KPU International Journal of Engineering & Technology
Volume 3, Issue1, Sep. 2023
e-ISSN:2790-0819, p-ISSN:2790-0800

Date Received: 2023-04-12
Date Accepted: 2023-06-04
Date Published: 2023-09-15

As study on the durability of concrete structures against carbonation in Afghanistan

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Abstract

The durability of reinforced concrete is significantly affected by the corrosion of reinforcing bars, and carbonation is a major factor in the corrosion of steel bars in concrete. However, In Afghanistan, according to the Afghanistan Building Code (ABC), the major concerns regarding the durability of concrete structures are defined in terms of freezing/thawing, sulfate attack, and chloride-induced corrosion. However, there is no defined exposure class for carbonation-induced corrosion. Therefore, in this study, carbonation rate of concrete in Afghanistan is evaluated, and the carbonation prediction model is used to predict rate of concrete based on environmental and climate conditions. To evaluate the carbonation rate of concrete, 75x75x75mm concrete cubes were prepared and exposed in four different regions; namely Afghanistan, Japan, Indonesia and Malaysia. To predict the carbonation rate of concrete, the Papadakis model was used to estimate the carbonation rate in terms of environmental conditions (relative humidity, temperature, the concentration of CO2) and concrete composition. The carbonation depths of the concrete were measured at 6 months and 1 year after exposure. It was observed that climatic and environmental conditions influenced carbonation progress. Higher carbonation was observed in Afghanistan. Moreover, the prediction of carbonation rate based on atmospheric parameters and concrete composition matched actual carbonation depth measurements in four different regions. Furthermore, the applicability of the model is also confirmed by comparing the predict results with the actual experimental data from accelerated and natural exposed carbonation depths.

Keywords: Carbonation rate, environmental conditions, carbonation prediction model

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1. Introduction

The construction industry in Afghanistan is very different from Western countries and faces many challenges in maintaining good quality. Availability of materials and lack of equipment dictate most construction methods. Until 2004, no building codes existed for the concrete industry. Outside of major cities, building design is rarely considered, if ever existing, has historically had any consideration for earthquake force with no influence from modern building codes. Currently, ASC (Afghan Structural Code) has been established by ANSA (Afghanistan National Standard Authority).

Recently in Afghanistan, according to Afghanistan Building Code (ABC)/ Afghanistan Structural Code (ASC), the major concerns about the durability of concrete structures have been defined in terms of freezing/thawing, sulfate attack, and chloride-induced corrosion [1]. However, there is no defined exposure class for carbonation-induced corrosion.

Physical and chemical processes such as acid, sulfate, or alkali attacks can cause the concrete deterioration in service. The most serious failure mechanism is the corrosion of steel bars and one of the main factors of the corrosion is carbonation [2], carbonation reduces the alkalinity of concrete and break the passivity layer of steel bars [3]. carbonation rate is directly related to the concrete strength, type of curing, quality of concrete, mix-proportion, and environmental and climatic factor such as (temperature, relative humidity, and Carbon dioxide concentration).

Relative humidity in concrete is of great importance. Many researchers have stated that the carbonation is significant at a relative humidity between 50-70% [2-6]. Hence, proper design should be carried out to avoid degradation of concrete due to carbonation. Therefore, much research has been done; and many concrete carbonation models have been formulated by applying appropriate modifications using different parameters to Fick's second law of diffusion. However, typical carbonation models have the format of $Xc=A\sqrt{t}$ [8-9]; but some models overestimate the carbonation depth after a certain time period.

2. Materials and Methods

2.1 Materials and Mix proportion

In this study, OPC was used as a binder. Crushed stone with a maximum size of 20mm and washed sea sand were used as fine aggregate. In addition, tap water was used as mixing water for concrete. The physical properties of materials and the concrete mix proportion are described in Table 1 and Table 2, respectively.

Table 1: Physical Properties of Materials

Material	Description
Cement	OPC Density = 3.16 g/cm^3, Specific surface area (SSA)= 3330cm^2/g
Gravel	Crushed stone Density (SSD) = 2.88 g/cm^3, Maximum size aggregate (MSA)= 20 mm
Sand	Washed Sea sand Density (SSD) = 2.53 g/cm^3, Fine modulus (FM)=2.69

Table 2: Mix proportion and Fresh properties of the Concrete

Mixture	W/B %	Unit Content (kg/m^3)						Slump (cm)	Air %	Temp ^{o}C
		W	C	Gravel	Sand	WR	AE (ml)			
N-60	60	165	275	1114	800	1031	1586	5.5	4.9	22

* W: Water, C: Cement, * WR: Water Reducer- 3.0 ml / 1 kg of cement

2.2 Methods

Concrete prism specimens of 75x75x75 mm were de-molded 24 hours after casting. Then specimens were then transferred to a temperature and humidity-controlled room. The specimens were kept for 28 days in air curing at a constant humidity of 60% and a temperature of 20 ^{0}C.

After 28 days of curing, samples were prepared to conduct exposure tests. For natural exposure, four distinct countries were selected; namely Japan, Afghanistan, Indonesia, and Malaysia. In addition, the specimens in the natural environment were exposed to normal conditions. Before starting the exposure test, four sides of the specimens were coated with epoxy, and two parallel sides were kept uncoated for CO2 diffusion (see photo 1). The detailed exposure plan is shown in Table 3 and the specimens in exposure site are shown in photo 2.

At 6 months and 1 year of age, the carbonation depths were measured in the laboratory, the specimens were split and cleaned, and 1% of phenolphthalein 90% ethyl alcohol solution was applied to the freshly cut surface. When the solution is sprayed onto broken concrete surface, the carbonated portion remains uncolored (concrete color) and the non-carbonated portion changes to dark purple. The average carbonation depths were measured at 10 points from each side and take the average carbonation depth at a certain age (see photos 3 and 4).



Photo 1: Specimens preparation photos.



Photo 2: Concrete specimens exposed in different regions.

Table 3: Detailed Exposure plan

Exposure Area	Mixture	Exposure Condition			
		Sheltered condition		Unsheltered condition	
		Age			
		6 Months	12 Months	6 Months	12 Months
Japan	N-60	☑	☑	☑	☑
Afghanistan		☑	☑	☑	☑
Indonesia		☑	☑	☑	☑
Malaysia		☑	☑	☑	☑

*N60- normal OPC concrete with 60 W/C ratio

* SH- sheltered condition, UnSH- unsheltered condition

3. Results and Discussions

3.1 Climate Conditions of Four Regions (exposure sites)

Exposure tests in the natural environment were conducted in four different regions, such as Kabul (Afghanistan), Fukuoka (Japan), Makassar (Indonesia), and Batu Pahat (Malaysia). Different regions have different climates and environmental conditions. The average relative humidity and maximum temperature data for four regions have been plotted in Figures 1 and 2, respectively. For Afghanistan, data were collected using hydrometer equipment and for the other three regions, the data are collected from internet sources [3], [11]–[15].

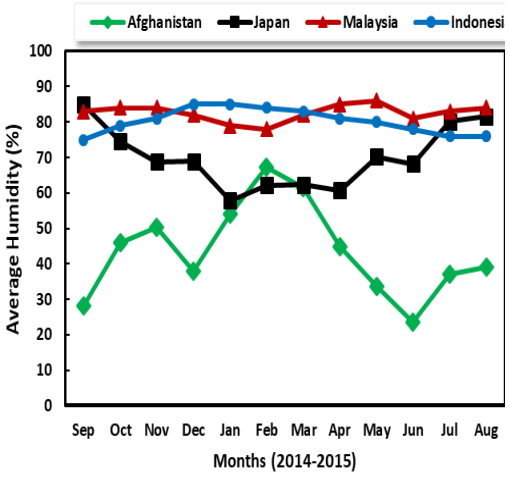


Fig. 1: Average Relative Humidity data

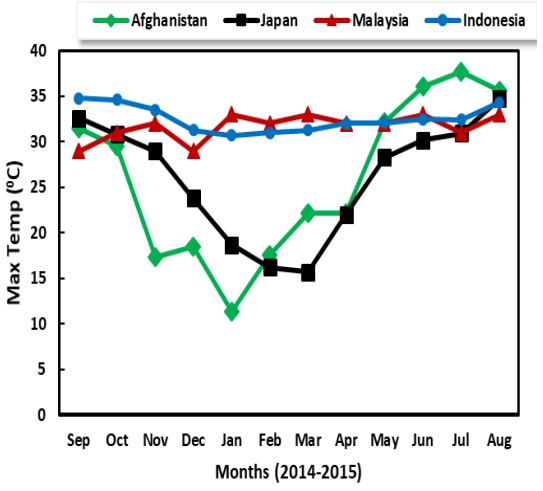


Fig. 2: Annual max temperature data

3.2 Carbonation Depth

Fig. 3 illustrates the carbonation progress for concrete exposed in four different regions with different climate conditions, it was observed that climatic and environmental conditions have influenced the carbonation progress. Higher carbonation has been observed in Afghanistan, the effect of sheltered and unsheltered conditions was insignificant compared to other regions due to the lower annual rainfall.

It was also observed that carbonation was significant in RH <50%; in the case of Afghanistan, the average annual relative humidity was recorded in the range of 45%. The average relative humidity and temperature in Fukuoka were recorded as 65-70% and 17 ^{0}C, respectively. While in Indonesia and Malaysia, the annual average annual relative humidity and temperature were (75-80%), and (28-30^{0}C), respectively. In the case of Japan, the carbonation progress was significant in sheltered conditions compared with

two other regions such as Indonesia and Malaysia. This may be due to the effect of temperature. Lower carbonation with high humidity and high temperature.

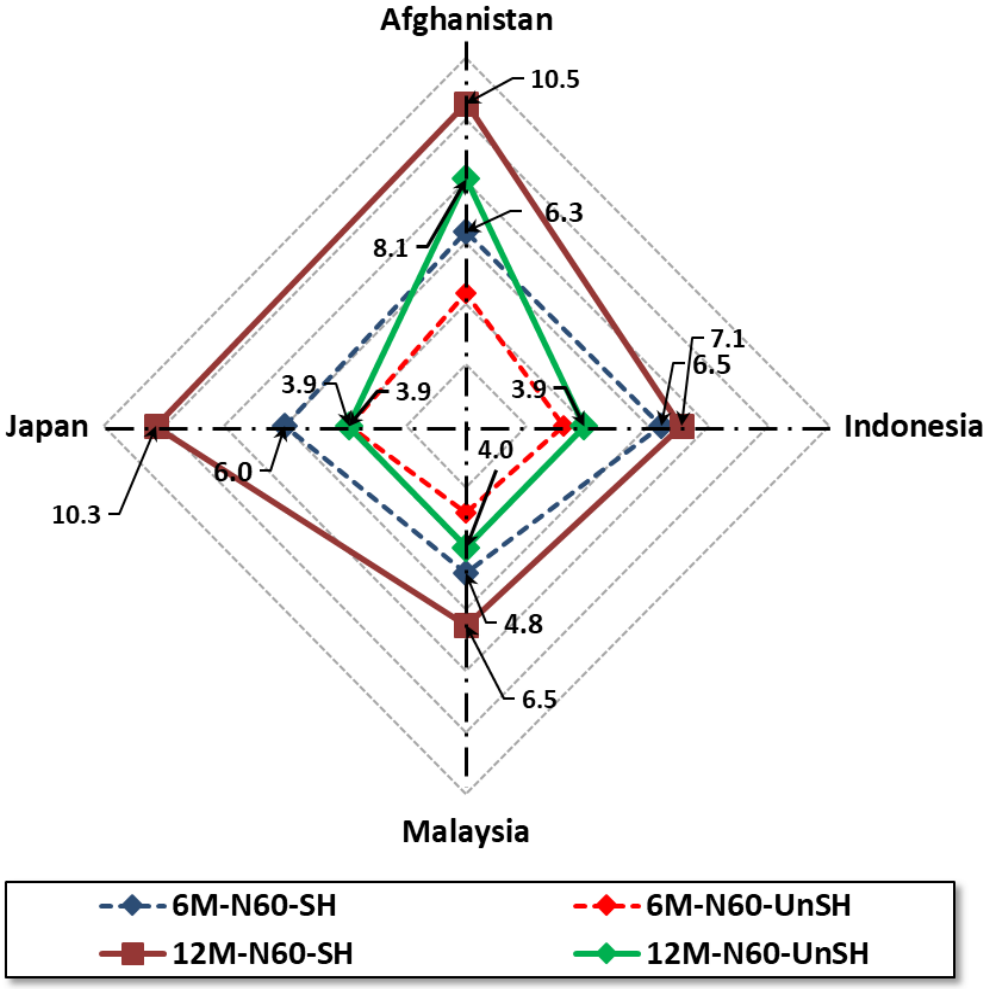


Fig. 3: The measured carbonation depths in four different regions

The climatic conditions of Indonesia are different from Afghanistan and Japan. The average annual temperature and humidity are high; According to research, carbonation is faster for warmer regions and sheltered conditions. Somewhat this statement holds for all exposure conditions at sheltered exposure sites, whereas it can be observed that although the annual temperature in Indonesia is higher than that of Afghanistan and Japan, the carbonation depth is lower than in other two regions, the reason may be the high relative humidity in Indonesia. Concrete faces higher carbonation in high temperatures unless the relative humidity is lower [6].

For the Malaysian environment, it was found that carbonation progress during the first six months was significant, while the increment was not significant until 1 year. The

increment in the first six months of the year can be attributed to the dry weather conditions from January to March, and March to February which is usually the rainy season in Malaysia, which causes the carbonation increment less than the 6 months and the carbonation was not significant at high humidity. This means that the drying and wetting processes have a great influence on carbonation progress. The carbonation depth of concrete for four different regions are shown in Photo.3 and Photo 4, respectively.

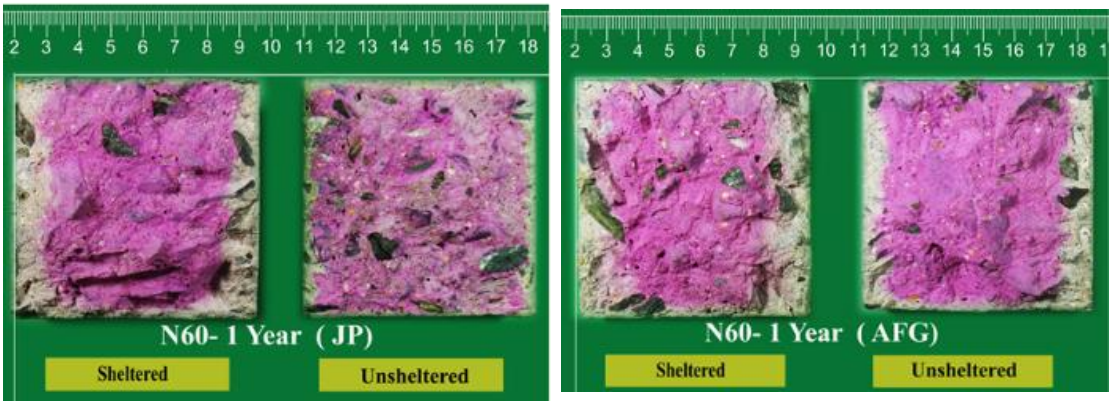


Photo 3: Graphical representation of carbonation depth of concrete for Afghanistan and Japan

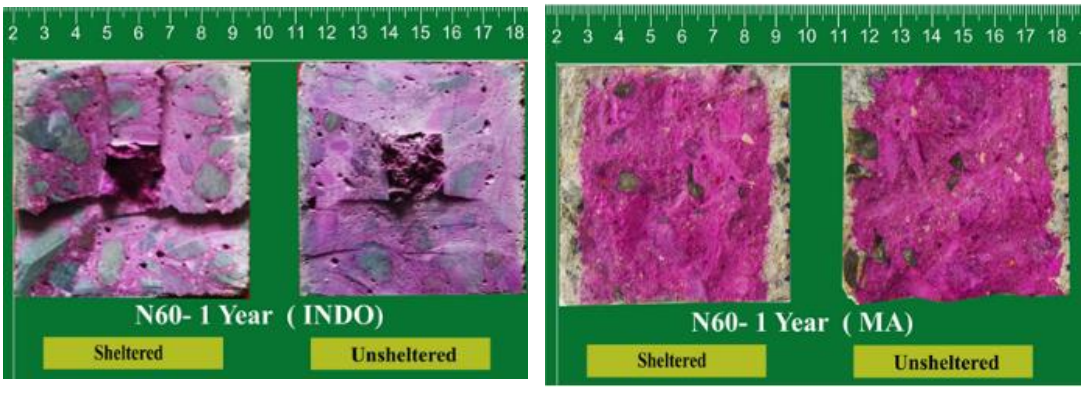


Photo 4: Graphical representation of carbonation depth of concrete for Indonesia and Malaysia

3.3 Carbonation Prediction model

The carbonation process is a complicated process, because it is a combination of the movement of gases and liquids through the pores of concrete. The carbonation of concrete is, in general, a diffusion process. The CO_2 diffusion rate mainly depends on the quality and exposure condition of concrete. Many concrete carbonation models have been formulated by applying suitable modification using different parameters to Fick's second law of diffusion. The models generally contain the parameter which relate to

environmental factors involved in carbonation process and the others which describe the capacity of the cement past matrix to bind the CO_2, but typically, the carbonation models take the format of **Eq 1.1** (DuraCrete: Modelling of Degradation 1998).

$$X_{ca} = K_{ca} \cdot \sqrt{t} \qquad (1.1)$$

X_{ca}: is the carbonation depth at time t [mm];
k_{ca}- is the carbonation rate [(mm/year) $^{0.5}$];
t- Is the age of the concrete [years].

The carbonation prediction model used for estimation was developed by Papadakis [3]. Which takes into account the influence of concrete composition, climate parameters such as relative humidity and temperature, and environmental parameter such as the concentration of CO2 on the carbonation of concrete [10-11].

$$Xc = k_{con} \cdot k_{RH} \cdot k_{cur} \cdot k_{CO2} \cdot k_{temp} \cdot \sqrt{t} \qquad (1.2)$$

Where

k_{con}: is the concrete quality related coeffecient
k_{Cur}: is the curring related coeffecient
k_{T}: temprature related coeffecient.
k_{RH}: is the relative humidity related coeffecient
k_{CO2}: the squar root of CO_2 content (Here the concentration of CO_2 0.05%)

Papadakis has summarized the main composition parameters of concrete, which affect the carbonation process as the water-to-cement ratio and aggregate-to-cement ratio. The effects of concrete composition is shown in **Eq 1.2.1** [9][12].

$$K_{con} = 350 \left(\frac{\rho_c}{\rho_w}\right) \frac{\left(\frac{w}{c} - 0.3\right)}{1 + \left(\frac{\rho_c}{\rho_w}\right) \cdot \frac{w}{c}} \cdot \sqrt{1 + \frac{\rho_c}{\rho_w} \cdot \frac{w}{c} + \frac{\rho_c}{\rho_a} \cdot \frac{a}{c}} \qquad (1.2.1)$$

Where

ρ_c – the mass density of the cement [kg/m^3],
ρ_w – the density of the water [kg/m^3],
ρ_a – the mass density of the aggregates [kg/m^3],
$\frac{w}{c}$ – the water-to-cement ratio, and
$\frac{a}{c}$ – the aggregate-to-cement ratio

The moisture content of the concrete is of great importance. As diffusion of CO_2 controls the carbonation process. It has been reported that the optimum mositure conditions for carbonation are 50% to 70% relative humidity. Papadakis et al. 1992 and Saetta et al. 1993 have indicated the effective diffusivity of CO_2 as a function of relative humidity in concrete as below [3], [18]:

$$D \propto (1 - RH)^n$$

Where in this part of research, the coefficient for expressing the effects of relative humidity is shown as below:

$$k_{RH} = \left(1 - \frac{RH}{100}\right)^n \qquad (1.2.2)$$

Where,

k_{RH} – is the relative humidity related coefficient
RH – is the relative humidity
n – is a humidity constant.

A group of researchers has suggested values of (n) values, ranging from 0.6 to 2.8 [13-21]. Meanwhile, De Ceukelair and Van Nieuwenburg proposed a relative humidity influence factor betwee 6064- 1.0288 [11] [20], while Papadakis et al. proposed 2.2 [3]. However, in this study, the influence factor was significantly different than that of Papadakis et al. The factor varies depending on the initial curing of concrete and exposure conditions (Sheltered and unsheltered). For W/C≥0.6 and RH<55%, the "n" and Kcur factors are between (21.-2.2) and (0.70-0.76); for W/C≥0.6 and RH>60%, the "n" and Kcur factors are between (1.6-1.9) and (0.65-0.76); for W/C≤0.55 and RH>60%, the coefficents "n" and Kcur factors are between (1.2-1.9) and (0. 5-0.70. Nevertheless, in this study, the initial curing conditions were the same for all concrete specimens, while the humidity levels were different based on the exposure area; these values enable the prediction to be close to actually measured carbonation depths.

The influence of ambient temperature of surrounding environment on the carbonation depth is shown as below:

$$k_t = EXP(\frac{Q}{R} * (\frac{1}{273 + T_0} - \frac{1}{273 + T})$$

Q- Is the diffusion active energy of the carbonation process (Q= 2.7 [kJ/mol]
R- Is the gas constant, R= 0.008314 [kJ/mol.K]
T_0- is the reference temperature, 25 ^{0}C
T- is the actual temperature of surrounding environment.

The influence factor of curing on carbonation of concrete is given in Duracrete (2000), as 1 and 0.76 for 7 and 28 days, respectively [9] . Although in this study, these values are valid only for air-curing specimens and do not take into count the influence of W/C, exposure conditions, and water curing. However, these values vary depending on the environmental conditions, strength level of concrete, and initial water curing.

The results from the four-exposure sites were compared with the predicted carbonation depths, as shown in Fig. 4. The actual carbonation depth well matches with the predictions. The coefficients were calculated as a function of the exposure conditions and are listed in Table 4. In addition, in Figure 4b, a strong correlation was found between actual and predicted carbonation. Therefore, the carbonation model is suitable for predicting the carbonation rate in both sheltered and unsheltered conditions.

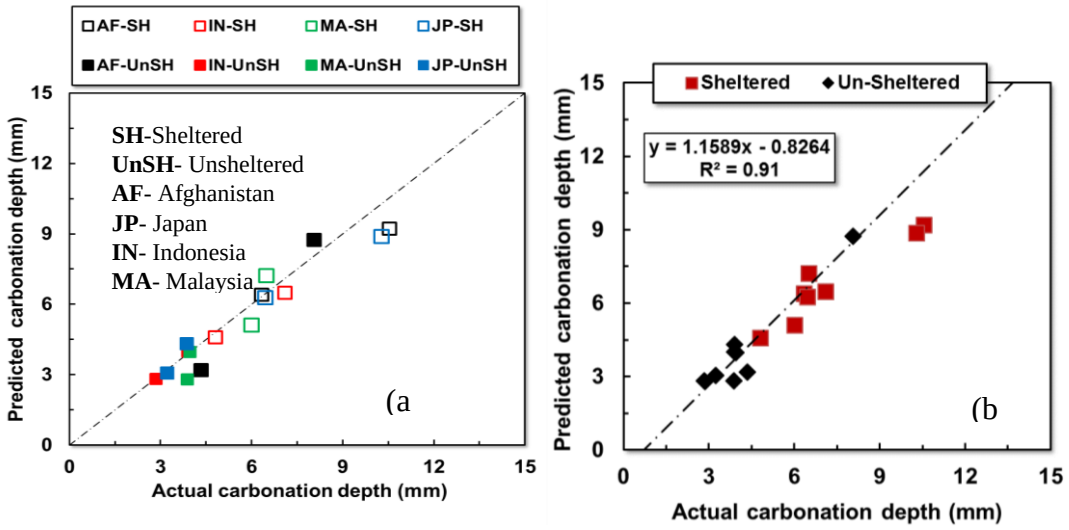


Fig. 4: actual carbonation depths vs. predicted carbonation depth (mm)

Fig. 5 depicts the carbonation prediction for long-term exposure at Fukuoka. The carbonation model is used to verify the long-term estimate of the carbonation depth; Here, the carbonation depth is estimated for over 15 years and compared with the actual data presented in a research paper published in the proceedings of the Trondheim Conference in 1989 [27]. The carbonation depths measured over 15 years are presented in Table 5. The model predictions are in good agreement with the actual data. Therefore, it can be concluded that the prediction of carbonation is significantly influenced by environmental and climatic conditions, concrete compositions, and initial curing parameters. Therefore, all the factors should be considered accordingly.

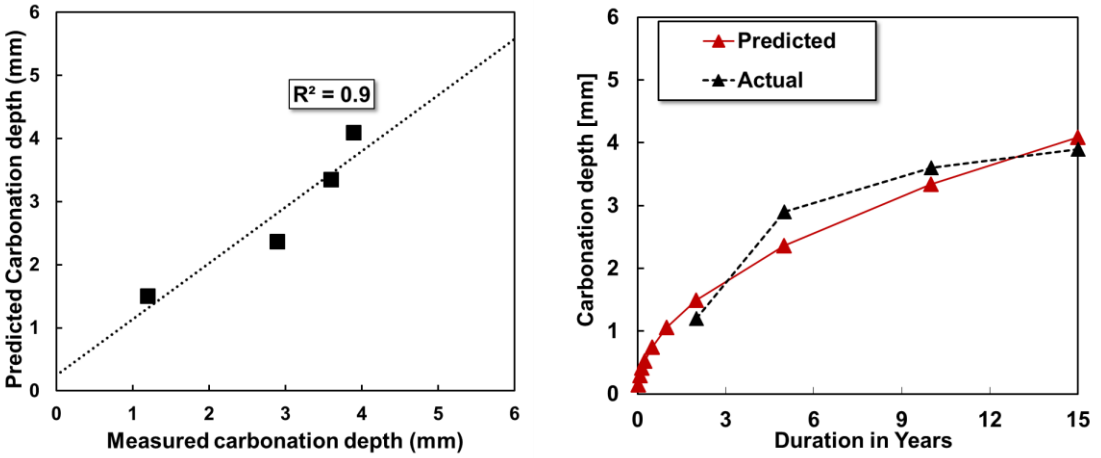


Fig 5: measured carbonation depth vs. model predictions for normal OPC concrete exposed for over 15 years at Fukuoka, Japan.

Table 4: Calculated coefficients for different exposure sites (regions).

Exposure area	Sheltered condition					X_c
	K_{con}	K_{RH}	K_{temp}	K_{cur}	Kco_2	(1) year
Japan	310	0.24	0.97	0.76	0.0224	8.9
Afghanistan		0.25	0.97			9.2
Indonesia		0.16	1.02			6.2
Malaysia		0.19	1.01			7.3
Exposure area	Unsheltered condition					X_c (1) year
	K_{con}	K_{RH}	K_{temp}	K_{cur}	Kco_2	
Japan	310	0.11	0.97	0.76	0.0224	4.1
Afghanistan		0.22	0.97			7.5
Indonesia		0.10	1.02			3.9
Malaysia		0.10	1.01			3.8

Table 5: Carbonation depth of concrete exposed in various regions. (Source: Proceedings of 1989 Trondheim Conference)

Exposure Area	Age (years)	Carbonation Depth (mm)			
		2	5	10	15
Hokkaido		2.0	3.5	3.8	3.3
Miyagi		0.7	2.4	2.6	3.3
Chiba		1.0	2.0	3.0	-
Tokyo		1.6	-	2.2	6.4
Kanagawa		2.2	3.8	3.9	5.5
Hyogo		1.2	2.9	2.3	5.2
Hiroshima		1.2	2.8	3.7	-
Fukuoka		1.2	2.9	3.6	3.9
Kanagawa (in seawater)		0.6	0.0	1.6	2.2

4. Conclusions

1. The carbonation rate of concrete exposed to natural exposure is significantly affected by climatic and environmental conditions; concrete exposed to a relatively dry environment and low annual rainfall indicates higher carbonation over the one-year exposure period. Therefore, it can be said that carbonation is still significant even when the relative humidity is less than 50% and proper durability design shall be carried out to resist the carbonation of concrete in Afghanistan.
2. The specimens under sheltered conditions showed a higher carbonation rate than those kept in unsheltered conditions, however, the carbonation was lower in the environment with high humidity and high-temperature, even when stored under sheltered conditions. The carbonation rate was lower for the specimens exposed with the possibility of rain subjection (non-sheltered) than that without rain subjection.
3. The carbonation model proposed by Papadakis(1992) is suitable for prediction. However, more attention is required to avoid overestimating a long-term estimate. The equation more accurately estimates the depth of carbonation by taking into account the coefficient of initial curing that strongly influences the carbonation process in concrete. Therefore, it can be concluded that the carbonation model considering the environmental and climatic conditions, concrete composition, and initial curing parameters can be an effective way to estimate the carbonation depth and make realistic prediction.

5. Acknowledgement

The authors would like to thank Kyushu university concrete engineering laboratory for providing research facilities in conducting experimental work.

6. Conflicts of Interest

On behalf of all authors, the corresponding author states that conflict of interest to disclose.

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