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論 文

[1154] Effect of Carbonation on Compressive Strength of Mortar

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1. INTRODUCTION

Change in compressive strength of concrete due to carbonation is usually believed mainly caused by change in its microstructure. Experimental results done by Bier, Th. A. and et al. [1] shows that cement paste made of ordinary portland cement (OPC) gives a pronounced reduction in the pore volume due to carbonation, which is more distinct for accelerated carbonation. The portland blast-furnace slag (PBFS)-cement paste shows a slight reduction of the intruded pore volume but a shift of the distribution curves towards greater pore radii. This coarsening of the pore system is more pronounced for accelerated carbonation. In this paper, effect of type of cement, initial water curing and CO_2 concentration on the change in pore volume and pore size distribution of mortar due to carbonation is studied. The change of its compressive strength is also investigated. It was found that carbonation also affects the characteristic strength of mortar and change in microstructure of carbonated portion affects the hydration process of uncarbonated portion of mortar by water reduction due to drying.

2. EXPERIMENTAL

2.1 MATERIALS AND MIX PROPORTIONS

Cements used in the experiments were ordinary portland cement and blended cements (50% and 75% ground granulated blast-furnace slag). Chemical composition of both the ordinary portland cement and the ground granulated blast-furnace slag are given in Table 1. Standard Toyoura sand was used as fine aggregate. Mortar with water-binder ratio of 0.6 were prepared. Mix proportions of mortar are given in Table 2.

2.2 FABRICATION AND CURING

All the specimens were cast as cylinders of diameter 5 cm and height 10 cm. After curing for one day in the moist room at 20°C, specimens were demolded. Slices with about 2 mm thickness were taken out from the middle portion of specimen (about 3 cm from top and bottom surface). Then, slices and cylinders were either initially cured in water for 27 days or directly transferred to various environments (air with 0.07% CO_2, water, carbonation chambers with 1% and 10% CO_2 and cyclic - one week in carbonation chamber with 10% CO_2 and one week in water -) with constant humidity of 60% and temperature of 20°C.

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After exposure, compressive strength and carbonation depth were measured at the ages of 1, 4, 8, 12, 20, 28 and 52 weeks. Three cylinder specimens were used at each condition of exposure for compressive tests. Porosity of sliced mortars, measured by mercury porosimetry, were determined at the ages of 4, 12, 28 and 52 weeks.

Table 2. Mix proportions of mortar (60% W/C ratio)

% slag content	Cement (kg/m³)	Water	Slag	Sand	Initial curing period
0	598	359	------	1196	0 and 27 days
50	297	356	297	1187	
75	148	355	444	1178	

Table 1. Chemical compositions and physical characteristics of OPC and GGBFS

	Ordinary Portland Cement	Ground Granulated Blast-furnace Slag
Ig. loss	1.2 %	---
Insol.	0.4 %	---
SiO_2	21.9 %	34.3 %
Al_2O_3	5.0 %	14.6 %
CaO	64.2 %	42.2 %
Fe_2O_3	2.8 %	0.2 %
MgO	1.7 %	6.4 %
Specific Weight	3.15	2.90
Specific Surface Area	3230 cm^2/g	4010 cm^2/g

3. RESULTS AND DISCUSSIONS

Experimental results reported in this paper are only up to the ages of 20 weeks. The values for compressive strength tests are the average values at each condition.

3.1 EFFECT OF WATER CURING

After exposing to various environments, it is shown in Figs. 1 and 2 that PBFSC (50% or 75% ground granulated blast-furnace slag) mortar initially cured in water gives higher compressive strength than those which were not initially cured in water. However, Fig. 3 shows that after exposing to high concentration of CO_2 (1% or 10% by volume) OPC mortar initially cured in water gives lower compressive strength than those which were not initially cured in water.

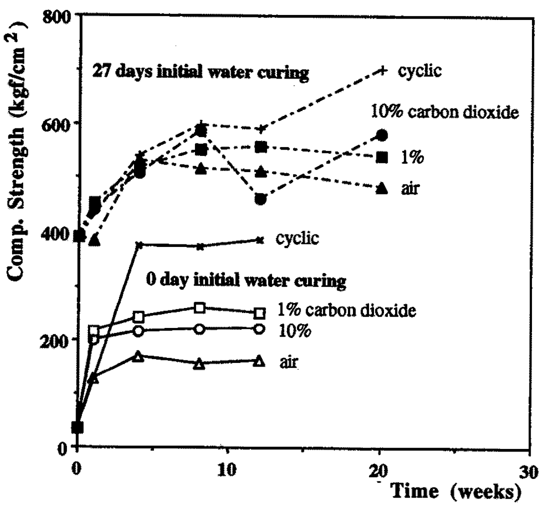

Figure 1. Effect of initial water curing on strength of 50% PBFSC mortar

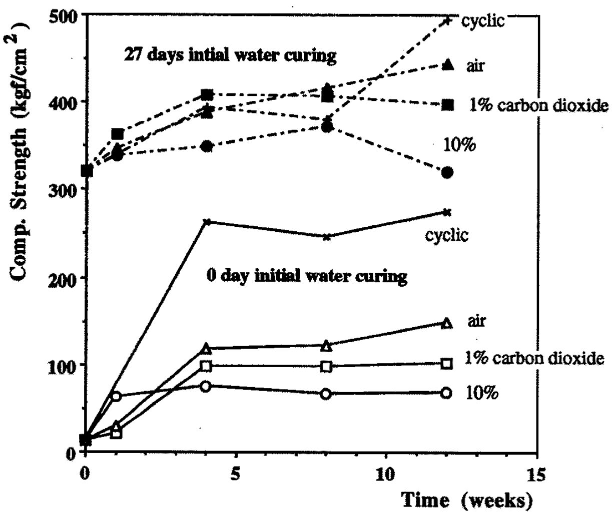

Figure 2. Effect of initial water curing on strength of 75% PBFSC mortar

3.2 EFFECT OF TYPE OF CEMENT

In case of mortar which is not initially cured in water, cement with higher slag content gives lower compressive strength. However, mortar which is initially cured in water shows that compressive strength in 50% PBFSC mortars is slightly higher than in OPC mortars, while both of them are still higher than those made of 75% PBFSC. This means that mortars made of higher slag content need longer initial water curing.

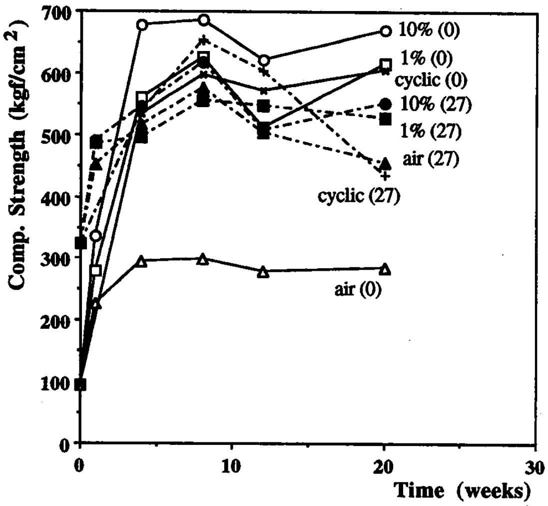

Figure 3. Effect of initial water curing on strength of OPC mortar

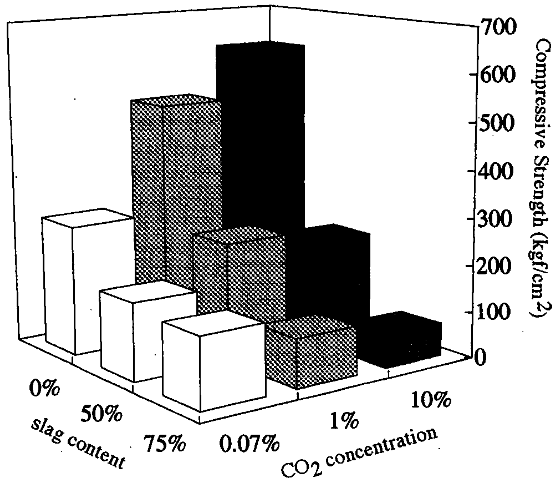

Figure 4. Effect of CO_2 concentration on strength of mortar made of various type of cement

3.3 EFFECT OF CO_2 CONCENTRATION

OPC mortars with or without initial water curing at the age of 20 weeks, has higher compressive strength when exposed to higher concentration of CO_2 (see Fig. 3).

In the case of mortars without initial water curing, it is shown in Figure 4, that maximum strength shifts from high to lower concentration of CO_2 with increasing of slag content.

3.4 RELATION BETWEEN COMPRESSIVE STRENGTH AND MICROSTRUCTURE

Change in microstructure of mortar due to carbonation is affected by initial water curing, type of cement and CO_2 concentration. If relation between compressive strength and microstructure can be obtained, the change in compressive strength, which is affected by those factors, is more predictable. Porosity and pore size distribution of mortar should become the main factors which affect its compressive strength besides its characteristic strength. Atzeni and et. al. [2] introduced a parameter called 'mean distribution radius' to relate pore size distribution to compressive strength.

$$\ln r_m = \frac{\sum V_i \ln r_i}{\sum V_i} \qquad (1)$$

An attempt was made to relate porosity (P) and 'mean distribution radius' (r_m) to compressive strength. Microstructure and compressive strength of uncarbonated specimens (cured in water) and completely carbonated specimens (cured in 1% or 10% CO_2) were taken to find out their correlation and some assumptions data were introduced in the case of completely carbonated specimens. After 'trial and error' process, it was found that the effect of porosity which pore radius is less than 30 nm on compressive strength should be neglected (especially for 50% and 75% PBFSC mortar). And so far, the best correlation between compressive strength and microstructure is achieved by combining the above two porosity parameters which leads to relation between R_c (compressive strength) and $P.r_m^{0.75}$ (P is porosity [mL/g], r_m is mean distribution radius [nm] which pore radius is greater than 30 nm). By curve fitting, it was obtained that exponential equation relate R_c and $P.r_m^{0.75}$ quite well. It is shown in Fig. 5 that the characteristic strength of carbonated mortar is higher. The increase of characteristic strength due to carbonation is large in OPC mortar and less in PBFSC mortar. Therefore, carbonation of mortar does not only change its microstructure but also its characteristic strength.

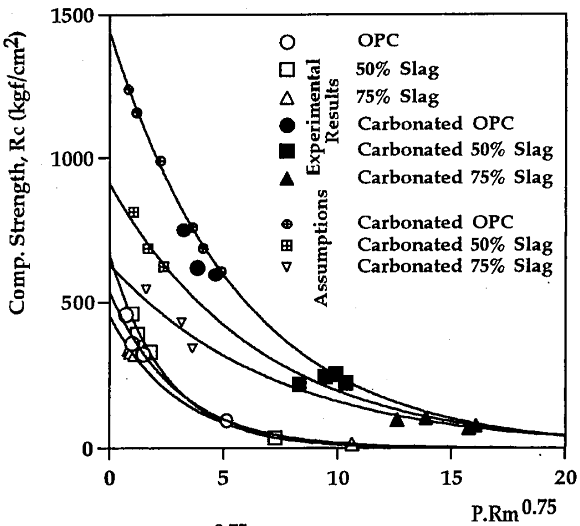

Figure 5. Rc vs $P.Rm^{0.75}$

3.5 STRENGTH OF UNCARBONATED PORTION OF INCOMPLETELY CARBONATED MORTAR

Figure 5 shows the relation between microstructure and compressive strength of completely uncarbonated mortar (cured in water) or completely carbonated mortar. This relation was used to find out strength of uncarbonated portion of incompletely carbonated mortar (see Fig. 6).

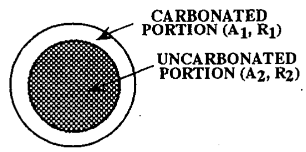

Figure 6. Section of incompletely carbonated mortar

Carbonation and hydration processes usually occur simultaneously which is more profound when initial water curing is not applied properly. Change in microstructure of carbonated portion may affect drying process in mortar. Therefore, microstructure and strength of uncarbonated portion may be affected by change of microstructure of carbonated portion. The simple calculation which based on following equation was done to find out those phenomena.

$$R_t.A_t = R_1.A_1 + R_2.A_2 \qquad (2)$$

where; R_t is compressive strength of mortar which obtained from compressive test and A_t is the total section area of mortar. A_1 is the section area of carbonated portion which can be calculated from carbonation depth. R_1 is compressive strength of carbonated portion which can be obtained from Fig. 5 if its porosity and pore size distribution are known. A_2 is the section area of uncarbonated portion. From equation (2), R_2, compressive strength of uncarbonated portion can be obtained. However, it has to be noticed that equation (2) should has limitation when carbonated area is extremely small or extremely large. Calculated results are shown in Table 3 (calculated from experimental results at the age of 4 weeks).

(1) Without initial water curing

Strength of uncarbonated portion of mortar exposed to air is lower than those cured in water continually. However, it decreases with increase of slag content in cement. In the case of mortar exposed to cyclic condition, it was found that strength of uncarbonated portion is higher than those exposed to air condition. This phenomenon is due to drying process which decreases the amount of evaporable water then hinders hydration process inside of mortar.

(2) With initial water curing

Strength of uncarbonated portion exposed to air is higher than those exposed to 1% and 10% CO_2. This may be related to the increase of pore size of carbonated portion with increase of concentration of CO_2. However, such kind of phenomena cannot be seen in 75% PBFSC mortar.

Table 3. Calculated comp. strength by using equation (2)

Initial Water Curing (days)	Slag Rep. Ratio (%)	Curing Condition	Microstructure		Compressive Strength (kgf/cm^2)		Carb. Depth (mm)
			$P_{>30nm}$ (mL/g)	r_m (nm)	Carb.	Uncarb.	
0	0	Air	0.0790	163.97	757.37	180.431	2.600
		1% CO_2	0.0818	232.89	606.44	194.31	16.535
		10% CO_2	0.0686	230.91	700.22	---	21.285
		Cyclic	0.0380	119.74	1126.45	385.02	2.660
	50	Air	0.1158	295.17	259.62	143.28	3.195
		1% CO_2	0.1109	374.93	212.26	---	25.0
		10% CO_2	0.0975	375.41	252.74	---	25.0
		Cyclic	0.0773	212.22	469.13	279.52	7.445
	75	Air	0.1266	343.55	156.30	107.39	3.020
		1% CO_2	0.1311	441.24	110.38	---	25.0
		10% CO_2	0.1324	601.57	68.44	---	25.0
		Cyclic	0.0993	238.47	274.44	236.96	11.270
27	0	Air	0.0343	68.55	1243.37	468.84	0.775
		1% CO_2	0.0301	131.77	1168.01	351.67	2.295
		10% CO_2	0.0456	176.25	972.60	336.65	4.515
		Cyclic	0.0436	158.13	1018.66	430.97	3.355
	50	Air	0.0262	133.34	776.12	517.31	0.705
		1% CO_2	0.0394	148.74	702.21	431.68	4.330
		10% CO_2	0.0486	176.29	633.07	432.73	5.215
		Cyclic	0.0320	207.78	694.34	509.20	2.125
	75	Air	0.0288	208.30	507.15	374.32	1.280
		1% CO_2	0.0674	178.31	408.43	407.18	9.460
		10% CO_2	0.0690	196.64	382.42	246.75	12.630
		Cyclic	0.0612	177.19	418.40	372.00	6.755

4. CONCLUSIONS

The results obtained from this study can be summarized as in the following :
1) Change in microstructure of mortar due to carbonation is affected by initial water curing, cement type and concentration of CO_2.
2) By using a parameter named 'mean distribution radius', an attempt was made to find out the relation between microstructure (porosity and pore size distribution) and compressive strength of carbonated and uncarbonated mortar made of OPC and BFSC.
3) Carbonation does not only change microstructure of mortar but also its characteristic strength which depends on slag content in cement.
4) By using simple calculation, strength of uncarbonated portion of mortar can be obtained. Change in microstructure of carbonated portion seems to affect drying process in mortar that influences strength of uncarbonated portion. However, such kind of phenomena is hardly found in 75% BFSC mortar.

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