days)} \quad\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (3)$$

The relation between virtual carbonation depth and crack width or crack depth are shown in **Fig. 12 & 13** respectively. The virtual carbonation depth (d_{vc}) was proportional to both crack width and depth (D). These relations are given by equations (4) and (5).

$$d_{vc} = 13.1 + 137.5 \ W \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (4)$$
$$d_{vc} = 0.53 \ D \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (5)$$

(2) Exposure test results

After two years of exposure of mortar specimens, it was found that the curing time had significant effect on carbonation depth. The carbonation depth was reduced by increasing the curing time. This is due to the reduction in porosity of mortar by increasing the curing time as shown in **Fig. 14**. The effect of curing time on the porosity was remarkable for the specimen made from BFS than that from OPC. Also, the porosity was affected by the fineness of slag (e. g. specific surface area). Therefore, the carbonation depth was affected by type of BFS used, and the effect of BFS depends on its specific surface area. For example, the specimens which were made from B 40 had higher carbonation depth than that made from OPC at different curing time and reversal results were obtained from specimens which were made from B 80.

Bacause the relationship between the porosity (measured by Hg porosimetry) and the other parameters was not distinct, relationships with other factors were also sought. **Fig. 15 & 16** show the pore size distribution of four kinds of mortar cured for 3 days and 28 days respectively. It was found that, the pore volume was reduced by increasing the curing time and specific surface area of the slag. However, when the BFS was cured enough (e. g. 28 days) the finer pore structure was found with blended cement (cement+ slag) especially with slag of high specific surface area. Also, the pore size distribution was affected with the change in blast furnace slag content as shown in **Fig. 17 and 18**. It is known that the rate of hydration of slag is lower than that of OPC, so that as the slag content (B 40) is increased the pore volume is somewhat increased at early curing time, but it is considerably decreased at the prolonged curing time. Therefore, the carbonation depth was increased by increasing the slag content (B 40), but its value was dependent upon curing time as shown in **Fig. 19**.

In addition, an increase in water-cement ratio would be accompanied by an increase in porosity, so that
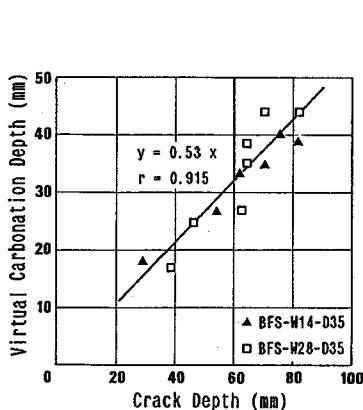

Fig. 13   The relation between the virtual carbonation depth and crack depth.
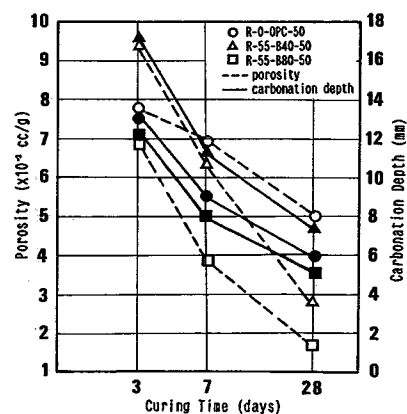

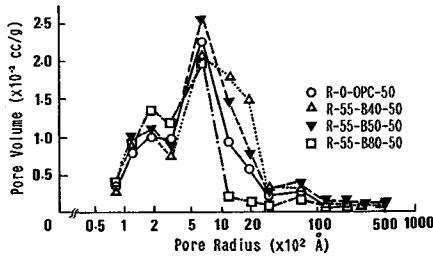Fig. 14   The effect of curing time on the carbonation depth and porosity.

Fig. 15 The pore size distribution of mortars made from OPC and different kinds of BFS (cured for 3 days).
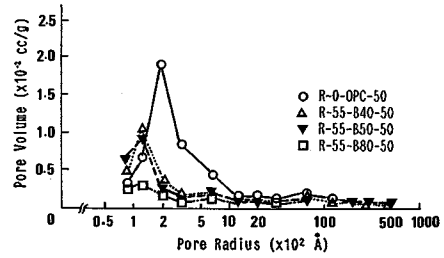

Fig. 16 The pore size distribution of mortars made from OPC and different kinds of BFS (cured for 28 days).
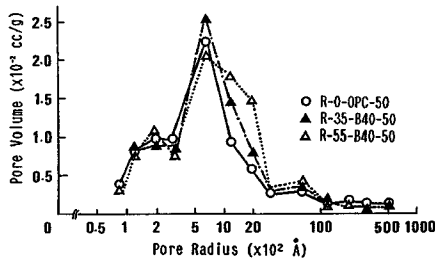

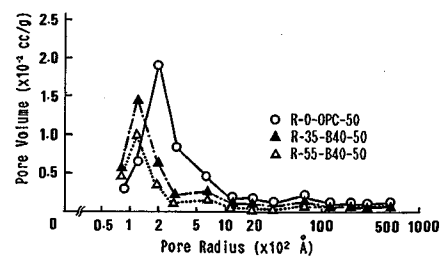Fig. 17 The effect of slag content (B40) on the pore size distribution at curing time 3 days.

Fig. 18 The effect of slag content (B40) on the pore size distribution at curing time 28 days.
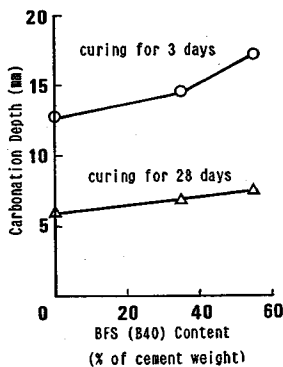

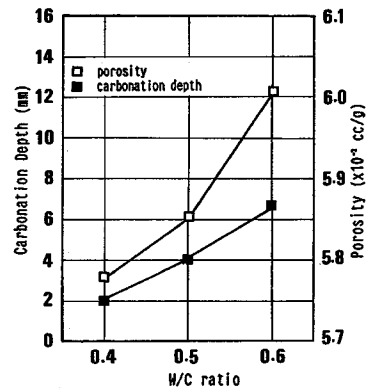Fig. 19 Influence of content of slag (B40) on carbonation depth.

Fig. 20 Influence of W/C ratio on porosity and carbonation depth.

an increase in carbonation depth could be expected, when water-cement ratio is increased. **Fig. 20** shows the relationship between W/C ratio, and both porosity and carbonation depth for those specimens which were cured for 28 days. The effect of initial curing time (t_w) and W/C ratio on carbonation depth (d_c) is given by the equation below.

$$d_c = a(t_w)^{-b} W/C(W/C - 0.23) \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (6)$$

where ; a & b are factors dependent upon the type of cement.

4. COMPARISON BETWEEN ACCELERATED AND EXPOSURE TEST RESULTS

Klopfer[9] shows that carbonation depth in concrete varies as square root of the time from casting. The decrease in the rate of carbonation with time has been attributed to filling of pores by the products of the reaction, resulting in a denser material. **Fig. 21** shows the relation between carbonation depth and time of
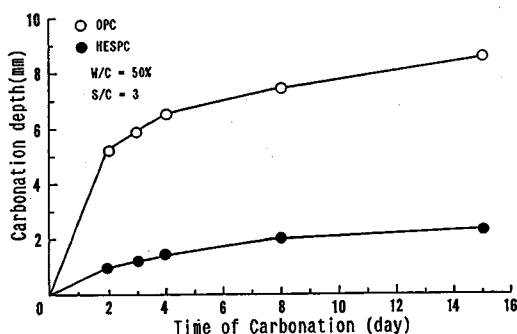
Fig. 21 The relation between carbonation depth and
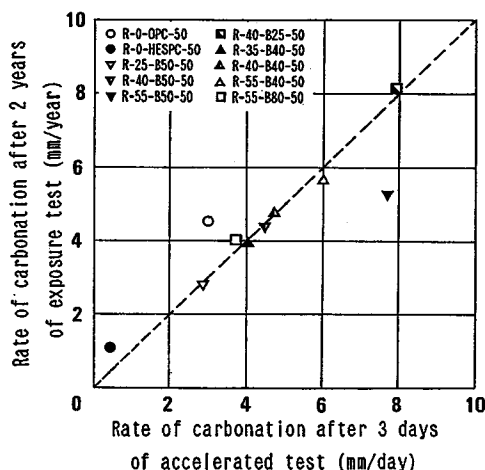time of carbonation.

Table 3 Accelerated and exposure test results for different kinds of
mortars cured for 7 days.

Mix No.	Type	W/(C+S) (%)	Accelerating Test Results		Exposure Test Results	
			Carbonation Depth (mm)	Carbonation Rate (mm/day)	Carbonation Depth (mm)	Carbonation Rate (mm/year)
1	R-0-OPC	40	2.0	0.7	---	---
2	R-0-OPC	50	4.0	1.3	9.0	4.5
3	R-0-OPC	60	6.5	2.2	---	---
4	R-0-HESPC	50	1.2	0.4	2.0	1.0
5	R-25-B50	50	8.6	2.9	5.6	2.8
6	R-40-B50	50	13.4	4.5	8.8	4.4
7	R-55-B50	50	23.2	7.7	10.4	5.2
8	R-40-B25	50	24.0	8.0	16.2	8.1
9	R-35-B40	50	12.0	4.0	7.8	3.9
10	R-40-B40	50	14.0	4.7	9.3	4.7
11	R-55-B40	50	18.0	6.0	11.2	5.6
12	R-55-B80	50	11.4	3.8	8.0	4.0

Fig. 22 The relation between rates of carbonation for
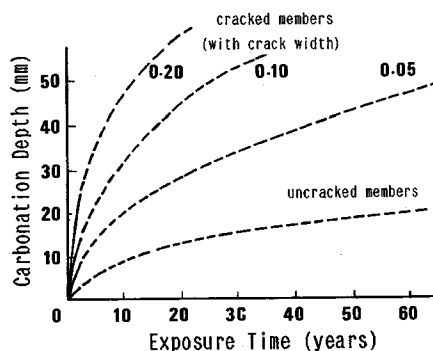accelerated and exposure test.

Fig. 23 Influence of crack width on the relation
between carbonation depth and exposure
time (extrapolated by equation No. 7).

carbonation during the accelerated test for two types of cement. The rate of carbonation was decreased with the time and their values of specimens which were made from HESPC were about 1/4 of those made from OPC with the same mix proportion. Table 3 presents the results observed for a limited number of mixes exposed for two years and those obtained from accelerated test. The results of exposure test were proportional with that obtained from accelerated test for different materials as shown in Fig. 22; in addition, there are two of anomalous points. Surprisingly, portland cements exhibited higher rate of carbonation in case of exposure test. Not enough samples however, were investigated to make valid comparisons with the other blended materials. The reversal result was obtained for slag B50 with 55 % content. Also, from Fig. 22 it can be said that the depth of carbonation after one year was approximately equal to the value obtained after one day of the accelerating test. By using the last results, and Fig. 21, the relation between exposure time and carbonation depth could be drawn. Finally, depending on a corelation between short-term and long-term test results, and equation (4), the relation between carbonation depth (D) and exposure time (t) as a function of crack width (W) and water-cement ratio (X) can be given by the following equation.

$$D=(X-a)(b+cW)\sqrt{t} \quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad (7)$$

where ; a, b & c are factors dependent upon curing time and type of cement.
The values of a were approximately from 0. 35 to 0. 38, the values of b were from 24 to 28 and the values of c were from 650 to 670.

By assuming equation (7), **Fig.** 23 which shows the relation between the carbonation depth and exposure time for uncracked and cracked members with different crack widths, could be drawn. This figure was drawn for W/C ratio 0.5 and curing time 7 days, where $a=0.38$, $b=24$ and $c=667$.

It was shown that after 50 years of exposure, less than 2 cm will be carbonated for uncracked members, but when even a very narrow crack is present then a depth of 2 cm will be carbonated within 10 years. Also, the crack widths have a significant effect, for example when crack width is 0.05 mm, it takes about 65 years to carbonate a depth of 5 cm, and when crack width is 0.1 mm it takes about 28 years, but when the crack width is increased to 0.2 mm or more, then the rate of carbonation is higher and it takes about 10 years to carbonate a depth of 5 cm.

5. CONCLUSIONS

The influence of cracks on the carbonation of mortar beams was investigated by using an accelerating test. Also, a limited number of mortar specimens were exposed to normal environment for two years. It was found that the presence of cracks had significant effects on the rate of carbonation. The carbonation depth and carbonation ratio were increased considerably by the increase in the crack width. The carbonated area around the crack which has great effect on destroying the passive layer of the steel reinforcement, is dependent upon both crack width and depth. The effect of crack width on the relation between carbonation depth and exposure time is proposed to be given by the equation (7).

The depth of carbonation was reduced considerably when the porosity was decreased by reducing the W/C ratio and increasing the initial curing time. The effect of curing time on the porosity and carbonation depth was remarkable for the specimen made from BFS than that from OPC. The carbonation depths of specimens made from BFS was dependent upon specific surface area of slag and their contents. The carbonation depth was increased by increasing the blast furnace slag content, but it was decreased by increasing the fineness of slag. Also, the rate of carbonation of the specimen made from HESPC was about 1/4 of that made from OPC with the same mix proportion.

Since the carbonation process was dependent upon the properties of the matrix, these results obtained for mortar could be applied for concrete which can be regarded as a composite material consisting of mortar matrix and coarse aggregate. Finally, the result of this work and of the others[6],[7] show that it is essential that new specification of JSCE should include statement about the ralationship between cracking and crabonation of concrete.

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