Research Article

Estimation of Concrete Carbonation Depth Considering Multiple Influencing Factors on the Deterioration of Durability for Reinforced Concrete Structures

Hae-Chang Cho,¹ Hyunjin Ju,¹ Jae-Yuel Oh,¹ Kyung Jin Lee,²
Kyung Won Hahm,² and Kang Su Kim¹

¹Department of Architectural Engineering, University of Seoul, 163 Seoulsiripdaero, Dongdaemun-gu, Seoul 02504, Republic of Korea

²Structural & Seismic Tech. Group, Power Transmission Laboratory, Korea Electric Power Research Institute, 105 Munji-ro, Yuseong-gu, Daejeon 34056, Republic of Korea

Correspondence should be addressed to Kang Su Kim; kangkim@uos.ac.kr

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While the durability of concrete structures is greatly influenced by many factors, previous studies typically considered only a single durability deterioration factor. In addition, these studies mostly conducted their experiments inside the laboratory, and it is extremely hard to find any case in which data were obtained from field inspection. Accordingly, this study proposed an Adaptive Neurofuzzy Inference System (ANFIS) algorithm that can estimate the carbonation depth of a reinforced concrete member, in which combined deterioration has been reflected based on the data obtained from field inspections of 9 buildings. The proposed ANFIS algorithm closely estimated the carbonation depths, and it is considered that, with further inspection data, a higher accuracy would be achieved. Thus, it is expected to be used very effectively for durability estimation of a building of which the inspection is performed periodically.

1. Introduction

In reinforced concrete (RC) structures, the carbonation depth is a key deterioration factor to determine the durability of concrete structures [1–4]. In the initial stage of construction, RC members exhibit strong alkalinity of about pH 12–13 due to the calcium hydroxide inside the concrete, and a protective passive film is formed on the steel bar. However, with time, carbon dioxide (CO₂) gas in the atmosphere penetrates into the concrete and reacts with calcium hydroxide (Ca(OH)₂). The pH of the concrete is then lowered, which is a process known as “carbonation.” Once the lower alkalinity of the carbonation front reaches the steel bar beyond the concrete cover thickness, the protective passive film surrounding the steel bar is destroyed, which initiates the corrosion process [4, 5]. Corrosion products are then generated on the periphery of reinforcing bars and cause volume expansion, which causes cracks in the concrete surrounding the steel bar. If

the cracks propagate to the surface of the member, concrete peeling or spalling occurs. In addition, the reduced bond strength between the steel bar and concrete reduces the strength and the durability of the member [6]. Therefore, the carbonation of concrete has been widely used as a basic indicator for determining the durability or remaining service life of structural members [7–9].

Although the intended service life of an RC structure differs depending on its use, size, and so forth, it is often set to approximately 65 years in many international standards [7, 10, 11]. To meet the intended service life, appropriate maintenance plans for the building structures are required, for which accurate inspections on the durability are very important. Various theoretical and experimental studies have been carried out to estimate the concrete carbonation depth [1–4] and, in particular, most of them focused on the estimation of the carbonation velocity coefficient (A_{Ca}) based on the diffusion theory [5]. According to the diffusion theory,

in a humidity environment, the concrete carbonation depth (C_a) is proportional to the square root of time (t) (i.e., $C_a = A_{Ca} \sqrt{t}$) [3, 7, 10]. The carbonation velocity coefficient (A_{Ca}) is affected by cement or binding agent, water-cement ratio, curing, and other environmental conditions and shows particularly significant differences depending on the cement type. In addition, the carbonation velocity increases under cracking or chloride attack and is also greatly affected by finishing condition of concrete surface [5]. Since various factors influence the carbonation velocity, it is very difficult to reflect it theoretically or experimentally. In addition, for the majority of structures older than 30 years, their design or maintenance documents such as drawings and concrete mix proportion tables are often lost or not available. Therefore, it is not easy to accurately estimate the carbonation depth through the data at the time of design. In response to this issue, this study was aimed at reasonably estimating the concrete carbonation depth, in which the combined deterioration is reflected, through an application of Artificial Neurofuzzy Inference System (ANFIS) [12, 13]. The application was based on the data obtained from field inspections and the accuracy of the analysis algorithm was verified through a comparison with measurement results.

2. Deterioration Factors of Concrete Carbonation

As previously mentioned, while the deterioration of an RC structure is influenced by various factors, it is practically impossible to consider all the factors. In this study, field inspections were performed to get the data such as the crack width, concrete compressive strength, chloride ion diffusion coefficient, and surface chloride ion concentration, and these were then considered as the input parameters of ANFIS.

2.1. Chloride Attack. Chloride attack is an important factor contributing to the deterioration of concrete durability. It accelerates the deterioration through a combined action with carbonation and has a particularly significant impact on the durability of structures exposed to a marine environment. The chloride ion concentration that can lead to corrosion of steel bars is called the critical chloride ion concentration. The chloride ion concentration (C_d) at the steel bar location can be estimated via the initial chloride ion concentration within the concrete (C_i), the chloride ion concentration absorbed on the surface (C_0), and the chloride ion diffusion coefficient (D_a). Based on Fick's laws of diffusion [14], Crank [15] proposed an estimation method for the chloride ion concentration (C_d), which is most widely used. The chloride ion concentration (C_d) at the time (t) from the completion of the structure construction to the measurement point is calculated as follows:

$$C_d - C_i = (C_0 - C_i) \left(1 + \operatorname{erf} \left(\frac{x}{2\sqrt{D_a t}} \right) \right), \quad (1)$$

where x represents the depth from the surface of the member. The critical chloride ion concentration of concrete is typically 0.4% of the cement weight ratio. However, it was reported that

the carbonated concrete can lead to the corrosion of steel bar even at a chloride ion concentration of 0.2% in CEB-FIP [16], which has been confirmed by several researchers [17–20]. Lee et al. [17] and Yoon [18] performed combined deterioration experiments considering concrete carbonation and chloride attack. According to their research, the chloride ion diffusion coefficients in the carbonated sections and the noncarbonated sections were very different, and drastic diffusion differences were observed at the boundary of the two sections due to the concentration phenomenon of diffusion. These observations were also reported in the studies by Andrade et al. [19] and Lee and Yoon [20], and the amounts of chloride ions ($C_{Cl,cb}$ and $C_{Cl,ucb}$) of carbonated and noncarbonated cross sections were suggested, respectively, as follows:

$$C_{Cl,cb}(x,t) = C_0 \sum_{n=0}^{\infty} \alpha^n \left[\operatorname{erfc} \left(\frac{2n \cdot C_a + x}{2\sqrt{D_{Cl,cb} t}} \right) - \alpha \right. \quad (2a)$$

$$\left. \cdot \operatorname{erfc} \left(\frac{(2n+2)C_a - x}{2\sqrt{D_{Cl,cb} t}} \right) \right],$$

$$C_{Cl,ucb}(x,t) = \frac{2kC_0}{k+1} \quad (2b)$$

$$\cdot \sum_{n=0}^{\infty} \alpha^n \operatorname{erfc} \left[\frac{(2n+1)x + k(x - C_a)}{2\sqrt{D_{Cl,cb} t}} \right],$$

where α is $(1 - k)/(1 + k)$, k is $\sqrt{D_{Cl,cb}/D_{Cl,ucb}}$, erfc is the Gaussian error function, and $D_{Cl,cb}$ and $D_{Cl,ucb}$ are the chloride ion diffusion coefficients of carbonated concrete and noncarbonated concrete, respectively. The statistical data [21] of the Korea Concrete Institute (KCI) also revealed that the carbonation depth is deeper in a structure located in a coastal environment than in a structure located inland. This suggests that the carbonation of concrete is accelerated by chloride attack and that the combined deterioration phenomenon caused by the chloride attack and carbonation should therefore be reflected in the evaluation of the durability of RC structures.

2.2. Concrete Compressive Strength. The concrete compressive strength of an existing concrete structure is typically measured by the Schmidt hammer test [22], a nondestructive testing method. Rebound hardness measured by the Schmidt hammer test is influenced by the environmental condition surrounding the concrete, and it is known to be about 20% lower in an environment where the surface is moist than where it is dry [23]. In particular, as the rebound hardness of the cross section in which concrete carbonation progresses is relatively large compared to that of the noncarbonated cross section, the actual compressive strength can be overestimated in such a case. It is therefore desirable to measure the rebound hardness after removal of the surface [23]. Since the concrete compressive strength is mainly affected by the water-to-binder ratio that affects the carbonation, the concrete compressive strength is considered to have a strong relationship with the carbonation. Chi et al. [24],

TABLE 1: Field investigation data (Building 9, construction completion year: 1976).

Measurement point	Member type	Concrete compressive strength (MPa)	Concrete carbonation depth (mm)	Cover depth (mm)	Crack width (mm)
B9P1	Column	21.1	20.13	45	—
B9P2	Column	26.1	23.45	40	Surface finishing crack
B9P3	Slab	22.2	19.12	65	—
B9P4	Beam	20.7	32.73	60	—
B9P5	Wall	20.9	20.19	45	—
B9P6	Wall	21.3	30.61	25	Surface finishing crack
B9P7	Slab	25.6	22.46	25	0.1
B9P8	Beam	20.9	49.87	70	—
B9P9	Beam	23.0	14.62	70	—
B9P10	Slab	22.8	16.49	20	—
B9P11	Beam	21.3	30.80	65	—
B9P12	Slab	24.7	23.92	20	—
B9P13	Beam	19.9	23.99	60	—
B9P14	Slab	21.5	23.06	30	—
B9P15	Beam	21.5	26.46	30	0.1
B9P16	Slab	27.3	19.06	35	Surface finishing crack
B9P17	Slab	22.9	26.47	30	—
B9P18	Beam	20.5	40.20	75	—
B9P19	Wall	22.2	25.54	45	Surface finishing crack
B9P20	Wall	31.9	26.24	55	—
B9P21	Wall	29.7	22.71	25	Surface finishing crack
B9P22	Wall	28.3	29.94	45	Surface finishing crack

Kim et al. [25], and Cho [26] experimentally confirmed that, as the concrete strength increased, the velocity of carbonation progression reduced.

2.3. Crack Width. Structural cracks in reinforced concrete structures have a significant impact not only on structural performance, but also on durability reduction. In addition, nonstructural cracks including surface finishing cracks accelerate the durability reduction of concrete as they facilitate the penetration of the carbon dioxide and chlorine ion from the concrete surface exposed to the outside air. Therefore, both structural cracks and nonstructural cracks can be considered as the factors contributing to durability reduction. Song et al. [27] reported that if cracks occur, in addition to the diffusion of carbon dioxide inside the concrete, the penetration of carbon dioxide in the cracking area also occurs; therefore, the carbonation progresses more rapidly than in the area where cracks do not occur. According to their experimental results, cracks were found to have a larger effect on the carbonation velocity coefficient than the water-to-cement ratio; the carbonation velocity coefficient of the cracking area eventually increased by up to 8 times depending on the crack width.

3. Artificial Neurofuzzy Inference System

The aim of this study was to estimate the carbonation depth of a reinforced concrete member in which combined deterioration is reflected. In this study, therefore, detailed safety inspection on a total of 9 buildings has been performed to get the field data that are required for the estimation of the carbonation depth. Table 1 shows a summary of the inspection results of Building 9, and Tables 3–10 show the inspection results of Buildings 1–8. The concrete compressive strength, carbonation depth, cover thickness, and crack width were measured at a total of 189 points, which were 20 to 24 points per building. For measurement of the chlorine ion diffusion coefficient, one core sample for each building was taken from a wall on the roof, and the chloride ion concentration was measured at the surface and the depth of every 10 mm. The chloride ion diffusion coefficient was then calculated as shown in Tables 2, 11, and 12. Unfortunately, however, the core sampling was not permitted inside the building, and, alternatively, concrete powder was taken at the depth of 10 mm from the surface, from which the surface chloride ion concentration was measured. In addition, the chloride ion diffusion coefficient inside the building was assumed to

FIGURE 1: Comparison between measured and estimated carbonation depths.

TABLE 2: Measurement of chloride concentration (Building 9).

Location	Chloride ion concentration (kg/m ³)	Chloride ion diffusion coefficient (m ² /year)
Inside		
Surface to 10 mm	0.22	
Outside		27.64 × 10 ⁻⁶
Surface to 10 mm	0.27	
10 to 20 mm	0.24	
20 to 30 mm	0.18	

be the same as that on the outside. The carbonation velocity coefficient typically ranges from about 3 to 8 outside and from about 3 to 10 inside [5].

In the design phase, KCI [23] and Japan Society of Civil Engineers (JSCE) [28] suggest that the carbonation velocity coefficient (A_{Ca}) shall be calculated as follows:

$$A_{Ca} = \left(-3.57 + 9 \cdot \frac{W}{B} \right), \quad (3)$$

where W/B represents the water-to-binder ratio. However, since the effects of other factors contributing to the durability reduction such as crack and chloride attack are not reflected in (3), the calculated carbonation velocity coefficient significantly can greatly differ from the one measured in the buildings used for a long period of time. The carbonation depth (C_a) can be calculated as follows [5]:

$$C_a = A_{Ca} \sqrt{t}. \quad (4)$$

Figure 1 shows a comparison between the carbonation depths measured in BIP6 and estimated by (3) and (4). Equations (3) and (4) estimate that the carbonation progresses up to the depth of about 7.9 mm from the surface. However, the carbonation depth measured in BIP6 was almost two times greater than 7.9 mm, with a depth of 14.3 mm. This difference clearly demonstrates that carbonation depths shall

be estimated considering the combined actions of durability factors. Thus, this study aimed at estimating the concrete carbonation depth that can reflect the effects of chloride attack, compressive strength, and crack width, regarding the value estimated from (3) as the carbonation velocity coefficient resulting from a single carbonation factor. The carbonation velocity coefficient, surface chloride ion content, chloride ion diffusion coefficient, compressive strength, crack width, and time were used as ANFIS input parameters.

3.1. Training Algorithm. ANFIS is a technique used for optimizing premise parameters and consequent parameters by introducing a training algorithm into Sugeno fuzzy inference system [12]. In this study, a 5-layer ANFIS structure was applied as shown in Figure 2. Sugeno fuzzy inference system is used to estimate output values for new input values by creating rules on the basis of known data, where all the inputs and outputs consist of fuzzy values that are membership functions assigned to crisp values [29, 30]. The membership function represents the degree to which the variable belongs to a fuzzy set [29, 30], and the fuzzy set is an extension of a crisp set. In the crisp set, each element represents the degree to which it belongs to any set as 0 or 1, whereas the degree is represented as a value between 0 and 1 in the case of the fuzzy set. Therefore, all the possibilities can be considered by representing the case of fully belonging as 1.0, the case of not belonging at all as 0, and the case in which there is a 50% chance of belonging as 0.5.

In Figure 2, Layer 1 calculates the membership functions of the input parameters. In order to calculate the membership functions, the shape of fuzzy set needs to be defined, and the most common shapes of fuzzy set are triangle, trapezoid, and bell shapes. Bell shape fuzzy set is becoming increasingly popular for specifying fuzzy set and training of ANFIS with the bell-shaped fuzzy set obtains a higher accuracy [12]. Thus, in this study, bell-shaped fuzzy set was used, as shown in Figure 3. The membership function of the bell-shaped fuzzy set ($\text{bell}(x_i^j; x_c, x_w, x_q)$) can be represented as follows:

$$\text{bell}(x_i^j; x_c, x_w, x_q) = \frac{1}{1 + \left| (x_i^j - x_c) / x_w \right|^{2x_q}}, \quad (5)$$

FIGURE 2: ANFIS structure.

FIGURE 3: Bell-shaped fuzzy set.

TABLE 3: Field investigation data (Building 1, construction completion year: 1981).

Measurement point	Member type	Concrete compressive strength (MPa)	Concrete carbonation depth (mm)	Cover depth (mm)	Crack width (mm)
B1P1	Beam	18.6	24.18	86	—
B1P2	Slab	22.4	17.07	67	—
B1P3	Wall	32.6	9.44	50	Finishing crack on surface
B1P4	Slab	20.6	19.75	52	
B1P5	Beam	17.7	8.87	67	—
B1P6	Column	29.5	14.33	67	—
B1P7	Wall	26.1	5.81	49	—
B1P8	Column	24.7	15.61	39	—
B1P9	Slab	23.8	9.98	57	—
B1P10	Beam	28.4	9.95	51	—
B1P11	Slab	28.6	5.62	32	—
B1P12	Beam	35.3	10.73	77	—
B1P13	Wall	36.6	5.06	58	—
B1P14	Wall	30.2	5.04	33	0.1
B1P15	Wall	37.7	5.39	26	—
B1P16	Wall	25.9	29.95	42	0.1
B1P17	Slab	26.1	10.10	49	Finishing crack on surface
B1P18	Beam	34.1	10.14	78	Finishing crack on surface
B1P19	Slab	37.4	10.85	55	Finishing crack on surface
B1P20	Beam	36.5	18.66	65	Finishing crack on surface

TABLE 4: Field investigation data (Building 2, construction completion year: 1981).

Measurement point	Member type	Concrete compressive strength (MPa)	Concrete carbonation depth (mm)	Cover depth (mm)	Crack width (mm)
B2P1	Slab	27.1	7.04	43	—
B2P2	Slab	32.9	4.55	40	—
B2P3	Beam	24.4	8.73	65	—
B2P4	Slab	23.1	8.95	40	—
B2P5	Wall	31.2	10.50	75	—
B2P6	Wall	33.2	12.88	55	—
B2P7	Column	23.2	11.52	40	Surface finishing crack
B2P8	Column	22.9	9.58	60	
B2P9	Beam	26.0	8.93	85	—
B2P10	Slab	20.7	7.59	35	—
B2P11	Beam	26.8	9.50	60	Surface finishing crack
B2P12	Slab	28.2	18.89	35	
B2P13	Beam	27.1	10.87	67	Surface finishing crack
B2P14	Slab	28.0	18.55	40	Surface finishing crack
B2P15	Beam	24.7	6.33	45	Surface finishing crack
B2P16	Slab	24.8	8.79	45	—
B2P17	Wall	21.3	4.91	100	—
B2P18	Wall	33.0	7.71	45	—
B2P19	Wall	24.3	7.62	25	—
B2P20	Wall	31.4	10.96	40	0.1

TABLE 5: Field investigation data (Building 3, construction completion year: 1981).

Measurement point	Member type	Concrete compressive strength (MPa)	Concrete carbonation depth (mm)	Cover depth (mm)	Crack width (mm)
B3P1	Beam	31.3	41.08	30	—
B3P2	Slab	29.9	34.74	25	—
B3P3	Beam	24.4	19.91	75	—
B3P4	Beam	24.5	41.3	55	—
B3P5	Wall	19.3	42.18	40	—
B3P6	Wall	26	29.49	40	—
B3P7	Beam	26	28.49	45	Surface finishing crack
B3P8	Slab	30.5	29.96	30	
B3P9	Slab	29.3	9.62	40	—
B3P10	Beam	32.8	7.06	70	—
B3P11	Slab	25.6	11.26	30	—
B3P12	Beam	19.4	34.83	45	—
B3P13	Wall	22.5	38.34	30	—
B3P14	Wall	29.3	26.48	65	—
B3P15	Wall	20.2	32.06	75	—
B3P16	Wall	27.8	14.72	35	Surface finishing crack
B3P17	Beam	25.4	55.9	30	
B3P18	Beam	25.5	51.41	40	—
B3P19	Slab	18.9	49.74	20	—
B3P20	Slab	25.2	44.05	30	—

TABLE 6: Field investigation data (Building 4, construction completion year: 1984).

Measurement point	Member type	Concrete compressive strength (MPa)	Concrete carbonation depth (mm)	Cover depth (mm)	Crack width (mm)
B4P1	Column	32.2	20.35	35	—
B4P2	Column	29.7	23.56	35	—
B4P3	Beam	29	17.9	20	—
B4P4	Beam	26.9	21.35	60	—
B4P5	Beam	31.7	12.89	70	—
B4P6	Beam	29.4	18.18	30	—
B4P7	Slab	26.5	71.06	44	0.2
B4P8	Slab	29.8	16.69	35	—
B4P9	Beam	26.6	45.91	60	0.5
B4P10	Slab	31.2	26.82	50	—
B4P11	Beam	26.5	28.49	20	—
B4P12	Slab	27.1	26.29	40	—
B4P13	Beam	24.8	22.74	30	Surface finishing crack
B4P14	Beam	30.9	19.09	35	
B4P15	Slab	20.5	25.74	35	Surface finishing crack
B4P16	Slab	18.6	46.42	20	Surface finishing crack
B4P17	Wall	34.3	15.9	90	—
B4P18	Wall	28.9	14.6	55	—
B4P19	Wall	32	11.21	50	—
B4P20	Wall	34.4	15.22	50	—

TABLE 7: Field investigation data (Building 5, construction completion year: 1983).

Measurement point	Member type	Concrete compressive strength (MPa)	Concrete carbonation depth (mm)	Cover depth (mm)	Crack width (mm)
B5P1	Wall	25.7	14.47	100	—
B5P2	Wall	30.9	18.39	60	—
B5P3	Beam	27.9	12.74	55	—
B5P4	Column	30.7	15.37	40	—
B5P5	Slab	34.0	8.77	25	—
B5P6	Beam	30.7	20.91	70	—
B5P7	Column	25.8	9.76	50	—
B5P8	Slab	34.0	21.46	35	—
B5P9	Beam	31.4	10.17	45	—
B5P10	Column	28.4	15.57	45	—
B5P11	Slab	25.4	20.04	25	—
B5P12	Beam	30.6	17.82	45	—
B5P13	Beam	27.7	40.23	50	—
B5P14	Slab	23.2	37.25	30	—
B5P15	Column	31.5	17.92	60	—
B5P16	Beam	29.2	12.85	55	—
B5P17	Column	25.9	14.65	50	Surface finishing crack
B5P18	Column	32.8	52.01	70	Surface finishing crack
B5P19	Column	27.3	77.60	80	—
B5P20	Beam	33.9	10.17	75	—
B5P21	Beam	27.6	18.01	50	—

where x_i^j is an input parameter and x_c , x_w , and x_q are coefficients that determine the width, shape, and median value of each fuzzy set, respectively. In the ANFIS, x_c , x_w , and x_q are defined as premise parameters. In this study, each of the three fuzzy sets for each input parameter was configured as shown in Figure 4.

In Figure 2, Layer 2 constitutes fuzzy rules. The fuzzy rules are composed of combinations of all input parameters, and since each of the three fuzzy sets is configured by 6 input parameters in this study, the combination of all fuzzy sets, or the number of rules, is 3^6 (729). Sugeno fuzzy inference assumes the consequent output part to be linear, unlike the input part composed of fuzzy sets. In the case of multiple dimensions, the output value (fr_i) of the rule can be determined through a multiple regression analysis shown as follows:

$$\begin{aligned}
 fr_1 &= a_1 C_v + b_1 C_s + c_1 D_a + d_1 f_c + e_1 C_r + f_1 t + g_1, \\
 fr_2 &= a_2 C_v + b_2 C_s + c_2 D_a + d_2 f_c + e_2 C_r + f_2 t + g_2, \\
 &\vdots \\
 fr_{729} &= a_{729} C_v + b_{729} C_s + c_{729} D_a + d_{729} f_c + e_{729} C_r \\
 &\quad + f_{729} t + g_{729},
 \end{aligned} \tag{6}$$

where C_v is the initial concrete carbonation velocity coefficient, C_s is the surface chloride ion content, D_a is the chloride ion diffusion coefficient, f_c is the concrete compressive strength, C_r is the crack width, t is time, and a_i , b_i , c_i , d_i , e_i , f_i , and g_i are constants determined by the least square method in this study. In the ANFIS, these coefficients are defined as consequent parameters. Since the output value of the rule is a fuzzy value, as in the input parameter, it has an inherent membership function. The membership function (w_i) for each rule can be calculated by the T -norm calculation method [12] as follows:

$$w_i = T(\mu_{C_{v_k}}, \mu_{C_{s_k}}, \mu_{D_{a_k}}, \mu_{f_{c_k}}, \mu_{C_{r_k}}, \mu_{t_k}) \tag{7}$$

$i = 1, 2, \dots, 729, k = 1, 2, 3,$

where w_i is the membership function of the i th rule (firing strength), $\mu_{C_{v_k}}$ is the membership function of the fuzzy set FC_{v_k} on the carbonation velocity coefficient, $\mu_{C_{s_k}}$ is the membership function of the fuzzy set FC_{s_k} on the surface chloride ion content, $\mu_{D_{a_k}}$ is the membership function of the fuzzy set FD_{a_k} on the chloride ion diffusion coefficient, $\mu_{f_{c_k}}$ is the membership function of the fuzzy set Ff_{c_k} on the concrete compressive strength, $\mu_{C_{r_k}}$ is the membership function of

FIGURE 4: Fuzzy sets of input parameters.

the fuzzy set FC_{r_k} on the crack width, and μ_{t_k} is the membership function of the fuzzy set Ft_k on the time (see Figure 4).

In Figure 2, Layer 3 normalizes the membership function of the rules (firing strength). Since the result value from the rule configured in Layer 2 is a fuzzy value, defuzzification needs to be performed, which is a technique of deriving the fuzzy value as a crisp value. For the defuzzification, the centroid-of-area method is typically used. The centroid-of-area method is used to normalize the sum of firing strengths calculated in (7) to be 1 and thus to calculate an expectation value using the normalized firing strength as a weight factor. The normalized firing strength ($\bar{w}_i$) can be calculated as follows:

$$\bar{w}_i = \frac{w_i}{\sum_{i=1}^{729} w_i}. \quad (8)$$

In Figure 2, Layer 4 outputs the modified rule (y_i) that reflects the normalized firing strength, which can be represented as follows:

$$y_i = \bar{w}_i fr_i = \bar{w}_i (a_i C_v + b_i C_s + c_i D_a + d_i f_c + e_i C_r + f_i t + g_i). \quad (9)$$

In Figure 2, Layer 5 performs the defuzzification of the result of Layer 4, and the carbonation depth (y_{ANFIS}) in which the combined deterioration is reflected can be calculated shown as follows:

$$y_{\text{ANFIS}} = \sum_{i=1}^{729} y_i = \sum_{i=1}^{729} \bar{w}_i fr_i. \quad (10)$$

TABLE 8: Field investigation data (Building 6, construction completion year: 1981).

Measurement point	Member type	Concrete compressive strength (MPa)	Concrete carbonation depth (mm)	Cover depth (mm)	Crack width (mm)
B6P1	Wall	22.1	25.82	60	—
B6P2	Wall	20.2	22.68	45	—
B6P3	Slab	25.0	17.20	55	Surface finishing crack
B6P4	Beam	27.9	13.72	45	Surface finishing crack
B6P5	Beam	30.3	17.24	60	0.1
B6P6	Slab	28.7	18.43	40	0.1
B6P7	Slab	22.4	11.70	35	—
B6P8	Beam	29.9	11.08	70	—
B6P9	Beam	28.4	15.87	50	—
B6P10	Slab	26.8	11.73	40	—
B6P11	Column	25.9	18.03	75	—
B6P12	Column	25.1	19.52	40	—
B6P13	Slab	22.9	12.98	40	Surface finishing crack
B6P14	Beam	28.6	12.50	70	—
B6P15	Beam	26.2	18.17	50	Surface finishing crack
B6P16	Slab	23.9	13.07	45	Surface finishing crack
B6P17	Beam	25.9	25.77	80	—
B6P18	Beam	26.5	21.92	90	Surface finishing crack
B6P19	Slab	23.1	19.53	45	—
B6P20	Slab	20.8	15.53	20	—
B6P21	Wall	20.6	13.58	50	—
B6P22	Wall	31.1	12.67	80	—
B6P23	Wall	27.8	13.26	95	—
B6P24	Wall	22.6	12.96	85	—

The coefficient that affects the shape of the fuzzy set, the premise parameter defined in Layer 1, was determined by referring to the inspection criteria presented by the Korea Infrastructure Safety & Technology Corporation [31]. The consequent parameters can be determined so that the error will be minimized through the least square method, but the premise parameters cannot be optimized in the same way. Accordingly, in this study, a backpropagation algorithm [12] was used to optimize the premise parameters. In the backpropagation algorithm, an error (E_p) is calculated as follows:

$$E_p = \sqrt{\frac{1}{m} \sum_{k=1}^m (y_{rp} - y_{ANFIS})^2}, \quad (11)$$

where m is the number of data sets, y_{rp} is the carbonation depth measured from the field investigation, and y_{ANFIS} is the carbonation depth derived from the ANFIS. The gradient descent method [12] is applied so that the error calculated

by (11) can be a minimum ($E_{\min}$), where the error increment (Δx_{cwq}) of the premise parameters is calculated as follows:

$$\Delta x_{cwq} = -\frac{\partial E_p}{\partial x_{cwq}}, \quad (12)$$

where x_{cwq} represents the premise parameters x_c , x_q , and x_w and the error increment (Δx_{cwq}) is calculated using a chain rule. The error increment (Δx_{cwq}) of the premise parameters is reflected in a new factor along with a training rate (η), and the $(t' + 1)$ th premise parameter ($x_{cwq}(t' + 1)$) is updated as follows:

$$x_{cwq}(t' + 1) = x_{cwq}(t') + \frac{\eta}{p} \Delta x_{cwq}, \quad (13)$$

where p represents the number of data sets. If the premise parameters are updated, an operation is performed again from Layers 1 to 5, and the updated consequent parameters are derived. The series of this process is repeatedly performed

TABLE 9: Field investigation data (Building 7, construction completion year: 1983).

Measurement point	Member type	Concrete compressive strength (MPa)	Concrete carbonation depth (mm)	Cover depth (mm)	Crack width (mm)
B7P1	Slab	25.2	7.69	35	—
B7P2	Beam	18.6	10.35	70	—
B7P3	Slab	25.5	11.78	40	—
B7P4	Beam	26.4	7.35	45	—
B7P5	Beam	31.4	11.36	55	0.1
B7P6	Slab	32.1	7.85	35	—
B7P7	Column	25.9	12.90	30	—
B7P8	Column	26.3	8.77	25	—
B7P9	Beam	25.1	11.98	55	—
B7P10	Slab	25.2	13.37	35	—
B7P11	Beam	26.0	7.82	35	—
B7P12	Slab	22.0	9.87	30	—
B7P13	Slab	20.0	12.31	25	0.1
B7P14	Beam	27.5	11.03	40	—
B7P15	Slab	19.9	8.02	35	—
B7P16	Beam	24.5	13.34	60	—
B7P17	Wall	19.7	17.89	45	—
B7P18	Wall	20.5	20.35	40	0.1
B7P19	Wall	24.4	18.41	30	—
B7P20	Wall	21.6	23.06	40	0.1

until the error calculated by (11) reaches minimum ($E_{\min}$), which is referred to as training. In this study, the diagnostic data of 8 buildings were used in random training, and the remaining data, that is, the diagnostic data of Building 9, was utilized in the verification. The fuzzy set of the finally updated input parameters is shown in Figure 5.

4. Analysis and Verification

As shown in Figure 6, Buildings 3, 4, and 7 among all 9 buildings used in this study are located very close to the coast; they are thus more likely to suffer deterioration due to chloride attack in comparison to other buildings. With the use of the optimized ANFIS algorithm, the carbonation depths of the buildings used in training were reevaluated, and the analysis results are shown in Figure 7. The analysis model was found to provide a reasonable estimation of the carbonation depths in most buildings. However, there was a significantly large error between the measurement values and the analysis values for some measurement points, including Building 3 and Building 8 as shown in Figures 7(c) and 7(h), respectively. Table 5 shows that, in the case of Building 3, a very large deviation was observed in the distribution of the measured concrete carbonation depths. In particular,

in the case of measurement points B3P2 and B3P9, the carbonation depths were found to differ by more than three times, even though the measurement data used as the input parameters, such as compressive strength and crack width, were very similar. On the other hand, for Building 4 with an environmental condition similar to that of Building 3 as it is located in the same region, ANFIS results were found to provide a very close estimation of the measurement values. This suggests that the error on Building 3 is due to the significant influence of factors other than the established input parameters (e.g., concrete surface finishing status) or there is a possible error in the measurement data. In the case of Building 8, the carbonation depths in measurement points B8P14 and B8P16 differed by more than four times, despite the very similar measurement data used as the input parameters, such as compressive strength and crack width. All the target buildings used in this study are over 30 years old, and partial repairs were quite frequently performed over a long period of time. In particular, Buildings 3 and 8 exhibited a larger difference in the surface states than other buildings due to the partial repairs. This implies that the surface states should be added as an input parameter in order to estimate the carbonation depths more accurately at which combined deterioration is reflected. Figure 8 shows the ratios

FIGURE 5: Fuzzy sets of input parameters after training.

of the ANFIS analysis results and measurement values with respect to concrete compressive strength, crack width, surface chloride ion concentration, and the chloride ion diffusion coefficient. It is considered that the ANFIS analysis well estimated the carbonation depths with no significant bias with respect to the input parameters.

Among the 9 buildings investigated in this study, Building 9 was not used in training and was used to verify the accuracy of the ANFIS algorithm in estimating the carbonation depths at which the combined deterioration is reflected. As shown in Table 1, Building 9 has one story below ground and four stories above ground and is located in Seoul, South

Korea. Its construction was completed in 1976, and the inspection was carried out in 2015. As shown in Tables 1 and 2, the average concrete compressive strength was measured as 23 MPa, the maximum crack width was 0.1 mm, the surface chloride ion concentration was 0.22 kg/m³ on the inside and 0.27 kg/m³ on the outside, and the chloride ion diffusion coefficient was 27×10^{-6} mm²/year. The analysis results of Building 9 through the optimized ANFIS algorithm are shown in Figure 9. Building 9 exhibited a slightly lower average compressive strength than other buildings used in training, and the surface chloride content was similar to that of Building 1, whereas the chloride ion diffusion coefficient

FIGURE 6: Location of target buildings in South Korea.

was 9 times larger than that of Building 1. In addition, the chloride ion diffusion coefficient was lower (about a half) than that of Building 2, but the surface chloride content was more than 1.5 times larger. For these reasons, the carbonation depths measured ranged from 20 to 30 mm, which is 1.5 to 2 times larger than those of Buildings 1 and 2 located at similar sites. The analysis model slightly overestimated the carbonation depths of Building 9, but a comparison with the carbonation depth calculated using (3) and (4), which is the carbonation velocity coefficient estimation equation presented by the Korea Concrete Institute and the Japan Society of Civil Engineers, reveals that the accuracy of the analysis model proposed in this study is relatively very good. This is because it can reflect the combined deterioration phenomenon. Since the ANFIS algorithm proposed in this

study can more accurately estimate carbonation depth as more inspection data are obtained, it is expected to be used very effectively in a building of which the inspection is performed periodically.

5. Conclusion

In this study, detailed safety inspection on a total of 189 spots of 9 buildings has been performed to get the field data that are required for the estimation of the carbonation depth. The ANFIS algorithm was proposed to estimate the carbonation depths of the buildings exposed to the actual environment, in which combined deterioration is reflected. From this study, the following conclusions were drawn:

FIGURE 7: ANFIS results for trained data.

FIGURE 8: ANFIS results with respect to input parameters.

FIGURE 9: ANFIS result for Building 9 (construction completion year: 1976).

TABLE 10: Field investigation data (Building 8, construction completion year: 1982).

Measurement point	Member type	Concrete compressive strength (MPa)	Concrete carbonation depth (mm)	Cover depth (mm)	Crack width (mm)
B8P1	Column	23.3	20.79	40	—
B8P2	Column	20.8	57.84	45	—
B8P3	Beam	20.8	41.53	40	—
B8P4	Slab	16.0	26.89	30	—
B8P5	Wall	33.5	11.36	85	—
B8P6	Wall	29.0	11.63	40	—
B8P7	Slab	29.0	22.84	25	—
B8P8	Beam	26.1	29.72	75	—
B8P9	Beam	22.4	16.29	20	—
B8P10	Slab	25.3	22.88	25	0.1
B8P11	Beam	23.1	43.93	40	—
B8P12	Slab	26.6	45.86	20	—
B8P13	Beam	27.4	16.62	60	0.1
B8P14	Slab	25.9	35.64	30	—
B8P15	Beam	31.4	13.83	40	0.2
B8P16	Slab	24.6	9.18	20	Surface finishing crack
B8P17	Beam	30.8	11.98	40	0.2
B8P18	Slab	26.8	21.00	20	0.1
B8P19	Wall	29.3	32.27	45	—
B8P20	Wall	25.6	69.13	70	—
B8P21	Wall	30.0	47.35	45	—
B8P22	Wall	28.4	38.69	55	—

- (1) Although a variety of factors affect the concrete carbonation, it is practically impossible to consider all factors in this study. Therefore, the carbonation velocity coefficient, surface chloride ion concentration, chloride ion diffusion coefficient, concrete compressive strength, and crack width were used as the input parameters of the ANFIS algorithm.
- (2) The optimized ANFIS rules were derived by training the inspection data of 8 of the 9 buildings. With the optimized ANFIS algorithm, the carbonation depths of these 8 buildings were reevaluated, and the result showed that the proposed model well reflected the combined effects of the surface chloride ion concentration, chloride ion diffusion coefficient, concrete compressive strength, and crack width. The analysis results also indicate that the finishing status of concrete surface shall be considered as an influencing factor for the estimation of the carbonation depths.
- (3) In addition, the inspection data of Building 9 which were not used in training were used to verify

the accuracy of the ANFIS algorithm, and the verification results showed that the proposed model provided relatively good accuracy compared to the carbonation depth estimation method presented by the Korea Concrete Institute and the Japan Society of Civil Engineers.

- (4) The accuracy of the proposed ANFIS algorithm in this study for estimating carbonation depth is due to consideration on the combined deterioration, and as more inspection data are obtained, it is expected to be used very effectively in a building of which the inspection is performed periodically.

Appendix

See Tables 3–12.

Competing Interests

The authors declare that they have no competing interests.

TABLE 11: Measurement of chloride concentration (Buildings 1–4).

Building 1		
Location	Chloride ion concentration (kg/m ³)	Chloride ion diffusion coefficient (m ² /year)
Inside		
Surface to 10 mm	0.27	3.19 × 10 ⁻⁶
Outside		
Surface to 10 mm	0.63	
10 to 20 mm	0.15	
20 to 30 mm	0.11	
Building 2		
Location	Chloride ion concentration (kg/m ³)	Chloride ion diffusion coefficient (m ² /year)
Inside		
Surface to 10 mm	0.15	46.55 × 10 ⁻⁶
Outside		
Surface to 10 mm	0.18	
10 to 20 mm	0.13	
20 to 30 mm	0.13	
Building 3		
Location	Chloride ion concentration (kg/m ³)	Chloride ion diffusion coefficient (m ² /year)
Inside		
Surface to 10 mm	0.47	11.17 × 10 ⁻⁶
Outside		
Surface to 10 mm	0.47	
10 to 20 mm	0.38	
20 to 30 mm	0.22	
Building 4		
Location	Chloride ion concentration (kg/m ³)	Chloride ion diffusion coefficient (m ² /year)
Inside		
Surface to 10 mm	0.40	73.86 × 10 ⁻⁶
Outside		
Surface to 10 mm	0.63	
10 to 20 mm	0.61	
20 to 30 mm	0.49	

TABLE 12: Measurement of chloride concentration (Buildings 5–8).

Building 5		
Location	Chloride ion concentration (kg/m ³)	Chloride ion diffusion coefficient (m ² /year)
Inside		
Surface to 10 mm	0.24	9.97 × 10 ⁻⁶
Outside		
Surface to 10 mm	0.42	
10 to 20 mm	0.33	
20 to 30 mm	0.18	
Building 6		
Location	Chloride ion concentration (kg/m ³)	Chloride ion diffusion coefficient (m ² /year)
Inside		
Surface to 10 mm	0.13	42.70 × 10 ⁻⁶
Outside		
Surface to 10 mm	0.38	
10 to 20 mm	0.29	
20 to 30 mm	0.27	
Building 7		
Location	Chloride ion concentration (kg/m ³)	Chloride ion diffusion coefficient (m ² /year)
Inside		
Surface to 10 mm	1.38	10.62 × 10 ⁻⁶
Outside		
Surface to 10 mm	1.58	
10 to 20 mm	0.72	
20 to 30 mm	0.70	
Building 8		
Location	Chloride ion concentration (kg/m ³)	Chloride ion diffusion coefficient (m ² /year)
Inside		
Surface to 10 mm	0.15	13.32 × 10 ⁻⁶
Outside		
Surface to 10 mm	0.22	
10 to 20 mm	0.15	
20 to 30 mm	0.11	

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