An Experimental Study on the Carbonation Resistance of Conventional Concretes in Vietnam

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ABSTRACT

Reinforced Concrete (RC) is widely used in global infrastructure development. Long-term performance of the RC structures is a primary objective for managers, engineers, and scientists. Global climate change leads to a significant rise in atmospheric CO_2 concentrations, particularly in developing nations like Vietnam, due to rapid urbanization. This study examines the carbonation resistance of concrete mixtures with water-to-cement ratios ranging from 0.35 to 0.55 and was conducted in a laboratory setting. Accelerated carbonation tests were performed at the Center for Cement and Concrete (Hanoi) in accordance with the latest standard. The results suggest that concrete with a Water-to-Cement ratio (W/C) greater than 0.50 has low carbonation resistance and should be used with caution in structural applications. Beyond this threshold, the carbonation depth increases rapidly.

Keywords-carbonation resistance; experimentation; CO_2; penetration; corrosion

I. INTRODUCTION

The rapid expansion of infrastructure in Vietnam has led to strict requirements for the durability and lifespan of Reinforced Concrete (RC) structures. Among the various factors, carbonation was identified as the primary cause of structural degradation, especially in urban and industrial areas. As the impact of global climate change escalates, atmospheric CO_2 concentrations — the most crucial factor influencing the carbonation process — have risen significantly. Authors in [1-3] estimated the time at which steel corrosion begins, as concrete's pH decreases from 13 to approximately 9. Authors in [4] indicated that pretreating materials with carbonation can significantly improve their mechanical properties in concrete mixtures, developing environmentally friendly concrete solutions [4]. Authors in [1] evaluated and compared predictive models for concrete carbonation depth, a key factor affecting the durability of reinforced concrete. Authors in [2] provided a thorough review of carbonation in cementitious materials, from fundamental mechanisms to contemporary analytical techniques, including Scanning Electron Microscopy (SEM). Authors in [5] emphasized the need to search for rapid durability prediction methods as an alternative to traditional testing, enabling engineers to quickly compare the resistance of various concrete mixes and eliminating the need for month-long experimental durations. The hot and humid climate of Vietnam, with high average annual temperatures, accelerates carbonation rates compared to temperate regions. Consequently, empirical research on the carbonation resistance of common concrete types in Vietnam is significant to provide appropriate technical recommendations for design and construction. Such data also serve as a crucial input parameter for service life prediction models for engineering works.

II. THEORETICAL BACKGROUND

Carbonation is the process by which atmospheric Carbon Dioxide (CO_2) penetrates the pore network of concrete, dissolves in the pore solution to form weak carbonic acid (H_2CO_3), and reacts with cement hydration products. The primary reactions include:

- Reaction with calcium hydroxide $Ca(OH)_2$: This reaction is important because it reduces the alkalinity of concrete:

$$Ca(OH)_2 + CO_2 = CaCO_3 + H_2O \quad (1)$$

After the $Ca(OH)_2$ content is depleted, the CO_2 continues to attack the C-S-H gel.

- Reaction with Calcium Silicate Hydrate (C-S-H) gel: This process involves decalcifying the C-S-H phase, which changes the internal microstructure. According to Fick's first law of diffusion, the carbonation depth is a function of time. Using this law, the depth of carbonation in concrete is determined as:

$$x_c = \sqrt{\frac{2D_{CO_2}}{a}\Delta C_{CO_2}}\sqrt{t} \quad (2)$$

where x_c is the carbonation depth, ΔC_{CO_2} is the carbon dioxide concentration difference, and:

$$a = 0.75 C_{CaO} C_C \alpha_h \frac{M_{CO_2}}{M_{CaO}} \quad (3)$$

where a is the binding capacity (kg/m^3) of concrete [6, 7], C_{CaO} is the Calcium oxide content in the cement, C_C is the cement content (mass of cement) in the concrete, and α_h is the degree of hydration [8]:

$$\alpha_h(t) = \frac{t}{2.0+t}\left[\frac{1.031W/C}{0.194+W/C}\right] \quad (4)$$

where M_{CO2} is the molecular weight of carbon dioxide, and M_{CaO} is the molecular weight of calcium oxide. The carbonation rate of concrete depends on several factors, including the Water-to-Cement ratio (W/C) [9, 10], ambient CO_2 concentration [6], porosity [8], humidity, ambient temperature [9, 11], and the concrete's compressive strength [12].

III. CARBONATION DEPTH ANALYSIS

A. Diffusion Coefficient

Authors in [13] proposed a formula for calculating carbonation depth, presenting the effective CO_2 diffusion coefficient in carbonated concrete as:

$$D_{CO_2} = 6.1 \times 10^{-6}\left(\frac{\varepsilon_c}{\frac{W_c}{\rho_c}+\frac{W_P}{\rho_p}+\frac{W_W}{\rho_W}}\right)^3\left(1-\frac{H}{100}\right)^{2.2} \quad (5)$$

where ε_c is the porosity of concrete, W_c, W_p, W_w are the contents of cement, supplementary materials, and water, ρ_c, ρ_p, ρ_w are the densities of cement, additives, and water, respectively, and H is the ambient humidity. The CO_2 binding capacity α is determined as:

$$a = 0.33 C_{CH} + 0.214 C_{CSH} \quad (6)$$

where C_{CSH} is the C-S-H content, and C_{CH} is the $Ca(OH)_2$.

B. Vietnamese Standards

According to the Vietnamese standard [14], the evolution of carbonation depth over time in experimental research is typically expressed as:

$$x_c = k\sqrt{t} \quad (7)$$

where x_c is the carbonation depth (mm), k is the carbonation rate coefficient ($mm/\sqrt{\text{week}}$), which reflects the material's resistance to CO_2 ingress, and t is the exposure time (weeks).

C. Model Code for Service Life Design

According to [9], the carbonation depth is calculated as:

$$x_c(t) = \sqrt{2k_e k_c (k_t R_{ACC,0}^{-1} + \varepsilon_t) C_s}\sqrt{t} W(t) \quad (8)$$

where $x_c(t)$ is the carbonation depth at time t (mm), and k_c is the environmental function depending on the ambient humidity,/.

$$k_e = \left[\frac{1-(RH_{real})^5}{1-(RH_{ref})^5}\right]^{2.5} \quad (9)$$

RH_{real} is the relative humidity of the carbonated layer (%), and RH_{ref} is the reference relative humidity used in the concrete carbonation resistance test (RH_{ref}=65%).

$$k_c = \left(\frac{t_c}{7}\right)^{b_c} \quad (10)$$

where t_c is the period of curing (day), b_c is the exponent of regression (b_c follows a normal distribution with a mean value of -0.567 and a standard deviation s = 0.024), k_t is a regression parameter (with a mean value of 1.25 and a standard deviation s = 0.35), and R_{Acc}^{-1} is the inverse effective carbonation resistance of the concrete [(mm^2/s)/(kg/m^3):

$$R_{Acc}^{-1} = \left(\frac{x_c}{\tau}\right)^2 \quad (11)$$

where x_c is the carbonation depth (m), and τ is the time constant [(s/kg/m^3)]$^{0.5}$ depending on the specific test conditions:

$$\tau = \sqrt{2\Delta_{CO_2} t} \quad (12)$$

For an accelerated test with 2% CO_2 concentration over 28 days τ = 420 ([(s/kg/m^3)]$^{0.5}$), ε_t is the error term [(mm^2/years)/(kg/m^3)] with a mean value of 315.5 and a standard deviation s = 48, C_s is the CO_2 concentration (kg/m^3), and $W(t)$ is the weather function.

D. Carbonation Depth Model

Authors in [15] found that the carbonation depth model is:

$$x_c = k\sqrt{t} = n_1 n_2 n_3 n_4 n_5 k_{av}\sqrt{t} \quad (13)$$

where x_c is the depth of the carbonated concrete layer (mm), n_1 is the carbonation front condition parameter (n_1=1.9 for all cases), n_2 is the exposure condition parameter (n_2=0.6 for outdoor exposure to rain; n_2=1.0; for sheltered outdoor conditions, and n_2=1.0 for indoor conditions).

E. Carbonation Model

Authors in [6] proposed the following model for calculating the carbonation depth in concrete:

$$x_c(t) = \sqrt{\frac{2D_{CO_2}(t)}{a} C_{CO_2}(t) t}\left(\frac{t_o}{t}\right)^{n_m} \quad (14)$$

$$D_{CO_2}(t) = D_1 t^{-n_d} \quad (15)$$

$$a = 0.75 C_e CaO \alpha_H \frac{M_{CO_2}}{M_{CaO}} \quad (16)$$

where x_c is the carbonation depth (cm), t_0 is the reference time (typically: t_0= 1 year), t is the time (years), C_{CO2} (t) is the time-dependent mass concentration of ambient CO_2 (10^{-3} kg/m^3), D_{CO2} (t) is the diffusion coefficient of CO_2 in concrete, D_1 is the CO_2 gas diffusion coefficient after one year, n_d is the age exponent for the CO_2 diffusion coefficient, C_e is the cement content (kg/m^3), CaO is the Calcium oxide content in the cement, α_H is the degree of hydration, M_{CaO} is the molar mass of CaO (M_{CaO} = 56), M_{CO2} is the molar mass of CO_2 (M_{CO2} = 44), and n_m is an age factor of microclimate conditions, which is associated with the frequency of wetting-drying cycles (n_m= 0 for sheltered outdoor; $n_m \leq 0.3$ for unsheltered outdoor).

F. Relationship between CO_2 Diffusion Coefficient, Inverse Carbonation Resistance and Carbonation Depth

Substituting (2) into (8) and squaring both sides gives:

$$\frac{2D_{CO_2}\Delta CO_2 t}{a} = 2k_e k_c (k_t R_{ACC}^{-1} + \varepsilon_t) C_s t W(t) \quad (17)$$

$$D_{CO_2} = a k_e k_c (k_t R_{ACC}^{-1} + \varepsilon_t) W(t) \quad (18)$$

$$D_{CO_2} = a k_e k_c [k_t \left(\frac{x_c}{\tau}\right)^2 + \varepsilon_t] W(t) \quad (19)$$

Under experimental conditions, the coefficients are considered as k_c=1, k_e=1, k_t=1, $W(t)$=1, ε_t=0.

IV. EXPERIMENTAL STUDY TO DETERMINE THE CARBONATION RESISTANCE OF ORDINARY CONCRETE

A carbonation resistance test was conducted to evaluate concrete's ability to impede CO_2 penetration and protect the reinforcement from corrosion caused by reduced pH in the pore solution. The primary objective is to determine the inverse carbonation resistance coefficient (R_{Acc}^{-1}) in order to design the concrete cover thickness and predict the structure's service life according to the model code for service life design [9]. This provides an important scientific basis for ensuring the durability and safety of infrastructure amid increasing atmospheric CO_2 concentrations.

A. Material Preparation

PC40 grade cement from the But Son cement plant was used. The coarse aggregate (crushed stone) was taken from Kien Khe in Ha Nam, whereas the fine aggregate, or yellow sand, came from the Lo River in Phu Tho. The superplasticizer was Sika Viscocrete 3000-20M. These materials were selected for the concrete mix proportions displayed in the Table I.

TABLE I. MIX PROPORTIONS (KG/M^3) OF CONCRETE

Mix ID	Compressive strength (MPa)	Cement (kg)	Sand (kg)	Stone (kg)	Water (lt)	Admixture (lt)	W/C
C1	50	517	646	1066	181	5.7	0.35
C2	45	452.4	701	1066	181	5.0	0.40
C3	40	402.1	744	1066	181	4.0	0.45
C4	25	403.4	735	1017	202	3.2	0.50
C5	20	366.8	766	1017	202	2.9	0.55

Prismatic concrete test specimens with dimensions of 100 × 100 × 400 mm are illustrated in Figure 1 and Table II.

B. Experimental Procedure

Compressive strength testing was performed on the concrete specimens at 28 days after casting in compliance with ASTM C39/C39M-24 [16], as presented in Table III.

Fig. 1. Fabrication of specimens for carbonation resistance determination.

TABLE II. NUMBER OF TEST SPECIMENS FOR CARBONATION RESISTANCE DETERMINATION

Mix ID	W/C	Cylindrical	Prismatic
C1	0.35	3 (C11; C12; C13)	3 (CP11; CP12; CP13)
C2	0.4	3 (C21; C22; C23)	3 (CP21; CP22; CP23)
C3	0.45	3 (C31; C32; C33)	3 (CP31; CP32; CP33)
C4	0.5	3 (C41; C42; C43)	3 (CP41; CP42; CP43)
C5	0.55	3 (C51; C52; C53)	3 (CP51; CP52; CP53)

TABLE III. COMPRESSIVE STRENGTH TEST RESULTS FOR CYLINDRICAL SPECIMENS

Mix ID	Specimen ID	W/C	Individual compressive strength (MPa)	Average compressive strength (MPa)
C1	C11	0.35	63.0	64.0
	C12		67.6	
	C13		61.3	
C2	C21	0.4	55.6	56.4
	C22		60.9	
	C23		52.7	
C3	C31	0.45	50.9	51.3
	C32		51.8	
	C33		51.4	
C4	C41	0.5	39.9	40.0
	C42		37.9	
	C43		42.0	
C5	C51	0.55	27.9	29.0
	C52		28.9	
	C53		30.1	

Fig. 2. Accelerated carbonation chamber.

The prismatic specimens were coated and placed in an accelerated carbonation chamber set to 27°C, with a CO_2 concentration of 4% and a Relative Humidity (RH) of 65%, as shown in Figure 2.

Multiple measurements of carbonation depth at various time intervals, including 1, 4, 6, and 8 weeks, were conducted. At earlier stages, specifically for mixes with low W/C ratios (0.35 and 0.40), the carbonation depth was virtually immeasurable and the carbonation depths were not recorded for all mix proportions until the 8-week mark. After eight weeks, the specimens were split, and the carbonation depth was measured using a phenolphthalein indicator solution [17], as portrayed in Figure 3.

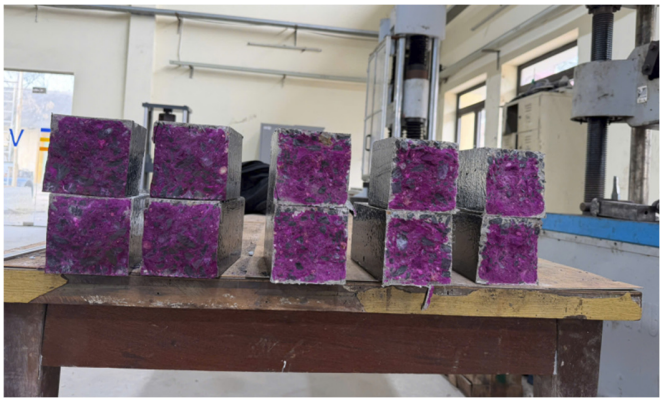

Fig. 3. Measurement of carbonation depth.

V. RESULTS AND DISCUSSION

The results obtained from the experiment are outlined in Table IV.

TABLE IV. ACCELERATED CARBONATION TEST RESULTS

Specimen ID	W/C	x_c (mm)	$R_{Acc}^{-1}(\times 10^{-11})$ $((m^2/s)/(kg/m^3))$	$D_{CO_2}(\times 10^{-9})$ (m^2/s)	COV (%)
C1	0.35	1.552	0.3406	0.43193	12.56
C2	0.4	3.202	1.4496	1.68386	13.12
C3	0.45	4.916	3.4169.	3.66058	11.74
C4	0.5	7.854	8.7214	9.66483	14.23
C5	0.55	11.858	19.8807	20.5545	12.89

A. Compressive Strength and Carbonation Depth of Concrete

Figure 4 illustrates the relationship between the compressive strength and carbonation depth of concrete. Based on this:

- The experimental data follow a linear regression model within the investigated range:

$$y = -0.2942x + 20.04 \quad (20)$$

- The coefficient of determination, R^2, is exceptionally high at 0.9929, showing that compressive strength is an accurate predictor of the carbonation depth of the concrete samples under study.
- The experimental curve shows strong agreement with [12, 18], particularly in the higher strength range (>40 MPa), revealing that controlling compressive strength is essential to enhancing the carbonation resistance of concrete structures.

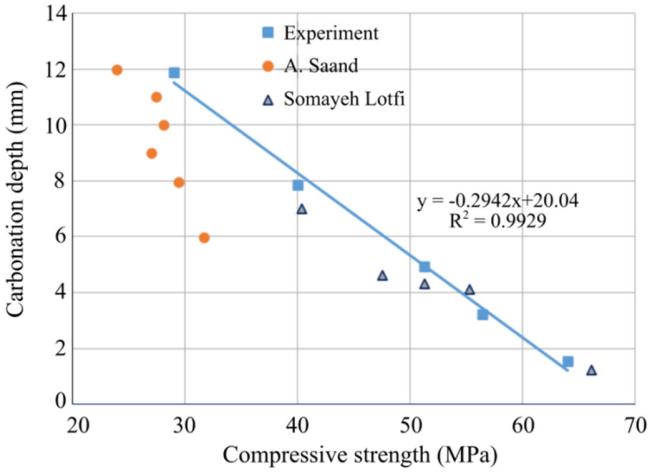

Fig. 4. Relationship between compressive strength and carbonation depth.

B. Water-to-Cement Ratio and Inverse Carbonation Resistance

Figure 5 shows the relationship between the water-to-cement ratio and inverse carbonation resistance. Based on this:

- The regression trendline for the experiment data follows an exponential power law:

$$y = 4.10^{-8}x^{8.8299} \quad (21)$$

- The coefficient of determination R^2 = 0,9998 indicates that this mathematical model is highly accurate and perfectly reflects the correlation within the experimental data. The rate of increase for R_{Acc}^{-1} becomes significantly sharper once the w/c ratio exceeds 0.5.
- The performance characteristics of the concrete testing fall within the established ranges for the standard types of cement defined by the Fib Model Code [9], which validates the experimental methodology employed at the Vietnam Institute for Building Materials.
- To ensure the design service life of RC structures in Vietnam, W/C ratio should be less than 0.5.

C. Water-to-Cement Ratio and the CO_2 Diffusion Coefficient

Figure 6 demonstrates the relationship between the water-to-cement ratio and the CO_2 diffusion coefficient. Based on this:

- The experimental data follow a clear exponential law relationship:

$$y = 3.10^{-6}x^{8.4193} \quad (22)$$

- The coefficient of determination, R^2, is exceptionally high at 0.9991, indicating an agreement between the mathematical model and the experimental findings.
- An increase in the w/c ratio leads to a higher CO_2 diffusion coefficient, thereby enhancing the susceptibility of concrete to carbonation-induced corrosion.

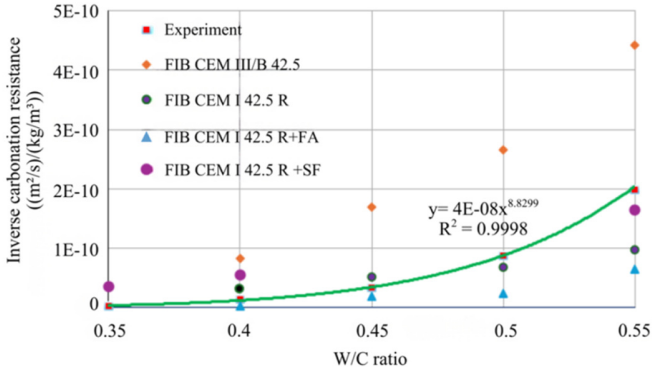

Fig. 5. Relationship between inverse carbonation resistance (R_{acc}^{-1}) and W/C ratio.

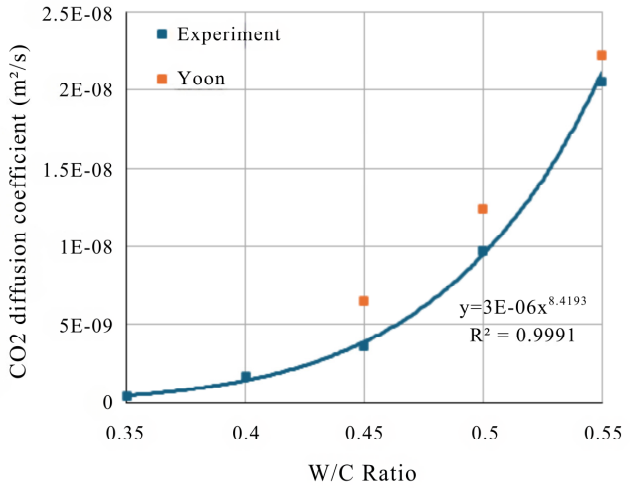

Fig. 6. Relationship between CO_2 diffusion coefficient and W/C ratio.

VI. CONCLUSIONS

This study provides a systematic overview of concrete carbonation resistance, emphasizing the importance of accelerated carbonation tests in determining input parameters for service life prediction models. The research results lead to the following conclusions:

- The experimental data indicate that the inverse carbonation resistance of the concrete ranges from 3.4×10^{-12} to 19.88×10^{-11} ($m^2/s/(kg/m^3)$) and the diffusion coefficients range from 4.32×10^{-10} to 2.055×10^{-8} (m^2/s), corresponding to Water-to-Cement ratios (W/C) between 0.35 and 0.55.
- The carbonation resistance strongly depends on the w/c ratio.
- These experimental data serve as a basis for researching the prediction of corrosion initiation time caused by carbonation in Reinforced Concrete (RC) structures in Vietnam.

DECLARATION OF COMPETING INTERESTS

The authorσ declare no competing financial interests.

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DATA AVAILABILITY

The original laboratory data are presented within the paper. Data from [6, 9, 12] are plotted in Figures 4–6 strictly for comparison.

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