Hindawi Publishing Corporation
Advances in Materials Science and Engineering
Volume 2014, Article ID 653753, 13 pages
http://dx.doi.org/10.1155/2014/653753

Research Article

Concrete Mix Design for Service Life of RC Structures under Carbonation Using Genetic Algorithm

Seung-Jun Kwon,[1] Byung Jae Lee,[2] and Yun Yong Kim[2]

[1] *Department of Civil and Environmental Engineering, Hannam University, 133 Ojeong-dong, Daedeok-gu, Daejeon 306-791, Republic of Korea*
[2] *Department of Civil Engineering, Chungnam National University, 99 Daehak-ro, Yuseong-gu, Daejeon 305-764, Republic of Korea*

Correspondence should be addressed to Yun Yong Kim; yunkim@cnu.ac.kr

Received 15 October 2013; Revised 18 December 2013; Accepted 18 December 2013; Published 18 February 2014

Academic Editor: Amit Bandyopadhyay

Steel corrosion in reinforced concrete (RC) structure is such a critical problem to structural safety that many researches have been performed for maintaining required performance during intended service life. This paper is for a numerical technique for obtaining optimum concrete mix proportions through genetic algorithm (GA) for RC structures under carbonation which is considered as a serious deterioration in underground sites and big cities. For this study, mix proportions and CO_2 diffusion coefficients are analyzed through the previous studies, and then the fitness function of CO_2 diffusion coefficient is derived through regression analysis. The fitness function from 69 test results includes 5 variables of mix proportions such as w/c (water to cement) ratio, cement content, sand content percentage, coarse aggregate content, and R.H. (relative humidity). Through GA technique, simulated mix proportions are obtained for 12 cases of verification and they show reasonable results with average relative error of 4.6%. Assuming intended service life and design parameters, intended CO_2 diffusion coefficients and cement contents are determined and then related mix proportions are simulated. The proposed technique can provide initial concrete mix proportions which satisfy service life under carbonation.

1. Introduction

CO_2 concentration is increasing due to fossil energy consumption and this causes more carbonation damage to RC structures [1, 2]. Carbonation means that pH in pore water drops to about 10.5 due to intrusion of exterior CO_2 [3] and consumption of $CaOH_2$. In carbonated concrete, embedded steel is easily corroded. It is so critical deterioration phenomenon that it should be considered in durability design for underground RC structures or those in metropolitan cities which have high CO_2 concentration.

With higher CO_2 concentration, carbonation depth increases but this can be comparatively controlled by a design of concrete mix proportions. The influencing parameters on carbonation are reported to be type of cement, unit content of cement, type of aggregate, and so on [2]. Semiempirical prediction techniques, so-called mesolevel, have been proposed and they are still utilized for the sake of simple and practical application [4, 5]. Carbonation mechanism can be explained as diffusion of CO_2 and carbonatable materials like calcium hydroxide ($Ca(OH)_2$) and calcium silicate hydrates (C–H–S). CO_2 diffusion represents how fast CO_2 gas (or liquid) intrudes into concrete, so that concrete with high CO_2 diffusion coefficient allows rapid carbonation. From the defensive point of view for carbonation, concrete with larger carbonatable materials can keep high alkali so long as they are not fully consumed due to carbonation reaction. From 1980, several physico-chemo carbonation models have been proposed. They are all constructed by both modeling on diffusion coefficient based on pore structure and modeling on carbonic reaction based on dissociation of carbonatable materials [3, 6–8]. Carbonation modeling for cracked and joint concrete is similarly performed considering the larger CO_2 intrusion due to crack effect and cold joint effect [9–12]. Recently, carbonation prediction techniques are proposed through experimentally measuring CO_2 diffusion coefficient

[13–15] and numerically obtaining CO_2 diffusion coefficient through neural network algorithm [16].

If environmental conditions like CO_2 concentration, temperature, and R.H. are quantitatively evaluated, intended carbonation depth in design stage can be determined considering design cover depth and intended service life. Provided that various mix proportions and the related CO_2 diffusion coefficients are experimentally given, intended CO_2 diffusion coefficient satisfying the intended service life can be obtained. Then mix proportions satisfying the intended CO_2 diffusion coefficient can be obtained through optimization technique as well.

GA (generic algorithm) technique is a representative optimization technique and widely utilized in civil engineering. Through reverse analysis, the parameters which satisfy the fitness function can be derived so that application of GA has been extended. For the application of GA to concrete researches, mix proportion optimizations are performed only for strength prediction in HPC (high performance concrete) [17, 18]. With regard to durability design for service life, very limited research has been performed for chloride attack [19]. For carbonation, optimization of mix proportions has not been carried out so far.

In this paper, CO_2 diffusion coefficients and the related mix proportions are investigated. Based on 69 mix proportions and diffusion coefficients; the fitness function for CO_2 is derived through MATLAB with parameters of mixing variables (w/c ratio, unit content of cement, and fine and coarse aggregates) and exterior variables (R.H.). Through comparison with the previous test results, the applicability of GA technique for optimum mix proportions is verified. Assuming the intended service life and environmental conditions, the intended CO_2 diffusion coefficient is calculated. Finally, the mix proportions which satisfy the intended CO_2 diffusion coefficient are derived through GA technique. This technique can be utilized for performance-based concrete mix design. The techniques for carbonation prediction and optimization of mix proportions are dealt with in this paper.

2. Background of GA and Influencing Parameters on Carbonation

2.1. Overview of GA. Unlike conventional search technique, GA technique constructs arbitrary solutions in initial group, and then the fittest solution is derived through modification of the solutions. GA technique is mainly utilized in the field of mechanical and electrical engineering and recently applied to civil engineering such as design optimization for structures, line network analysis, and concrete mix design for strength. This technique can provide more accurate results than other algorithms having many local solutions [20, 21]. GA technique starts with an initial set of random solutions called population. Each individual in the population is called a chromosome, which represents a solution to the problem at hand. The evolution operator simulates Darwinian evolution process to create population from generation to generation. The availability of genetic algorithm depends on its ability to keep existing parts of solution, which have a positive effect on the outcome, and proceed with optimizing the nonoptimal part. The transition rules which combine and change those samples for improving the solutions are probabilistic and not deterministic. This enables genetic algorithm to reach a global optimum without being fixed in local optima [18]. In the selection stage, GA fundamentally starts from Darwinian natural selection and the initial individuals are selected in this process. Selection provides the driving force in genetic algorithm, and selection pressure is critical in it. The selection directs genetic algorithm search toward promising regions in the search space [18]. The second stage, crossover is the most important genetic operator in which the bit-strings of two (or more) parents are cut into two (or more) pieces and the parts of bit-string are crossed over. The point where the parents are cut is randomly determined. Through the crossover operator, a new child population has been created using inherited values from the parent population. Mutation operator is used to insert new information into the new population, preventing GA from getting stuck in certain regions of the parameter space [18]. Mutation consists of making slight changes in parameters of child population after they have been generated by crossover. More detailed information on GA can be found in many researches [17–21]. The process of GA is presented in Figure 1.

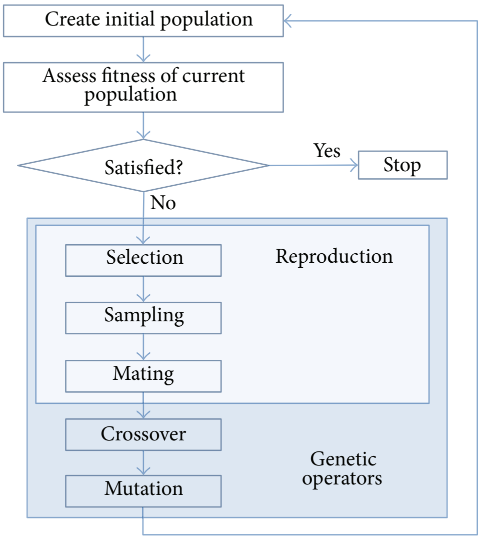


Figure 1: Genetic algorithm process [29].

2.2. Study of Carbonation Parameters and Prediction Techniques. Influencing parameters on carbonation can be classified into two groups. One is for external parameters regarding environmental conditions and the other is for internal parameters regarding diffusion coefficient and carbonatable materials. Considering these parameters, many carbonation prediction techniques have been proposed in semiempirical form. These equations assume that carbonation depth is proportional to square root of exposed time. This assumption was verified through experiments, field investigations [1, 2, 9, 22], and analytical solution [6, 23]. In Table 1, carbonation parameters are summarized. Conventional techniques for carbonation prediction are listed in Table 2 [1, 2].

Table 1: Influencing parameter on carbonation behavior.

Internal parameter (mixture)	Low w/c and large unit cement amount	(i) Holding pH in alkali through producing large amount of hydration of CSH and $Ca(OH)_2$ (ii) Low CO_2 diffusion through dense pore structure
	Aggregate	CO_2 intrusion through artificial light weight aggregate
	Mineral admixture (slag and fly ash)	(i) Small amount of $Ca(OH)_2$ due to pozzolanic reaction and latent hydraulic reaction (ii) Low diffusion coefficient of CO_2
	Mixed chloride content	Rapid carbonic reaction due to high pH from ion dissociation
	Alkali	(i) Rapid carbonic reaction due to high alkali cement (ii) Residual metallic oxide (K_2O, Na_2O)
External parameter	CO_2 concentration	Rapid carbonation through higher concentration of CO_2
	Temp.	Increasing activity energy due to high temperature (Arrhenius law)
	R.H.	(i) Decreasing carbonation in low R.H. due to insufficient H_2O (ii) Decreasing carbonation in high R.H. due to low CO_2 diffusion
	Induced chloride ion	Rapid carbonation due to dissociated chloride ion (cation)

Table 2: Semiempirical equations for carbonation process.

Researcher	Equations
Syrayama	$t = \alpha\beta\gamma\delta\varepsilon \dfrac{5000C^2}{(x-38)^2}$ C: carbonation depth, x: w/c ratio $\alpha, \beta, \gamma, \delta, \varepsilon$: factors for admixtures, cement type, exposure condition, and so forth
Kishitani	$t = \dfrac{0.3(1.15+3\text{w/c})C^2}{R^2(\text{w/c}-0.25)^2} \quad (\text{w/c} \geq 0.6)$ $t = \dfrac{7.2C^2}{R^2(4.6\text{w/c}-1.76)^2} \quad (\text{w/c} < 0.6)$ C: carbonation depth R: factor for cement type, aggregate type, and surface treatment
Hamada	$t = \dfrac{kC^2}{R}, \quad k = \dfrac{0.3(1.15+3x)}{(x-0.25)^2}$ C: carbonation depth, x: w/c ratio R: factor for cement type, aggregate type, and surface treatment
Ida	$t = \alpha\beta\gamma \dfrac{KC^2}{(100x-18)^2}$ C: carbonation depth, x: w/c ratio K: factor for exposure and cement type α, β, γ: quality, retardation, and environmental condition

The flowchart for this study is shown in Figure 2. Through this study, fitness function for diffusion coefficient, intended diffusion coefficient for service life, and mix proportions satisfying intended diffusion coefficient are derived using GA technique.

3. Concrete Mix Optimization Using GA

3.1. Fitness Function for Diffusion Coefficient

3.1.1. Previous Test for Diffusion of CO_2 [14, 16]. For the derivation of fitness function, the previous test results are adopted. In the test, CO_2 diffusion coefficients were measured through diffusion cell. Three different mix conditions and 4 different R.H. were considered [14]. So far, several researches have been reported for the test of CO_2 diffusion coefficients; however, they are not for concrete but for cement mortar or cement paste [6, 13]. Very limited cases are reported for CO_2 diffusion coefficient in concrete. In Table 3, the procedures for the adopted test are summarized. Mix proportions and cement properties are listed in Table 4. The test adopted in this paper covers only OPC (Ordinary Portland Cement, type I) concrete since concrete with mineral admixtures has different carbonation behavior due to the decreased diffusion coefficient and pozzolan reaction [3, 7].

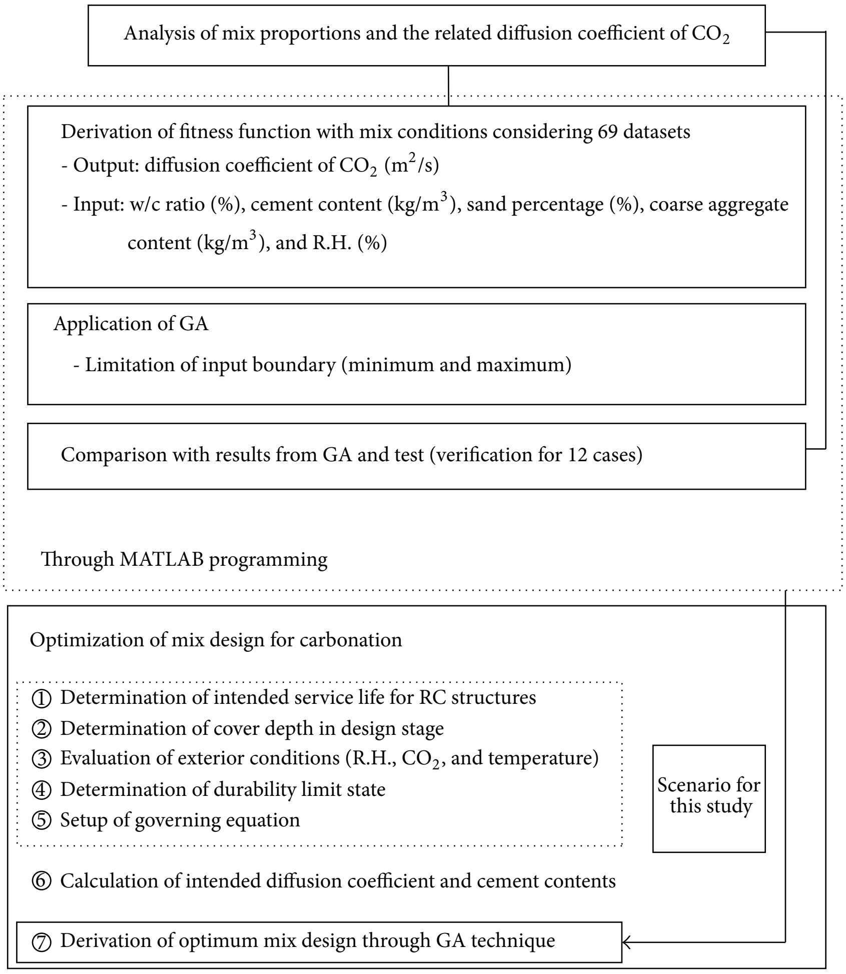


FIGURE 2: Flowchart for this concrete mix optimization.

TABLE 3: Summary of test setup [14].

Steps
(a) Installation of test equipment in room (20°C)
(b) Measurement of concrete sample thickness and diameter
(c) Installation of sample (concrete disk) in cell
(d) Applying N_2 gas and CO_2 gas to different cells with same pressure
(e) Measurement of CO_2 concentration when CO_2 concentration in N_2 gas keeps constant (steady state)
$D_{CO_2} = \dfrac{Q f_{CO_2} L}{(1 - f_{CO_2}) A}$
D_{CO_2}: diffusion coefficient of CO_2; Q: flow rate of gas
f_{CO_2}: mol fraction in $N_2 + CO_2$; L: thickness of disk; A: area of disk

TABLE 4: Mix proportions for CO_2 diffusion measurement [14].

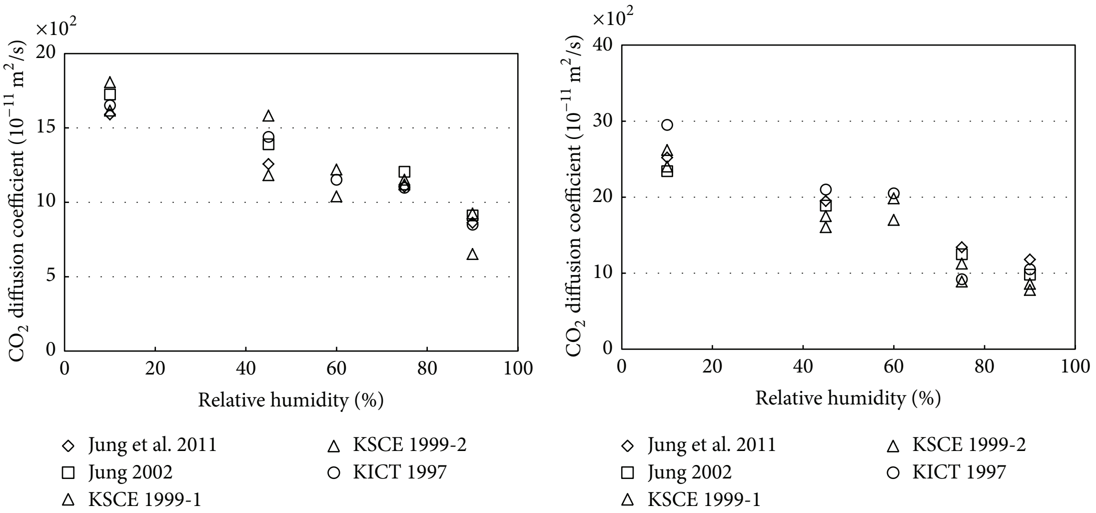
(a)

Case	w/c (%)	Cement (kg/m^3)	Water (kg/m^3)	Sand (kg/m^3)	Coarse aggregate (kg/m^3)
1	42	425	179	714	895
2	50	315	158	748	1,076
3	58	277	161	726	1,117

(b)

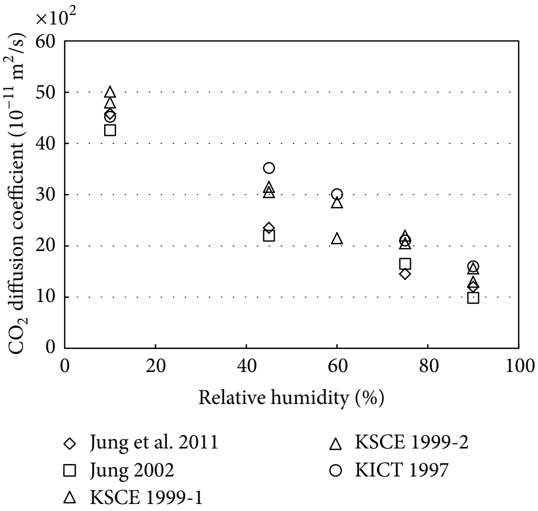
	Aggregate properties		
Type	Specific gravity	Absorption (%)	Fineness modulus
Fine	2.56	2.18	2.85
Coarse	2.60	0.94	6.51

3.1.2. Derivation of Fitness Function. The adopted test was performed considering 4 different R.H. as 10%, 45%, 75%, and 90%. In order to obtain more reasonable fitness function, several previous test results [15, 24, 25] are considered. Carbonation process is very sensitive to R.H. since concrete with high saturation allows active carbonation reaction but low diffusion of CO_2, and concrete with low saturation allows high diffusion of CO_2 but it has little H_2O for carbonic reaction. With higher R.H. and lower w/c ratio, CO_2 diffusion coefficients decrease as in Figure 3. In Figure 3, several results



(a) w/c 42%

(b) w/c 50%



(c) w/c 58%

FIGURE 3: CO_2 diffusion coefficients with w/c ratios and R.H.

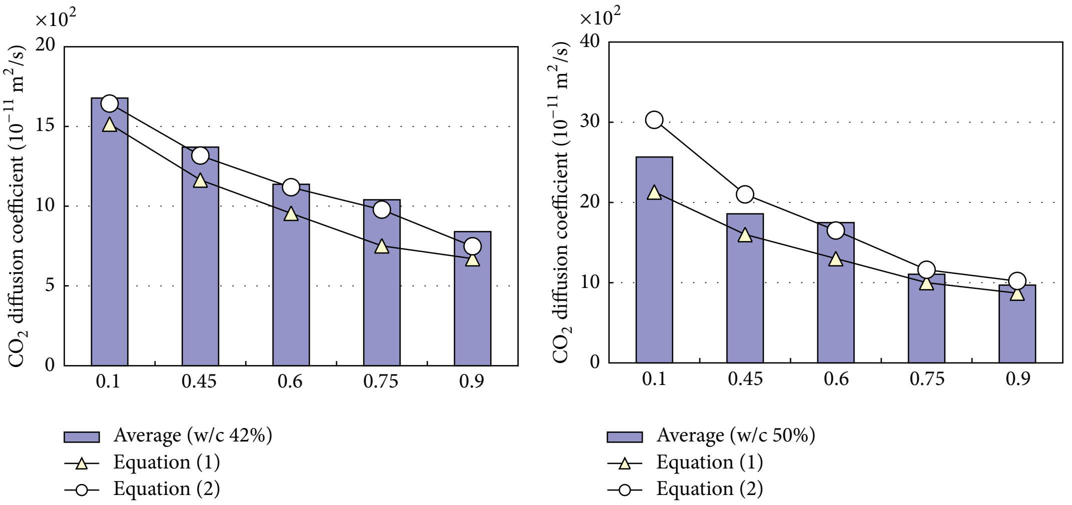
TABLE 5: Variables for fitness function.

Type	w/c (%)	C (kg/m^3)	S/a (%)	G (kg/m^3)	R.H. (kg/m^3)	a and b	Constant
Max	100	0	10	10	30	1	200,000
Min	–100	–100	–10	–10	–30	–1	0

[25, 26] are obtained from reverse analysis based on measured carbonation depth with constant R.H.

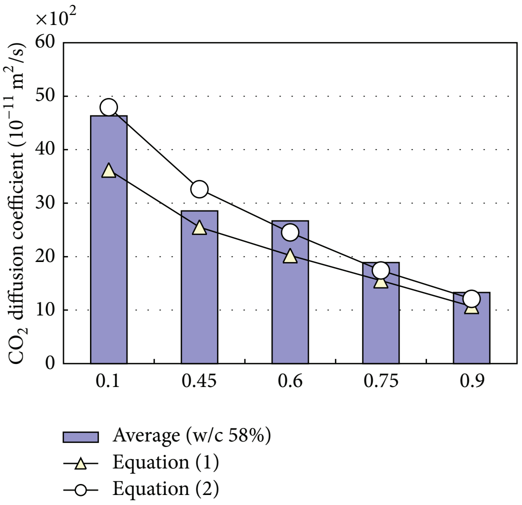
For the relation with mix proportions and CO_2 diffusion coefficient, fitness function with mix components should be obtained. In the previous researches, fitness function for strength was derived through linear multiregression curve, which contained the variables of mix components like w/c ratio and unit amount of cement [18]. Unlike the fitness function for strength, R.H. is very critical to CO_2 diffusion coefficient, so that both mix components (w/c ratio, content of cement, sand ratio, and content of coarse aggregate) and R.H. are considered as variables in the fitness function in this analysis.

In the optimization technique, many local solutions can be obtained. For avoiding convergence to local solution, initial variables (starting variables) and wide ranges for each solution are necessary. Even wide ranges of solutions are considered, local solutions may be obtained because of the initial variables in conventional optimization techniques, so that GA technique is preferred for searching solution in overall ranges. The variables and the related ranges are listed in Table 5.



(a) w/c 42%

(b) w/c 50%



(c) w/c 58%

FIGURE 4: Test and simulated results for diffusion coefficient.

TABLE 6: Variables and constants in regression analysis.

	I	A	B	C	D	E
Equation (1)	1018.56	16.08	−1.42	2.75	0.60	−9.75
Equation (2)	15,427.82	49.562	−29.60	5.48	−4.42	9.79
	a: −0.005825; b: 0.7542					

w/c: w/c ratio (%); C: cement content (kg/m^3); S/a: sand percentage (sand/total aggregate) (%); Agg: coarse aggregate content (kg/m^3); R.H: relative humidity (%); I: Intersection (constant).

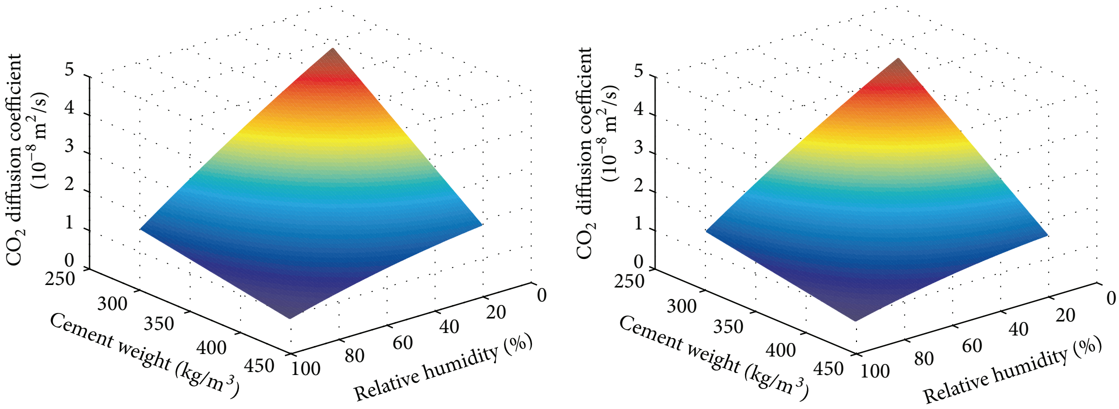
With larger unit content of cement, diffusion coefficient decreases, so that C in Table 5 is set to have below zero. w/c ratio is assumed to have a range of −100~100. S/a (sand to total aggregate) and G have relatively small effect on CO_2 diffusion, so that they are assumed to have small range of −10~10. CO_2 diffusion coefficient is much dependent on R.H., so that the range of R.H. is assumed as −30~30.

Typical multiregression analysis is shown in (1). In (2), additional term for the consideration of R.H. is added. Averages of relative error are evaluated to be 17.3% from (1) and 7.6% from (2), respectively. The results of multiregression curves are listed in Table 6. For the derivation of constant in (1) and (2), GA technique is utilized. Consider

$$D_{CO_2} = I + A\left(\frac{\mathrm{w}}{\mathrm{c}}\right) + B(C) + C\left(\frac{\mathrm{S}}{\mathrm{a}}\right) + D(\mathrm{Agg}) + E(\mathrm{RH}), \tag{1}$$

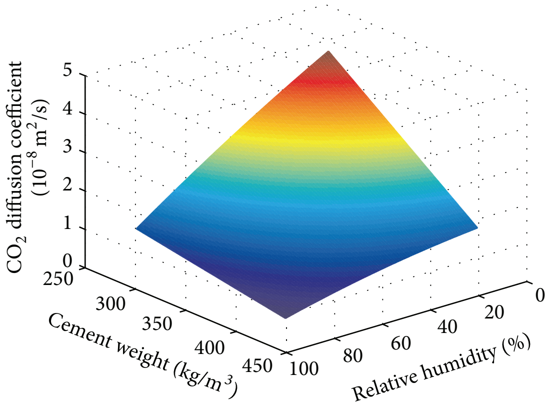
$$D_{CO_2} = \left[I + A\left(\frac{\mathrm{w}}{\mathrm{c}}\right) + B(C) + C\left(\frac{\mathrm{S}}{\mathrm{a}}\right) + D(\mathrm{Agg}) + E(\mathrm{RH})\right](a\mathrm{RH} + b). \tag{2}$$

In Figure 4, the results of regression analysis ((1) and (2)) and test results (averages) are compared. As shown in Figure 4, when (1) is selected, it provides a big error for the case of high w/c ratio (w/c 58%), so that (2) is selected for fitness function for this study. For the case of w/c 58%, (1)



(a) Case 1: w/c 42%

(b) Case 2: w/c 50%



(c) Case 3: w/c 58%

FIGURE 5: Diffusion coefficient contour with cement content and relative humidity.

shows the relative error range of 10.6~24.3% but (2) shows 3.3~14.2%. If a better fitness curve can be defined through nonlinear regression analysis, it would provide the more reasonable mix proportions based on the test dataset.

CO_2 diffusion coefficients are strongly dependent on mix proportions. The contours are shown in Figure 5. Case 1 represents w/c 42% in Table 4, where unit cement content is changed from 277 kg/m^3 to 425 kg/m^3 and R.H. is changed from 10% to 90%. Cases 2 and 3 show the simulations of CO_2 diffusion coefficient in w/c 50% and 58%, respectively. With larger cement content and higher R.H., CO_2 diffusion coefficients decrease in every case.

3.2. Evaluation of GA Applicability to Generating Mix Proportion. In order to evaluate the applicability of GA, verification is performed for 3 different cases (w/c 42% with R.H. 10%, w/c 50% with R.H. 75%, and w/c 58% with R.H. 90%). Population size is set as 20 and the number of generation is set as 10,000 for avoiding early convergence. For formation of 1st generation, uniform function is adopted. For parent selection for next generation, stochastic uniform function is utilized and two superior chromosomes are transferred to next generation. Crossover function of two-point is adopted and normal distribution is considered for mutation operator with mutation ratio of 0.8.

Determination of up/down boundary conditions is important to obtain each mix component and this needs user's experience. The range of boundary conditions, obtained mix components through GA, and the range of relative errors are listed in Table 7. Output results are mix component and CO_2 diffusion coefficient. R.H. is set to fix since it can be known from exterior condition. The fixed R.H. is made through letting up/down boundaries have the same R.H. value.

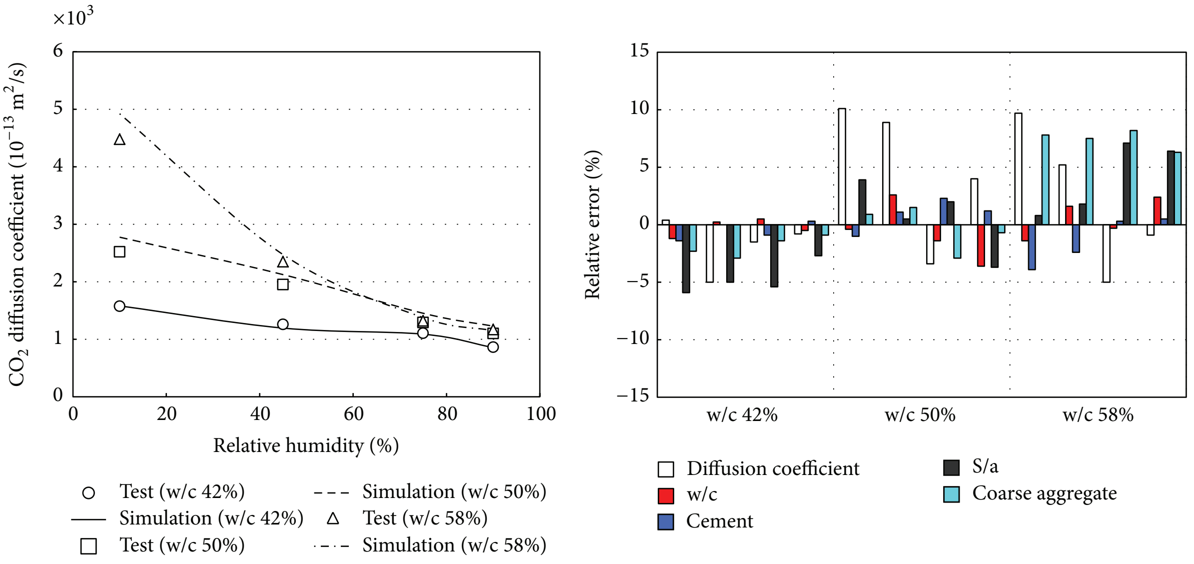
For 12 data [14], the comparison with test and simulated results from GA are shown in Figure 6(a) with regard to CO_2 diffusion coefficient, which shows a reasonable agreement. In Figure 6(b), the comparison of relative errors is shown for 12 cases and the average relative error of each component is shown in Figure 6(c). The processes of searching the optimum solutions are plotted in the case of w/c 42% with R.H. 10% from Figure 7(a) to Figure 7(e).

As listed in Table 7, this technique reasonably estimates the CO_2 diffusion coefficients and mix proportions with −5.0~10.1% of relative errors.

Table 7: Comparison with results from test and simulation from GA.

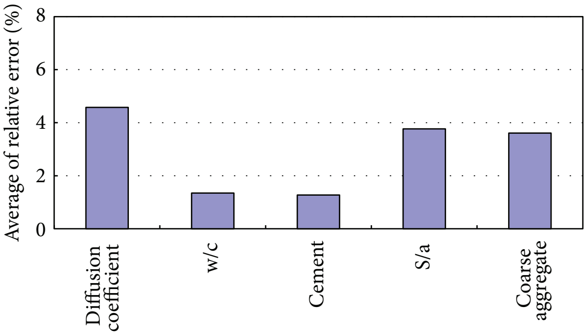
w/c (%)	Diffusion coefficient (10^{-11} m^2/sec)	w/c (%)	R.H. (%)	Cement (kg/m^3)	S/a (%)	Coarse aggregate (kg/m^3)
42	1574	42.0	10	425	44.4	895
Input range	—	40–45	10-10	400–450	39–45	800–895
Result from GA	**1580.5**	**41.5**	—	**419.2**	**41.8**	**874.5**
Relative error (%)	**0.4**	**−1.2**		**−1.4**	**−5.9**	**−2.3**
42	1257	42.0	45	425	44.4	895
Input range	—	40–45	45-45	400–450	39–45	800–895
Result from GA	**1194.2**	**42.1**	—	**420.8**	**42.2**	**869.7**
Relative error (%)	**−5.0**	**0.24**		**0.0**	**−5.0**	**−2.9**
42	1105	42.0	75	425	44.4	895
Input range	—	40–45	75-75	400–450	39–45	800–895
Result from GA	**1088.4**	**42.2**	—	**421.2**	**42.0**	**882.1**
Relative error (%)	**−1.5**	**0.5**		**−0.9**	**−5.4**	**−1.4**
42	862	42.0	90	425	44.4	895
Input range	—	40–45	90-90	400–450	39–45	800–895
Result from GA	**855.2**	**41.8**	—	**426.1**	**43.2**	**887.2**
Relative error (%)	**−0.8**	**−0.5**		**0.3**	**−2.7**	**−0.9**
50	2520	50.0	10	315	41.0	1076
Input range	—	47.5–52.5	10-10	290–330	39–45	950–1100
Result from GA	**2775.2**	**49.8**	—	**311.8**	**42.6**	**1085.3**
Relative error (%)	**10.1**	**−0.4**		**−1.0**	**3.9**	**0.9**
50	1950	50.0	45	315	41.0	1076
Input range	—	47.5–52.5	45-45	290–330	39–45	950–1100
Result from GA	**2124.2**	**51.3**	—	**318.5**	**41.2**	**1092.5**
Relative error (%)	**8.9**	**2.6**		**1.1**	**0.5**	**1.5**
50	1503	50.0	75	315	41.0	1076
Input range	—	47.5–52.5	75-75	290–330	39–45	950–1100
Result from GA	**1452.2**	**49.3**	—	**322.2**	**41.8**	**1044.7**
Relative error (%)	**−3.4**	**−1.4**		**2.3**	**2.0**	**−2.9**
50	1105	50.0	90	315	41.0	1076
Input range	—	47.5–52.5	90-90	290–330	39–45	950–1100
Result from GA	**1127.3**	**48.2**	—	**318.9**	**39.5**	**1068.5**
Relative error (%)	**4.0**	**−3.6**		**1.2**	**−3.7**	**−0.7**
58	4480	58.0	10	277	39.4	1117
Input range	—	55–60	10-10	260–330	39–45	950–1300
Result from GA	**4922.3**	**57.2**	—	**266.2**	**39.7**	**1204.2**
Relative error (%)	**9.7**	**−1.4**		**−3.9**	**0.8**	**7.8**
58	2350	58.0	45	277	39.4	1117
Input range	—	55–60	45-45	260–330	39–45	950–1300
Result from GA	**2472.3**	**58.9**	—	**270.5**	**40.1**	**1200.8**
Relative error (%)	**5.2**	**1.6**		**−2.4**	**1.8**	**7.5**
58	1450	58.0	75	277	39.4	1117
Input range	—	55–60	75-75	260–330	39–45	950–1300
Result from GA	**1377.2**	**57.8**	—	**277.7**	**42.2**	**1208.7**
Relative error (%)	**−5.0**	**−0.3**		**0.3**	**7.1**	**8.2**
58	1172	58.0	90	277	39.4	1117
Input range	—	55–60	90-90	260–330	39–45	950–1300
Result from GA	**1150.2**	**59.4**	—	**278.5**	**41.9**	**1187.5**
Relative error (%)	**−0.9**	**2.4**		**0.5**	**6.4**	**6.3**

The bold numbers are results from GA.



(a) Diffusion coefficient

(b) Relative errors of CO_2 diffusion coefficient and simulated mix components



(c) Average of relative errors

Figure 6: Comparison with results of CO_2 diffusion coefficient and relative errors.

4. Design of Concrete Mix Proportions for Carbonation

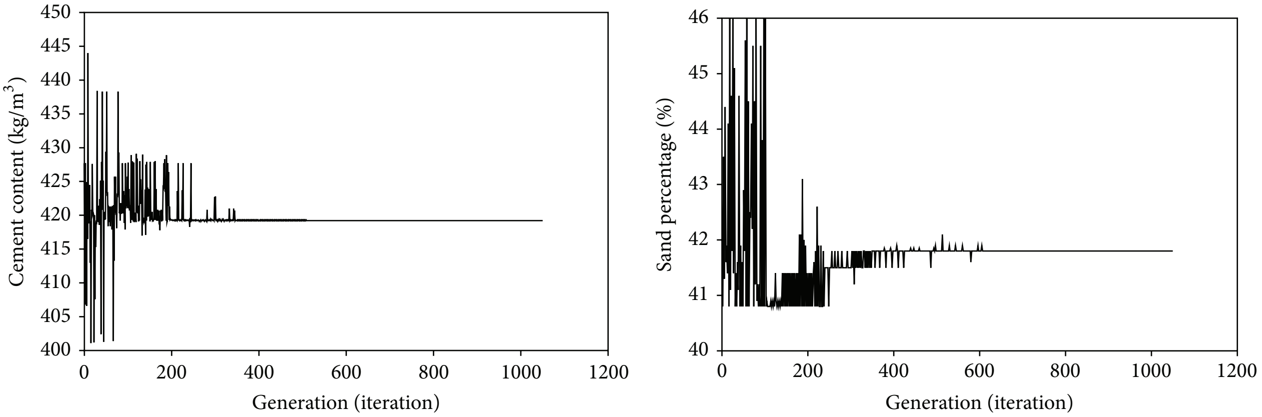
4.1. Scenario for Mix Design Considering Carbonation. In this section, concrete mix design is performed considering exterior condition-carbonation. The design flow is as follows:

(a) determination of intended service life,
(b) determination of design cover depth,
(c) evaluation of exterior condition,
(d) determination of durability criteria,
(e) determination of governing equation,
(f) mix optimization through GA.

If reduction factors or safety factors are considered [26, 27], conservative design can be induced. However, intended diffusion coefficient is derived assuming 1.0 of reduction and safety factor in this paper. Generally, underground site and urban area are reported to be the environments where durability design for carbonation is necessary since they have relatively high CO_2 concentration and normal R.H. (50%~70%). In the previous research [25], durability design for carbonation is strongly recommended over 300 ppm of CO_2 concentration. In urban cities, CO_2 concentration over 350 ppm is reported; furthermore, CO_2 concentration over 650 ppm is reported in underground sites like subway structures [25]. Several specifications [26–28] guide durability design for carbonation in urban cities and underground structures.

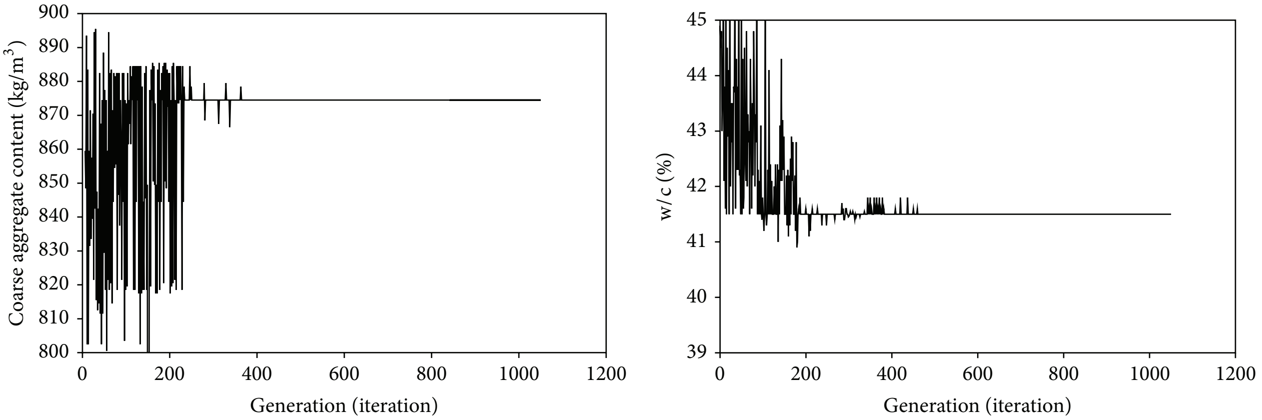
4.2. Mix Design Considering Exterior Conditions and Design Parameters

4.2.1. Scenario for Concrete Mix Design. Based on the design flow in Section 4.1, concrete mix proportions are simulated. The target structures are assumed as underground structures and two types (A and B) are considered. A structure has 75 years and B structure has 100 years for intended service life. Design cover depths are assumed as 50 mm for A structure and 30 mm for B structure. A structure has 65% of R.H. and 12.7°C of temperature. B structure has 75% of R.H. and 22°C of temperature, which are normal exterior conditions



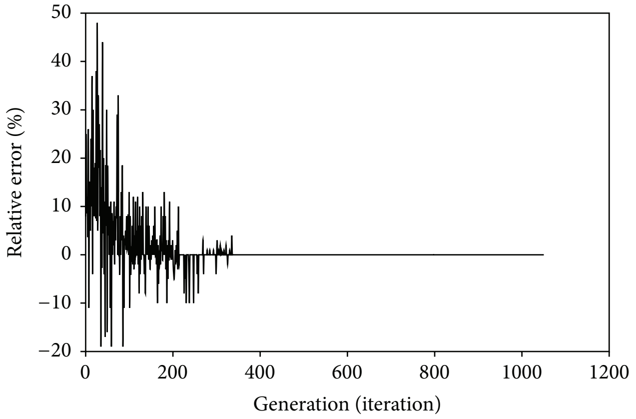
(a) Cement content

(b) Sand percentge



(c) Coarse aggregate content

(d) w/c ratio



(e) Relative error

Figure 7: Simulated process through GA (w/c 0.42 and R.H. 10%).

in underground site. Extremely high CO_2 concentration of 2,700 ppm is assumed for A structure and 980 ppm which is normal condition in underground structure is assumed for B structure. Durability limit state is determined as the condition when carbonation proceeds to steel location [23, 27]. For governing equation, mesolevel equation from CEB [23] is adopted as follows:

$$d_C = \sqrt{2k_1k_2k_3\Delta c} \cdot \sqrt{\frac{D_{CO_2}t}{a}\left(\frac{t_0}{t}\right)^n}, \tag{3}$$

Table 8: Design parameters for carbonation design.

(a)

Type	Structure A	Structure B
Intended service life (year)	75	100
Design cover depth (mm)	50	30
Exterior condition	R.H.: 65% Temp.: 12.7°C	R.H: 75% Temp.: 22°C
CO_2 concentration (ppm)	2,700	980
Durability limit state	carbonation depth = cover depth	

(b)

Assumed cement weight (kg/m^3)	300	330	335	370
Intended diffusion coefficient $\times 10^{-11}$ (m^2/sec)	1,742	1,916	1,248	1,378

Table 9: Mixture design through proposed GA technique.

Case		Intended diffusion coefficient (10^{-11} m^2/sec)	w/c (%)	Cement (kg/m^3)	S/a (%)	Coarse aggregate (kg/m^3)	R.H. (%)
A	Structure A	1,742	**42.3**	**300**	**38.4**	**1191.0**	**65**
	Input range		42–58	300-300	37–43	800–1,200	65-65
B	Structure A	1,916	**52.7**	**330**	**38.1**	**960.2**	**65**
	Input range		42–58	330-330	37–43	800–1,200	65-65
C	Structure B	1,248	**49.6**	**335**	**41.2**	**1172.8**	**75**
	Input range		42–58	335-335	37–43	900–1,200	75-75
D	Structure B	1,378	**51.4**	**370**	**40.1**	**875.3**	**75**
	Input range		42–58	370-370	37–43	800–1,200	75-75

The bold numbers are results from GA.

where d_C is carbonation depth (mm), k_1 is constant for local condition, k_2 is constant for curing condition, k_3 is constant for locally different w/c ratio, Δc is CO_2 concentration (kg/m^3), D_{CO_2} is CO_2 diffusion coefficient (m^2/sec), a is carbonation reaction function with hydrate amount, n is constant for cyclic drying and wetting, t_0 is reference time (1 year), and t is exposed period (year).

For considering the effect of temperature on carbonation, a parameter like (4) is considered [4]. Consider

$$f(T) = D_{\text{ref}} \exp\left[\frac{U}{R}\left(\frac{1}{T_{\text{ref}}} - \frac{1}{T}\right)\right], \qquad (4)$$

where D_{ref} is referential CO_2 diffusion coefficient, U is activation energy of CO_2(8500 Cal/mol·K), R is universal gas constant, T_{ref} is reference temperature (298 K), and T is exterior temperature (K).

In (3), the target structure is assumed to have normal construction level and to be sheltered from rain and k_1, k_2, k_3, and n can be assumed as 1.0 and 0.0, respectively [23]. Considering the temperature parameter, (3) can be written as follows:

$$d_C = \sqrt{2\Delta c} \cdot \sqrt{\frac{D_{CO_2} f(T)}{a} t}, \qquad (5)$$

where a can be expressed as follows (CEB 1997):

$$a = 0.75 \cdot C \cdot \text{CaO} \cdot \alpha_H \frac{M_{CO_2}}{M_{\text{CaO}}}, \qquad (6)$$

where C is unit content of cement (kg/m^3), CaO is content of CaO (calcium oxide, 0.65), α_H is hydration rate (0.85), and M is molar weight (CO_2: 44 g/mol, CaO: 56 g/mol).

In (5), Δc, a, t, and T are given by design parameter. Considering the durability limit state (carbonation depth = cover depth), intended diffusion coefficient can be calculated.

The design parameters above are summarized in Table 8.

In (5), two unknown variables exist so that unit content of cement is assumed referring to conventional mix proportions in domestic condition [25]. Four different contents of cement are assumed and the related intended diffusion coefficients are derived through (5).

4.2.2. Derivation of Optimum Mix Proportions.

In this section, optimum mix proportions are derived through GA technique. The fitness function of (2) is utilized for obtaining mix components with fixed R.H. and cement content.

The results of mix proportions are listed in Table 9.

As shown in Table 9, intended diffusion coefficient and unit cement content are given and mix proportions for concrete can be obtained through GA technique. When this technique is applied, convergence of relative error to 0.0 should be checked.

In this paper, fitness function for CO_2 diffusion coefficient is derived based on the previous test results, and then concrete mix design is proposed through GA technique. However, this technique is only for OPC concrete mix design and has limitation of range for mix proportion. The applicable ranges of unit content of cement and w/c ratio are 277 kg/m^3 ~425 kg/m^3 and 0.42~0.58 since both the fitness function and the process for generating each mix proportion are governed by test dataset which is previously adopted.

With more data-set containing CO_2 diffusion coefficient and an accurate fitness function, the proposed technique would be much improved. This technique is applied for mix proportion of concrete under carbonation. With similar procedures, this can be applied to generation of mix proportions which can guarantee the service life of RC structures exposed to different deteriorations like chloride attack, freezing and thawing action, and sulfate attack.

5. Concluding Remark

The conclusions on concrete mix optimization technique for service life of RC structures under carbonation using genetic algorithm are as follows.

(1) Based on the previous experimental results, fitness function for CO_2 diffusion coefficient containing the variables like mix proportions (w/c ratio, unit content of cement, sand/aggregate ratio, and unit content of coarse aggregate) and R.H. (relative humidity) is derived. Through consideration of the parameters of R.H., variation of relative errors decreases.

(2) Through GA technique, three concrete mix proportions are simulated for verification. The simulated results provide below 10.1% of relative errors for each mix component such as w/c ratio, unit content of cement, sand ratio to total aggregate, and unit content of coarse aggregate.

(3) Assuming the exposure conditions of carbonation and design parameters, intended diffusion coefficients are determined and optimum concrete mix proportions which satisfy intended service life are obtained through GA technique. The results from this study are only applicable to OPC concrete. If data-set with mineral and chemical admixtures is prepared, this technique can be applied more widely to durability design for RC structures under carbonation.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgment

This research was supported by a grant (Code 11-Technology Innovation-F04) from Construction Technology Research Program funded by Ministry of Land, Infrastructure and Transport.

References

[1] K. Kobayashi and Y. Uno, "Mechanism of carbonation of concrete," *Japan Society of Civil Engineers*, vol. 1, no. 1, pp. 139–151, 1990.

[2] I. Izumi, D. Kita, and H. Maeda, *Carbonation*, Kibodang Publication, 1986.

[3] T. Ishida and K. Maekawa, "Modeling of PH profile in pore water based on mass transport and chemical equilibrium theory," *Japan Society of Civil Engineers*, vol. 1, no. 37, pp. 151–166, 2001.

[4] T. Saeki, H. Ohga, and S. Nagataki, "Change in micro-structure of concrete due to carbonation," *Japan Society of Civil Engineers*, vol. 1, no. 18, pp. 1–11, 1991.

[5] CEB, *Durable Concrete Structures-Design Guide*, Thomas Telford, London, UK, 2nd edition, 1992.

[6] V. G. Papadakis, C. G. Vayenas, and M. N. Fardis, "Physical and chemical characteristics affecting the durability of concrete," *ACI Materials Journal*, vol. 88, no. 2, pp. 186–196, 1991.

[7] T. Ishida and K. Maekawa, "Modeling of durability performance of cementitious materials and structures based on thermo-hygro physics," in *Proceedings of the 2nd International RILEM Workshop on Life Prediction and Aging Management of Concrete Structures*, 2003.

[8] F. P. Glasser, J. Marchand, and E. Samson, "Durability of concrete—degradation phenomena involving detrimental chemical reactions," *Cement and Concrete Research*, vol. 38, no. 2, pp. 226–246, 2008.

[9] S. J. Kwon, S. S. Park, S. H. Nam, and H. J. Cho, "A study on survey of carbonation for sound, cracked, and joint concrete in RC column in metropolitan city," *Journal of the Korea Institute For Structural Maintenance and Inspection*, vol. 11, no. 3, pp. 116–122, 2007.

[10] H. W. Song, S. J. Kwon, K. J. Byun, and C. K. Park, "Predicting carbonation in early-aged cracked concrete," *Cement and Concrete Research*, vol. 36, no. 5, pp. 979–989, 2006.

[11] O. B. Isgor and A. G. Razaqpur, "Finite element modeling of coupled heat transfer, moisture transport and carbonation processes in concrete structures," *Cement and Concrete Composites*, vol. 26, no. 1, pp. 57–73, 2004.

[12] S. J. Kwon and U. J. Na, "Prediction of durability for RC column with crack and joint under carbonation based on probabilistic approach," *International Journal of Concrete Structures and Materials*, vol. 5, no. 1, pp. 11–18, 2011.

[13] Y. F. Houst and F. H. Wittmann, "Influence of porosity and water content on the diffusivity of CO_2 and O_2 through hydrated cement paste," *Cement and Concrete Research*, vol. 24, no. 6, pp. 1165–1176, 1994.

[14] S. H. Jung, M. K. Lee, and B. H. Oh, "Measurement device and characteristics of diffusion coefficient of carbon dioxide in concrete," *ACI Materials Journal*, vol. 108, no. 6, pp. 589–595, 2011.

[15] S. H. Jung, *Diffusivity of carbon dioxide and carbonation in concrete through development of gas diffusion measuring system [Ph.D. thesis]*, Deptartment of Civil Engineering, Seoul National University, Seoul, Republic of Korea, 2002.

[16] S. J. Kwon and H. W. Song, "Analysis of carbonation behavior in concrete using neural network algorithm and carbonation modeling," *Cement and Concrete Research*, vol. 40, no. 1, pp. 119–127, 2010.

[17] I. C. Yeh, "Computer-aided design for optimum concrete mixtures," *Cement and Concrete Composites*, vol. 29, no. 3, pp. 193–202, 2007.

[18] C. H. Lim, Y. S. Yoon, and J. H. Kim, "Genetic algorithm in mix proportioning of high-performance concrete," *Cement and Concrete Research*, vol. 34, no. 3, pp. 409–420, 2004.

[19] S. J. Kwon and S. C. Kim, "Concrete mix design for service life of RC structures exposed to chloride attack," *Computers and Concrete*, vol. 10, no. 1, pp. 687–607, 2012.

[20] E. Cantú-Paz and D. E. Goldberg, "Efficient parallel genetic algorithms: theory and practice," *Computer Methods in Applied Mechanics and Engineering*, vol. 186, no. 2–4, pp. 221–238, 2000.

[21] D. E. Goldberg, *Genetic Algorithms in Search, Optimization and Machine Learning*, Addison-Welsley, Reading, Mass, USA, 1989.

[22] Y. Abe, "Result of reference review on crack width effect to carbonation of concrete," in *Proceedings of the Symposium on Rehabilitation of Concrete Structures*, 1999.

[23] CEB Task Group 5.1, 5.2, New Approach to Durability Design, CEB, Sprint-Druck, Stuttgart, Germany, pp. 53–62, May 1997.

[24] KICT-Korea Institute of Construction Technology, "Durability improvement of concrete with sea/normal sand," Tech. Rep. R&D/97-0001, section 1–3, Bon Press, Seoul, Republic of Korea, 1997.

[25] KSCE-Korea Society of Civil Engineering, "Study on durability improvement for underground structure," Tech. Rep., Seoul Metropolitan Government Office of Subway Construction, KSCE Press, Seoul, Republic of Korea, 1999.

[26] KCI-Korea Concrete Institute, Concrete Specification-Durability, 2004.

[27] RILEM, "Durability design of concrete structures," Report of RILEM Technical Committee 130-CSL, E&FN, 1994, pp. 75–78.

[28] JSCE-Concrete Committee, Standard Specification for Concrete Structures, 2002.

[29] Mathworks, Genetic Algorithm and Direct Search Toolbox 2, User's Guide, 2007.