

# INVESTIGATION OF CARBONATION RATE COEFFICIENT IN MORTARS WITH BLAST FURNACE SLAG HIGH CONTENT

Junya Nakamura<sup>1</sup>, Takeshi Iyoda<sup>2</sup>, Seishi Goto<sup>3</sup>

<sup>1</sup>3-7-5, Toyosu, Koto-ku, Tokyo 135-8548, Japan,  
[me18091@shibaura-it.ac.jp](mailto:me18091@shibaura-it.ac.jp), Shibaura Institute of Technology  
<sup>2</sup>3-7-5, Toyosu, Koto-ku, Tokyo 135-8548, Japan,  
[iyoda@shibaura-it.ac.jp](mailto:iyoda@shibaura-it.ac.jp), Shibaura Institute of Technology  
<sup>3</sup>1677-1, Yoshida, Yamaguchi-shi, Yamaguchi 753-8511, Japan,  
[sgoto410@yahoo.co.jp](mailto:sgoto410@yahoo.co.jp), Yamaguchi University

## ABSTRACT

Recently, in the cement industry, admixtures are used to reduce CO<sub>2</sub> emissions. Ground granulated blast furnace slag fine powder (GGBFS) can be used as a high replacement for cement. On the other hand, the utilization of admixtures in concrete reduces the resistance to carbonation, this is verified by calculating the carbonation rate coefficient. There are two main methods for calculating the carbonation rate coefficient, the first method is experimental calculation and the second method is formula calculation based on prediction. In this study, we investigated the possibility of the hardened cement with high replacement rate of GGBFS linked with each other. A correlation was made with the two methods as the replacement rate of GGBFS was about 50%, but there was a tendency to shift with the high replacement rate of GGBFS. The reason for the shifting tendency was because of the progress of carbonation of calcium hydroxide and C-S-H which are hydrates that has been carbonated.

**Keywords:** *GGBFS, Carbonation, Carbonation Rate Coefficient, High Replacement*

## 1. INTRODUCTION

Recently, the construction industry is promoting the use of admixtures in order to reduce the environmental burden. There are various kinds of admixture. Fly ash (FA) and ground granulated blast furnace slag (GGBFS) are generally used in Japan. By using the admixture as an alternative material for cement, it is possible to reduce the CO<sub>2</sub> emissions significantly. Figure.1 shows the amount of CO<sub>2</sub> emissions at the time of manufacturing each cement and the amount of reduction rate of CO<sub>2</sub>. It is considered that using admixtures, especially GGBFS, can reduce large amount of CO<sub>2</sub> emissions. And also the amount of CO<sub>2</sub> reduction rate of GGBFS has reached 50%. In this figure the data of GGBFS is about 50% replace of cement. The replacement rate of GGBFS

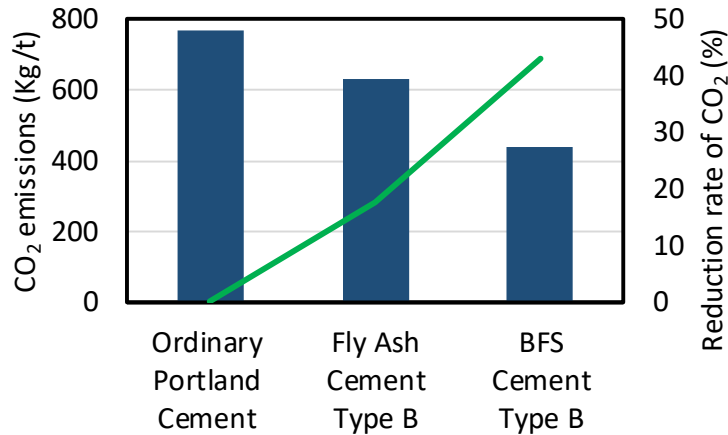


Figure.1 CO<sub>2</sub> emission for the manufacture of different cements and CO<sub>2</sub> reduction rate of different cements compared to that of OPC

can increase to 70%, that means GGBFS can replace the cement in high volume and as a result of that it can greatly contribute to reducing the environmental burden. It is conceivable that GGBFS can be used with higher replacement rate of cement, as the usage rate increases from the viewpoint of reducing the environmental burden. From the above GGBFS has a tremendous effect to reduce the environmental burden. In addition, the utilization of GGBFS as a replacement of cement has many advantages characteristics such as increase in salt damage resistance, suppression of ASR, and long-term strength enhancement. However, the resistance to carbonation decreases as the replacement rate of GGBFS increases in the cement. Carbonation is one of the most important factor to evaluate the durability of concrete. Carbonation is the loss of alkalinity due to the reaction of alkaline concrete with carbon dioxide in the air. Carbonation of concrete surface, that penetrate into the rebar position destroys the nonconductor film covering the rebar that lead to corrosion of the rebar, this generate cracks in the concrete and the proof stress decreases. In this way, the evaluation of carbonation, that leads to the deterioration of concrete, is generally estimated based on the carbonation rate coefficient. There are two methods to calculate the carbonation rate coefficient. The first is to obtain carbonation depth for each age by carrying out a carbonation test. The carbonation rate coefficient can be obtained based on the carbonation depth by placing the depth in to the square root of time as shown in the Equation (1) and since the long-term measurement is required in the test in the case of natural environment accelerated carbonation tests were conducted.

Carbonation coefficient can also be calculated using the carbonation rate formula represented by Equation (2) described in the Concrete Standard Specification published by the Japan Society of Civil Engineers. The formula shows that the carbonation rate coefficient can be calculated according to the type of cement used and the water binder ratio. This means that we set up a prediction formula based on the enormous carbonation data accumulated so far.

In previous studies, there are other considerations environmental conditions such as humidity and the action of water in this carbonation rate formula. However, there are not many studies on cement with high replacement rate of admixture. Therefore, in this study, concrete made of blast furnace cement with the high replacement rate of

GGBFS from the viewpoint of reducing environmental burden, the correlation and validity of Equation (1) and (2).

$$y = \alpha\sqrt{t} \quad (1)$$

where  $y$ : Carbonation Depth  
 $\alpha$ : Carbonation Rate Coefficient  
 $t$ : Carbonation Period

$$y = \gamma_{cd} \cdot (-3.57 + 9.0W/B)\sqrt{t} \quad (2)$$

where  $y$ : Carbonation Depth  
 $\gamma_{cd}$ : Safety factor on prediction accuracy  
 $W/B$ : Effective water bonding ratio =  $W/(C_p + k \cdot A_d)$   
 $W$ : Amount of water per unit volume  
 $B$ : Mass of effective water bonding ratio per unit volume  
 $C_p$ : Mass of OPC per unit volume  
 $k$ : Constant by admixture (GGBFS = 0)  
 $A_d$ : Mass of GGBFS per unit volume

## 2. FLOW OF RESEARCH

We focused on the correlation and validity of carbonation rate coefficient. Figure.2 shows how the carbonation rate coefficient was organized. First, the carbonation rate coefficient was calculated from the carbonation depth by carrying out the accelerated carbonation test and natural carbonation test. The depth of carbonation is proportional to the square root of time. On the other hand, the carbonation rate coefficient was calculated from the carbonation rate formula in the standard specification form using the value determined in the mix proportion. Thereafter the calculated carbonation rate coefficient was compared.

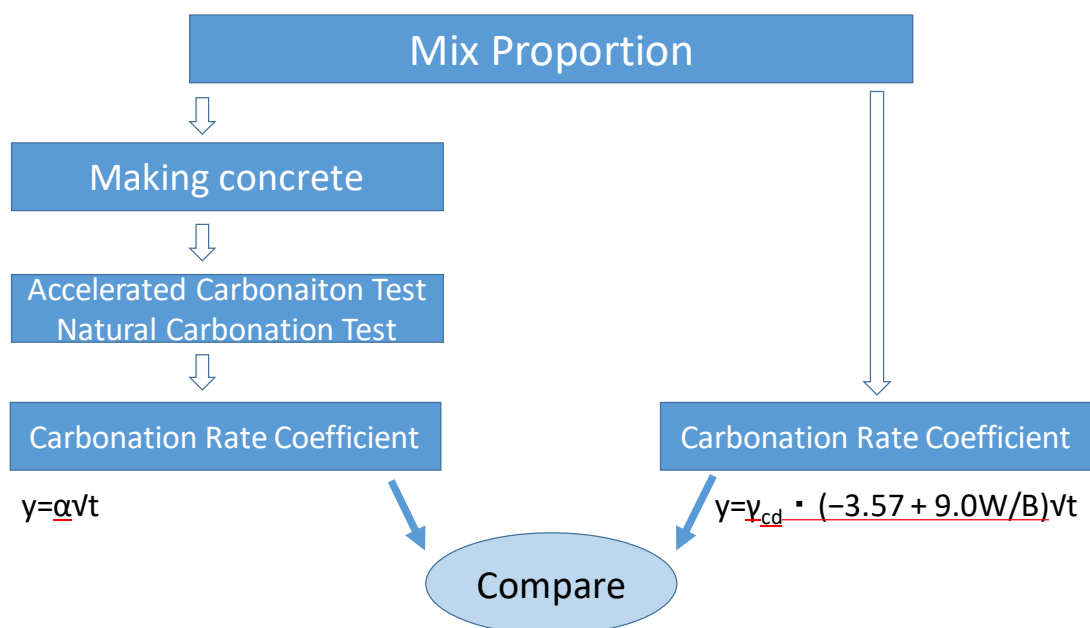


Figure.2 Research flowchart

### 3. OUTLINE OF RESEARCH

#### 3.1. Specimen Specifications

Table.1 shows the details of the materials used in this research. Table. 2 shows the mix proportion of the concretes prepared in this research. Four blast furnace slag cements and a plain Ordinary Portland cement (OPC) were tested. In the blast furnace cements GGBFS replaced 50% (concrete 50-b50), 60% (concrete 50-b60), 70% (concrete 50-b70) and 80% (concrete 50-b80) of OPC. The OPC-based concrete is shown as 50-b0. The water to cement ratio was kept constant for each concrete and equal to 50%.

Table.1 Details of materials used

Materials	Symbol	Types and Physical Properties
Water	W	Water Supply
Cement	OPC	Ordinary Portland Cement (Density: 3.16g/cm <sup>3</sup> )
	GGBFS	Ground Granulated Blast Fine Slag Powder (Density: 2.91g/cm <sup>3</sup> )
Fine Aggregate	S	Crushed Sand (Density: 2.62g/cm <sup>3</sup> )
Coarse Aggregate	G	Limestone (Density: 2.70g/cm <sup>3</sup> )

Table.2 Mix Proportion

Symbol	W/C (%)	Replacement Ratio	s/a (%)	Unit Weight (Kg/m <sup>3</sup> )					Flesh Results		
				W	C		S	G	CT (°C)	Slump (cm)	air (%)
					OPC	GGBFS					
50-b0	50	0	46	165	330	0	826	1000	24.8	16.5	5.4
50-b50		50			165	165	821	993	25	11.0	5.1
50-b60		60			132	198	820	992	25.1	12.0	4.0
50-b70		70			99	231	819	990	24.9	11.5	4.0
50-b80		80			66	264	818	989	24.6	10.0	4.0

s/a: Fine Aggregate Ratio, CT: Concrete Temperature

#### 3.2. Carbonation Test

Figure.3 shows the flow of the carbonation test. The carbonation test was carried out in accordance with "Concrete accelerated carbonation test" prescribed in JIS A 1153. The dimensions of the specimen were 100×100×400 mm prisms. The cast concrete was demolded after 24 hours of casting. There were two condition of curing, first the specimen was not cured in water and the second was that the specimen was cured for four weeks in water which is a standard curing. After standard curing, the preliminary curing was carried out for 4 weeks at a constant temperature of 20±2°C and humidity 60% and a week outdoor environment curing was also carried out in a place where there is no rain and also no direct sunlight. The carbonation depth was measured once at the end of pre-curing, and this value was recorded as the carbonation depth at the

Environment	Curing	0 Day	1 Day	1 week	4 weeks	5 weeks	9 weeks	10 weeks		
Accelerated Environment	non-curing	Cast	Form Placement	Demold	Constant Temperature room	Outside (pre-curing)		Accelerated Test		
	Standard				Standard Curing		Constant Temperature room	Outside (pre-curing)	Accelerated Test	
Natural Environment	non-curing				Constant Temperature room	Outside (pre-curing)		Natural Test		
	Standard				Standard Curing		Constant Temperature room	Outside (pre-curing)	Natural Test	

Figure.3 Carbonation test flowchart

origin of the carbonation period. Thereafter, the specimen was carbonated in an outdoor environment and in accelerated carbonation test chamber (temperature 20°C, relative humidity 60%, CO<sub>2</sub> concentration 5%) wound with aluminum tape excluding the two sides of the side, and the carbonation depth was also measured. The concentration of CO<sub>2</sub> in an outdoor environment is 0.04% on average. Phenolphthalein method was used for carbonation depth measurement. The measurement age of the carbonation depth was formulated separately from the previous research. accelerated test was measured up to 26 weeks.

#### 4. CARBONATION RATE COEFFICIENT FROM CARBONATION TEST

##### 4.1. Result of Carbonation Test

Figures.4 and 5 show the results of the time course of Carbonation test. Although the resistance to carbonation decreases by increasing the replacement rate of BFS, it has been found that resistance to carbonation is greatly improved by curing. The carbonation was progressed because the specimen was exposed at the stage of pre-curing after curing. This is because the progress of carbonation is as a result of the hydration reaction in the cement hardened has progressed and the pore become dense as a result of underwater curing and carbon dioxide, which is a deterioration factor, does not easily enter conceivable.

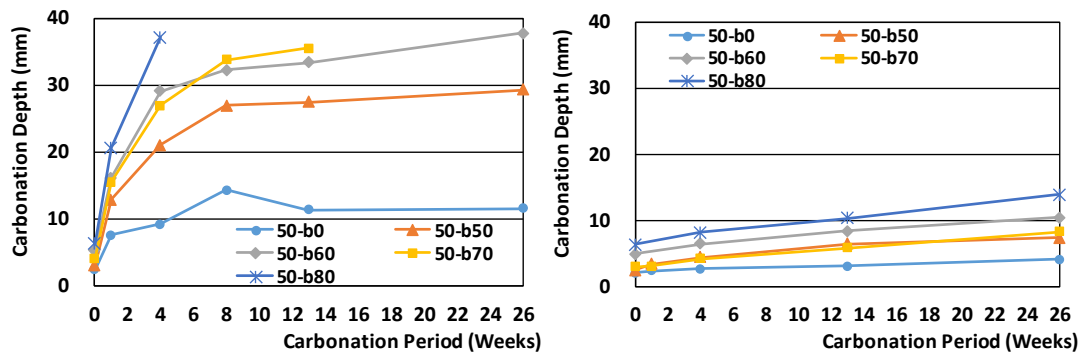


Figure.4 Time course of carbonation depth in non-curing (left: accelerated test, right: natural environment)

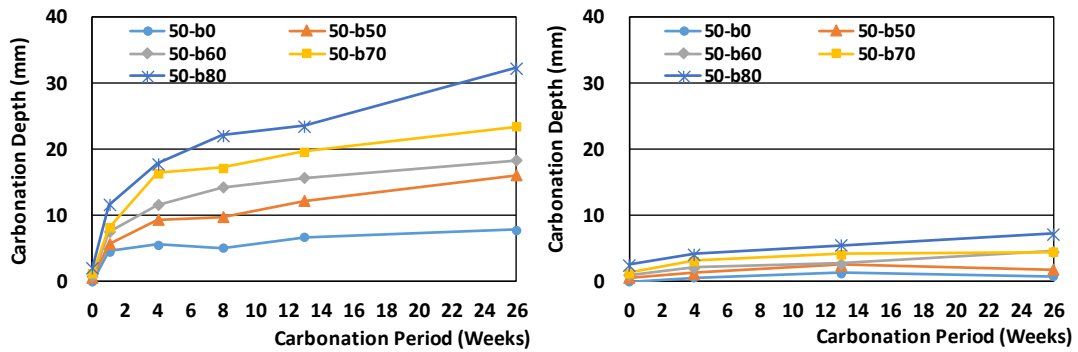


Figure.5 Time course of carbonation depth in standard curing (left: accelerated test, right: natural environment)

#### 4.2. Calculating Carbonation Rate Coefficient

The carbonation rate coefficient is the slope when taking the square root of the carbonation period on the horizontal axis and the carbonation depth on the vertical axis as shown in Equation (1). Therefore, we created Figures.6 and 7. As the inclination became linear, it can be confirmed that the carbonation test progressed according to previous research. Therefore, the carbonation rate coefficient was calculated by the slope line.

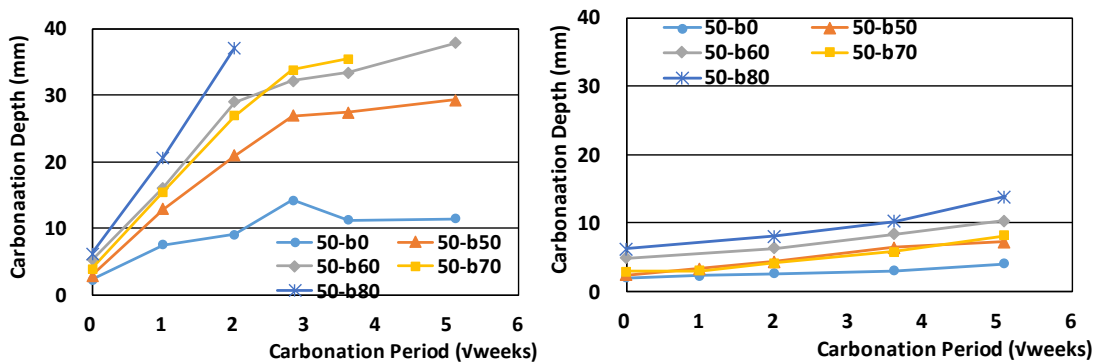


Fig. 6 Square root time course of carbonation depth in non-curing (left: accelerated test, right: natural environment)

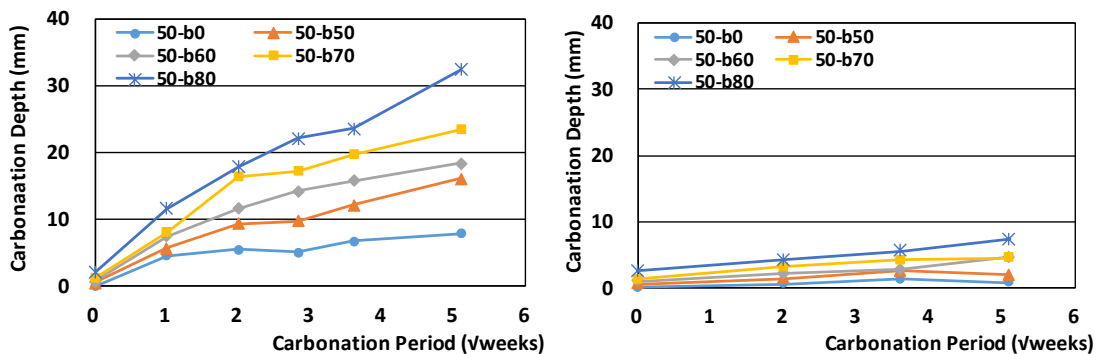


Figure.7 Square root time course of carbonation depth in standard curing (left: accelerated test, right: natural environment)

Figure.8 show the carbonation rate coefficient. As replacement rate increases, the value of the carbonation rate coefficient increases. There is a big difference between the values obtained in the natural environment and the accelerated environment. Those non-curing in the accelerated environment rapidly increased from the point where the replacement rate exceeds 60%.

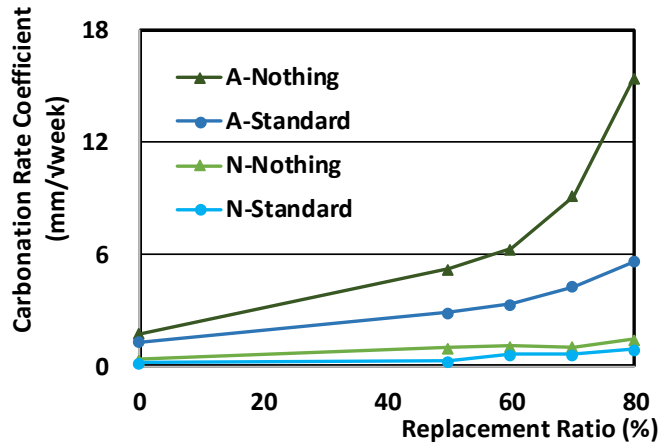


Figure.8 Carbonation rate coefficient (A: Accelerated, N: Natural)

Figure.9 is the carbonation rate coefficient in both environments. This figure compares the carbonation rate coefficient in both environments. When the replacement rate of GGBFS exceeds 60%, there is no correlation.

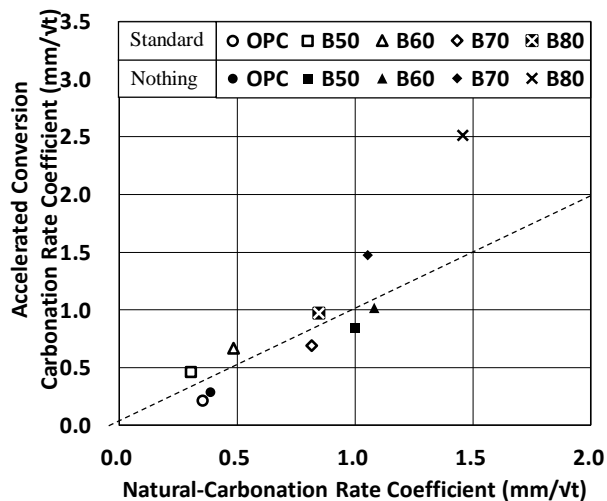


Figure.9 Compare carbonation rate coefficient in each environment

Figure.10 shows the carbonation rate coefficient from equation (1) and (2). this figure focus on carbonation rate coefficient from standard curing and carbonation rate formula. By curing, there is almost no difference between the accelerated experiment and the natural environment, showing a similar trend. On the other hand, the carbonation rate coefficient calculated from the carbonation rate formula differs from those results. There are three things that can be considered on this factor. First, as the

replacement rate of the admixture increases, the hydrates in the concrete, especially calcium hydroxide, decrease. This influence is not considered in the carbonation rate equation. Secondly, since the amount of hydrate is different, it is possible that in high replacement, it may be different from the considered original reaction mechanism. Thirdly, it is conceivable that the K value of the influence factor defined by the kind of admixture is incorrectly set.

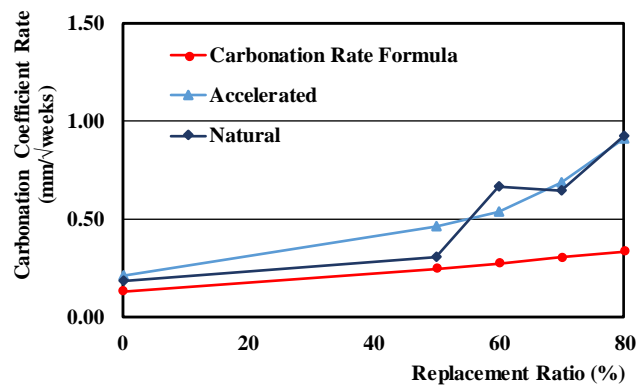


Figure.10 Carbonation rate coefficient from Equation (1) and (2)

## 5. CONCLUSION

With the aim of investigating the possibility of the hardened cement with high replacement rate of GGBFS that interlink with each other. A correlation was made with the formula based method and the depth approach method as the replacement rate of GGBFS was about 50, the following conclusion were drawn:

- (1) It is better to lengthen the carbonation period to calculate the carbonation rate coefficient.
- (2) When assessing the progress of carbonation from accelerated environment, it is important to do the curing.
- (3) It is difficult to judge the progress of carbonation at higher replacement than the current carbonation rate equation.

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