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Concrete mix design for service life of RC structures exposed to chloride attack

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Abstract. The purpose of this research is to propose a design technique of concrete mix proportions satisfying service life through genetic algorithm (GA) and neural network (NN). For this, thirty mix proportions and the related diffusion coefficients in high performance concrete are analyzed and fitness function for diffusion coefficient is obtained considering mix components like *w/b* (water to binder ratio), cement content, mineral admixture (slag, flay ash and silica fume) content, sand and coarse aggregate content. Through averaging the results of 10 times GA simulations, relative errors to the previous data decrease lower than 5.0% and the simulated mix proportions are verified with the experimental results. Assuming the durability design parameters, intended diffusion coefficient for intended service life is derived and mix proportions satisfying the service life are obtained. Among the mix proportions, the most optimized case which satisfies required concrete strength and the lowest cost is selected through GA algorithm. The proposed technique would be improved with the enhancement of comprehensive data set including wider the range of diffusion coefficients.

Keywords: concrete; durability; genetic algorithm; chloride diffusion; neural network.

1. Introduction

Concrete has been used as a construction material with good structural performance and cost benefit. However corrosion of steel in RC (Reinforced Concrete) structures subjected to chloride attack can be initiated through intrusion of chloride ions and this can lead structural degradation with cracking and spalling of cover concrete (Broomfield 1997, Song *et al.* 2006). For the significance of durability, chloride threshold which is permitted at the steel location is controlled in several Concrete Specifications and chloride diffusion coefficient is crucial for the evaluation of chloride behavior in RC structures (JSCE 2002, KCI 2004). Many researches have been focused on the evaluation of diffusion coefficient considering mix proportions and exterior conditions. Rapid chloride migration tests have been widely adopted for the reliable determination of diffusion coefficient of chloride ion since it takes relatively short duration time (Tang 1996a, b, Tang and Nillson 1993, ASTM 1997). However it also needs preparation of sample, setting of electrical device and indicator of silver nitrite solution. Apparent diffusion coefficients from field investigation or long term submerged test can provides direct profiles of chloride content through Fick's 2^{nd} Law (Thomas and Bamforth 1999, Thomas and Bentz 2002, Gjorv *et al.* 1994). They can be changed significantly even in the same mix proportions according to varying exterior conditions such as temperature, R.H. (Relative Humidity)

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and exterior chloride concentration. Many studies on apparent diffusion coefficients are performed considering time effect (Thomas and Bamforth 1999, Poulsen 1993, Tang and Joost 2007), mineral admixture effect (Thomas and Bamforth 1999, Thomas and Bentz 2002) and crack effect (Kwon *et al.* 2009, Yokozeki *et al.* 1998). Experimental evaluation of apparent diffusion coefficient has been performed in spite of the time and cost limitation since it is a key parameter both for modeling and analyzing chloride behavior.

NN technique is applied to the evaluation of diffusion coefficients and modeling the deterioration phenomena (Kwon and Song 2009, 2010). It can consider various interior and exterior conditions for accurate diffusion coefficient. GA (Genetic Algorithm) is an optimization technique and utilized for structural design in civil engineering. Its application increases due to the capability of both prediction from input parameters and optimization of input parameters from reverse analysis (Lin and Hajela 1992, Chou and Ghaboussi 2001, Hao and Xia 2002). For the research on concrete, GA technique is mainly applied to optimization of concrete mix proportions for required strength (Yeh 1998, 2007, Lim *et al.* 2004). Many researches are performed for durability design but very limited studies have dealt with mix proportions for durable concrete. For high durable concrete mixing, engineers are mainly dependent on not quantitative technique but on the experience or trial mix proportions. For trial mixing, certain boundaries to guarantee durability performance is necessary.

In this paper, thirty mix proportions with related diffusion coefficients are studied and analyzed, which contain various mineral admixtures like slag, fly ash and silica fume. Unlike the previous studies of GA and NN on concrete mix design, this paper is focused on optimum concrete mix proportions which can satisfy an intended service life, required strength and cost benefit. In this paper, applicability of GA and NN for concrete mix design is discussed and durability design for concrete mix is attempted.

2. Genetic algorithm and test plan

2.1 Background of GA

2.1.1 Overview

GA technique can provide more accurate results than other algorithms having many local solutions. GA technique, unlike the conventional one, 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. More information on GA can be found in several literatures (Cantu'-Paz and Goldberg 2000, Goldberg 1989, Lim *et al.* 2004). The Major genetic operators are explained in Sections 2.1.2~2.1.4.

2.1.2 Selection

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. There are several selection methods like Roulette wheel, ranking and tournament selection. For chromosome with fitness, its selection probability is determined as Eq. (1) (Lim *et al.* 2004, Goldberg 1989).

$$P_k = \frac{f_k}{\sum_{i=1}^{population} f_i} \tag{1}$$

where P_k is the selection probability of a chromosome from population k, f_k is the size of population and f_i is the size of whole population.

2.1.3 Crossover

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. The crossover rate is defined as the ratio of the number of offspring produced in each generation to the population size. This ratio controls the expected number of chromosomes to undergo the crossover operation. There are three kinds of crossover; single-point, two-point and uniform crossover (Lim *et al.* 2004, Goldberg 1989).

2.1.4 Mutation

Mutation operator is used to insert new information into the new population, preventing GA from getting stuck in certain regions of the parameter space. Mutation consists of making slight changes in parameters of child population after they have been generated by crossover. Changes in parameters of each individual are calculated using a Gaussian distribution. Standard deviation of the distribution is set to shrink as the number of generations increases, which lets GA search more global at the very first generation and more local at final generations where the algorithm is about to converge (Lim *et al.* 2004, Goldberg 1989). GA process is schematically shown in Fig. 1 and flowchart for this study is shown in Fig. 2.

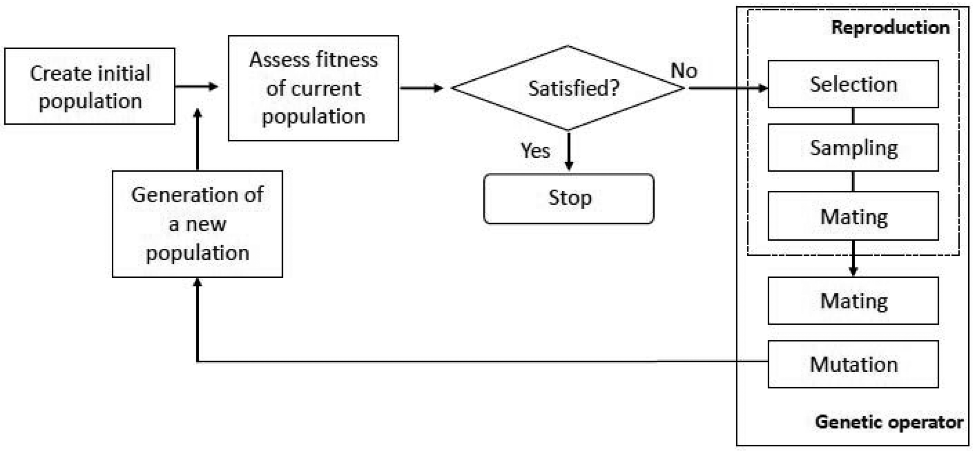


Fig. 1 Genetic algorithm process

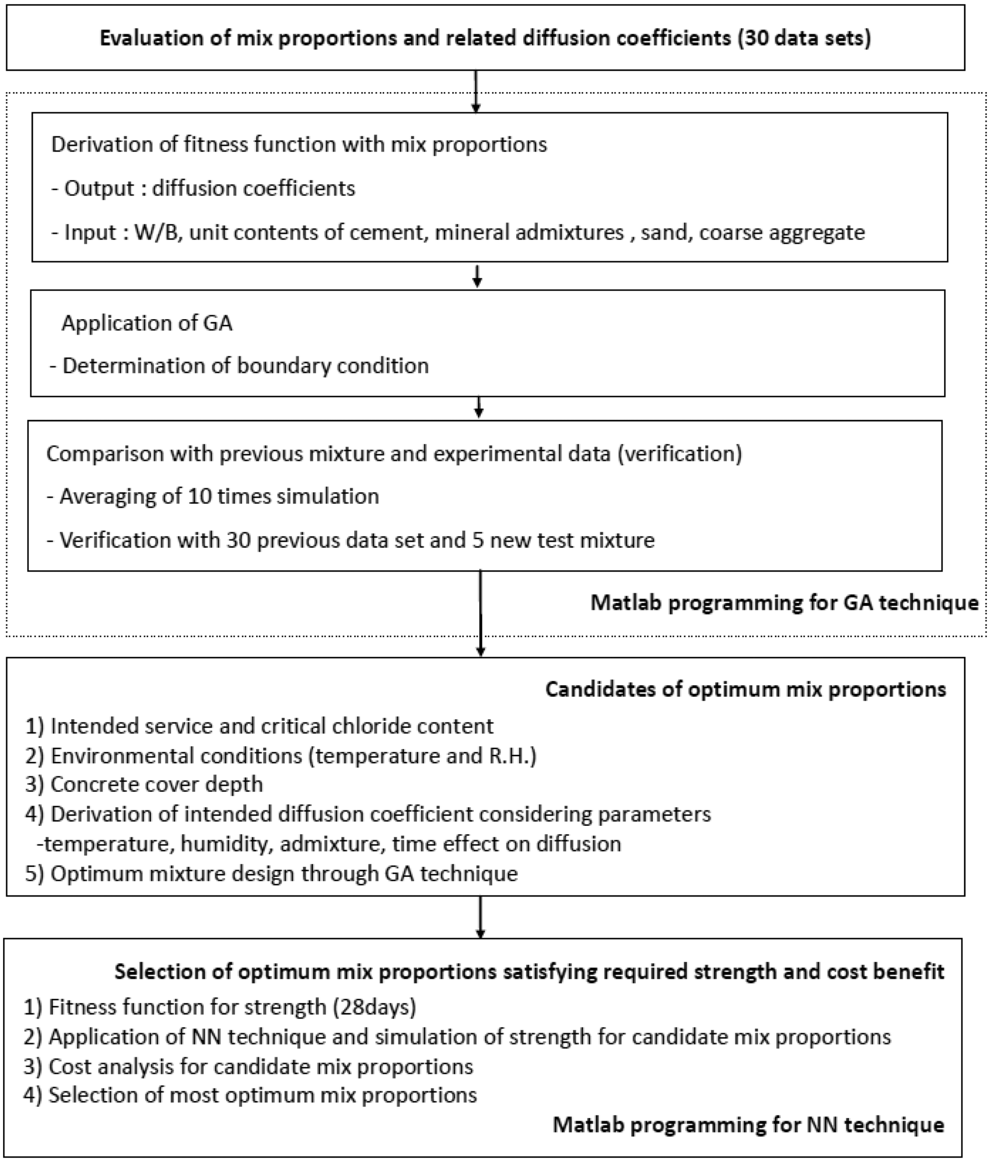


Fig. 2 Flowchart for this study

2.2 Test results in previous research

For data set of GA, test results in previous research are briefly summarized (Samsung construction 2003). Three different *w/b* ratios were considered as 37%, 42% and 47% with slump of 15±1.5 cm and air content of 4.5±1.0%. Mix proportions, compressive strength at the age of 28 days, and the apparent diffusion coefficient which is key parameter of this study are listed in Table 1. Chemical composition and properties of binding materials are presented in Table 2 and the properties of sand and coarse aggregate are shown Table 3.

Table 1 Mix proportions, compressive strength and diffusion coefficient

Items case names of Mix.	*w/b* (%)	*S/a* (%)	Unit weight (kg/m^3)							Binder×%		Strength (MPa-28 days)	Diffusion coefficient (m^2/sec)
			W	Cementitious materials				*S*	CA	Admixture			
				C	GGBFS	FA	SF			SP	AE		
1 NPC100-37	37	45	168	454	-	-	-	767	952	1.00	0.017	49.0	4.1
2 NPC100-42	42	45	168	400	-	-	-	787	976	0.90	0.015	44.3	5.2
3 NPC100-47	47	47	168	357	-	-	-	838	960	0.85	0.017	38.5	7.3
4 G30N70-37	37	45	168	318	136	-	-	762	946	0.80	0.018	47.0	2.1
5 G30N70-42	42	45	168	280	120	-	-	783	972	0.75	0.013	40.5	3.0
6 G30N70-47	47	47	168	250	107	-	-	835	956	0.65	0.015	37.0	3.2
7 G50N50-37	37	45	168	227	227	-	-	760	943	0.75	0.017	47.3	1.4
8 G50N50-42	42	45	168	200	200	-	-	780	969	0.70	0.014	42.6	1.6
9 G50N50-47	47	47	168	178	179	-	-	832	953	0.60	0.015	38.2	1.7
10 F10N90-37	37	45	168	409	-	45	-	760	943	0.75	0.018	44.2	3.5
11 F10N90-42	42	45	168	360	-	40	-	780	969	0.90	0.021	38.0	5.2
12 F10N90-47	47	47	168	321	-	36	-	832	952	0.75	0.017	34.3	6.2
13 F20N80-37	37	45	168	363	-	91	-	752	934	0.75	0.018	42.5	3.2
14 F20N80-42	42	45	168	320	-	80	-	774	961	0.85	0.025	37.3	4.0
15 F20N80-47	47	47	168	286	-	71	-	826	946	0.70	0.017	32.3	5.9
16 F30N70-37	37	45	168	318	-	136	-	745	952	0.75	0.200	38.2	3.9
17 F30N70-42	42	45	168	280	-	120	-	768	953	0.75	0.015	33.0	4.3
18 F30N70-47	47	47	168	250	-	107	-	820	939	0.65	0.019	28.5	5.9
19 F10S05-37	37	45	168	386	-	45	23	756	938	1.00	0.023	49.0	2.2
20 F10S05-42	42	45	168	340	-	40	20	777	965	0.90	0.021	42.6	2.8
21 F10S05-47	47	47	168	303	-	36	18	829	950	0.90	0.021	38.0	3.3
22 F20S05-37	37	45	168	340	-	91	23	749	929	0.90	0.023	45.2	2.5
23 F20S05-42	42	45	168	300	-	80	20	771	957	0.85	0.025	40.9	3.6
24 F20S05-47	47	47	168	268	-	71	18	810	927	0.90	0.025	36.1	3.8
25 G30S05-37	37	45	168	295	136	-	23	759	942	0.75	0.015	49.1	1.4
26 G30S05-42	42	45	168	260	120	-	20	765	949	0.75	0.015	43.6	1.9
27 G30S05-47	47	47	168	232	107	-	18	832	952	0.80	0.015	36.3	1.8
28 G35F15-37	37	45	168	227	159	68	-	751	932	0.65	0.014	48.1	1.8
29 G35F15-42	42	45	168	200	140	60	-	773	959	0.65	0.014	41.0	1.9
30 G35F15-47	47	47	168	178	125	54	-	804	921	0.70	0.014	36.0	2.3

GGBFS: ground granulated blast furnace slag
FA: fly ash
SF: slica fume
S: sand
w/b: water to binder ratio
CA: coarse aggregate
SP: super plasticizer
AE: Air entrainer

Diffusion coefficients in Table 1 decrease with lower *w/b* ratios and more mineral admixture contents. In order to evaluate apparent diffusion coefficient, cylindrical specimens (10×20 cm) were cured for 28 days and then they are submerged in 3.5% NaCl solution for 6 months. After 6 months, chloride profiles were evaluated through colormetric method of $AgNO_3$ based on AASHTO T 260 (AASHTO 1997).

Table 2 Chemical composition and properties of binding materials

Items types	Chemical composition (%)							Physical properties	
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Ig. loss	Specific gravity	Blaine (cm^2/g)
NPC	21.96	5.27	3.44	63.41	2.13	1.96	0.79	3.16	3,214
GGBFS	32.74	13.23	0.41	44.14	5.62	1.84	0.2	2.89	4,340
FA	55.66	27.76	7.04	2.70	1.14	0.49	4.3	2.19	3,621
SF	93.3	0.5	1.21	0.27	1.03	0.02	1.1	2.21	190.620

Table 3 Physical properties of sand and coarse aggregate

Items types	G_{max} (mm)	Specific gravity	Absorption (%)	F.M.
Sand	-	2.58	1.01	2.90
Coarse aggregate	25	2.64	0.82	6.87

3. Optimum concrete mix design through GA

3.1 Derivation of fitness function for mix proportions

For the application of GA technique for target value (diffusion coefficient), fitness function containing mix components should be prepared. In this study, MATLAB program is utilized for derivation of fitness function. Variables are set as seven mix components containing *w/b* ratio, unit cement content (*C*), mineral admixtures content of ground granulated blast furnace slag (GGBFS), fly ash (FA), silica fume (SF), unit content of sand (*S*) and coarse aggregate (CA). *w/b* is reported to basic parameter for mix design controlling workability and strength. More cement content per unit concrete volume, more of cement hydrates is formed, which makes concrete with denser pore structure and more chemical absorption of chloride ion (Thomas and Bamforth 1999, Song *et al.* 2007, Metha and Monteiro 1993). Concrete with mineral admixtures shows high resistance to chloride penetration through lower diffusion coefficient and larger amount of C-S-H due to pozzolanic reaction (Song and Kwon 2009, Song *et al.* 2007, Yang 2006). The reasons for selecting mix components as parameters is (1) they are basic mix proportions, (2) mix components are easily provided for user's convenience and (3) they play a very important role in durability performance in hardened concrete.

3.2 Application of GA using fitness function

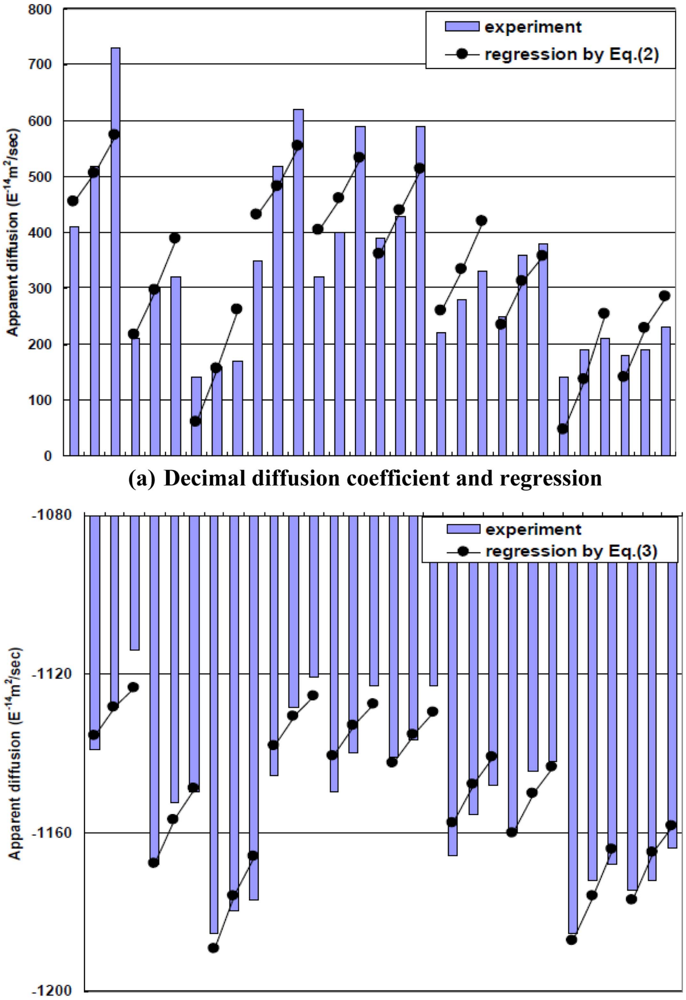
3.2.1 Fitness function

The size of population and generation are designated as 20 and 10000, respectively. Uniform and stochastic uniform functions are utilized for the formulation of the 1st generation and transfer of superiority of parents to next generation, respectively. Two-point crossover and stochastic uniform function are used for crossover and mutation. Crossover rate of 0.8 is applied. In this paper, 2 types of fitness function are obtained. In the previous research (Lim *et al.* 2004), linear regression

Table 4 Results from regression analysis for fitness function

Type	*a*	*b*	*c*	*d*	*e*	*f*	*g*	*I*	*K*
Eq. (2)	-43.512	-4.569	-6.044	-4.641	-8.271	-0.992	0.262	4622.882	10^{-14}
Boundary range	-100~100	-100~0	-100~0	-100~0	-100~0	-5~5	-5~5	2000~6000	-
Eq. (3)	-3.268	-0.382	-0.615	-0.417	-1.211	0.104	0.027	-946.998	10^{-2}
Boundary range	-10~10	-10~10	-10~10	-10~10	-10~10	-1.0~1.0	-1.0~1.0	-1000~1000	-

function with multi-variables of mix components is selected for concrete strength prediction. For chloride diffusion coefficient, logarithmic functions with mix components are proposed through regression analysis (Thomas and Bentz 2002). The results of regression analysis for decimal and logarithmic diffusion coefficients are shown in Eqs. (2) and (3), respectively. The results with



(a) Decimal diffusion coefficient and regression

(b) Logarithmic diffusion coefficient and regression

Fig. 3 Test and regression results for chloride diffusion coefficient regression analysis are presented in Table 4 with boundary range of variables.

$$D_{app} = K[a(w/b)+b(C)+c(GGBFS)+d(FA)+e(SF)+f(S)+g(CA)+I] \quad (2)$$

$$Log(D_{app}) = K[a(w/b)+b(C)+c(GGBFS)+d(FA)+e(SF)+f(S)+g(CA)+I] \quad (3)$$

where, D_{app} is apparent diffusion coefficient (m^2/sec), *w/b* is water to binder ratio (%), *C* is cement content (kg/m^3), *GGBFS*, *FA* and *SF* are mineral admixture contents of ground granulated blast furnace slag, flay ash and silica fume. *S* and *CA* are unit content of sand and coarse aggregate (kg/m^3), respectively. *I* and *K* are constants for regression. For derivation of fitness function, it would be desirable to cover the content of chemical admixtures, however it is assumed that appropriate amount of them are mixed for required air content and workability. After derivation of mix components through this technique, chemical admixtures can be added reasonably based on Table 1.

The average of relative error from Eq. (3) show better correlation with experimental results, 0.39% while that from Eq. (2) shows 18.72% of error. The comparisons with the previous data and those from fitness function are shown in Fig. 3. Decimal and logarithmic diffusion coefficients including their comparison with regression analysis are shown in Figs. 3(a) and (b), respectively.

3.3 Optimum mix design through GA technique

3.3.1 Verification with previous mix proportions

Through set of target value (diffusion coefficient), mix proportions are simulated based on the proposed fitness function in Eq. (3). The results are shown in Table 5, which shows reasonable applicability of GA for mixture design. There are numerous mix proportions which satisfies fitness function with target diffusion coefficient. For the reasonable derivation of results, boundary conditions for input variables are set as ±20%. If cement content is 300 kg/m^3, boundary conditions for cement content are determined as 240 kg/m^3 (minimum) and 360 kg/m^3 (maximum), within which an optimum content is derived with iterations. In the case without mineral admixtures, boundary conditions of minimum and maximum are intentionally considered as 0.0. Regarding the mix proportions in Table 1, the simulated mix proportions are presented in Table 5. GA technique is applied 10 times and averaged mix components are obtained in the Table 5. Maximum error between test and simulated component is estimated to be lower than 5.0%

In Fig. 4, the simulation processes with iterations with (a)-*W/C* ratio, (b)-Cement content, (c)-Sand content and (d)-Coarse aggregate content are shown in the case of NPC 100-37. In the same Fig, (e) shows changes in fitness function with obtained variables and (f) shows relative errors between test and simulated results, which decrease to 0.0.

For the stable derivation of mix proportions, average of results from 10 times simulations is adopted. Fig. 5 shows variations in relative error with simulations in the case of F10N90-42 and G35F15-47 representatively. The relative error decreases with simulations and average from 10 simulations shows lower relative error than 5.0%.

3.3.2 Verification with experimental results

To verify the proposed technique, 5 different mix proportions are prepared. The properties of binding materials and aggregates are same as Tables 2 and 3. Based on the same procedures and curing conditions, 5 diffusion coefficients are obtained. For the given diffusion coefficient, simulation through GA is performed 10 times and derived mix components are averaged as one value. The

Table 5 Simulated mix proportions and comparison with test data

Mix case		*W/B* (%)	*C* (kg/m^3)	GGBFS (kg/m^3)	FA (kg/m^3)	SF (kg/m^3)	*S* (kg/m^3)	CA (kg/m^3)
NPC100-37	Simulated average	37.74	453.52	0.00	0.00	0.00	761.48	950.32
	Test	37.00	454.00	0.00	0.00	0.00	767.00	952.00
	Relative error (%)	-2.00	0.10	-	-	-	0.72	0.18
NPC100-42	Simulated average	40.66	411.63	0.00	0.00	0.00	790.69	981.18
	Test	42.00	400.00	0.00	0.00	0.00	787.00	976.00
	Relative error (%)	3.19	-2.91	-	-	-	-0.47	-0.53
NPC100-47	Simulated average	45.26	348.68	0.00	0.00	0.00	840.32	1,001.47
	Test	47.00	357.00	0.00	0.00	0.00	838.00	960.00
	Relative error (%)	3.70	2.33	-	-	-	-0.28	-4.32
G30N70-37	Simulated average	36.97	312.32	136.69	0.00	0.00	749.67	942.57
	Test	37.00	318.00	136.00	0.00	0.00	762.00	946.00
	Relative error (%)	0.07	1.79	-0.51	-	-	1.62	0.36
G30N70-42	Simulated average	42.59	272.52	116.96	0.00	0.00	806.32	965.51
	Test	42.00	280.00	120.00	0.00	0.00	783.00	972.00
	Relative error (%)	-1.40	2.67	2.54	-	-	-2.98	0.67
G30N70-47	Simulated average	47.99	243.94	106.57	0.00	0.00	843.09	940.59
	Test	47.00	250.00	107.00	0.00	0.00	835.00	956.00
	Relative error (%)	-2.11	2.42	0.40	-	-	-0.97	1.61
G50N50-37	Simulated average	36.87	222.13	222.84	0.00	0.00	758.92	929.09
	Test	37.00	227.00	227.00	0.00	0.00	760.00	943.00
	Relative error (%)	0.35	2.14	1.83	-	-	0.14	1.48
G50N50-42	Simulated average	42.98	204.15	199.65	0.00	0.00	795.26	960.44
	Test	42.00	200.00	200.00	0.00	0.00	780.00	969.00
	Relative error (%)	-2.33	-2.07	0.17	-	-	-1.96	0.88
G50N50-47	Simulated average	48.34	181.45	182.48	0.00	0.00	798.28	982.77
	Test	47.00	178.00	179.00	0.00	0.00	832.00	953.00
	Relative error (%)	-2.85	-1.94	-1.95	-	-	4.05	-3.12
F10N90-37	Simulated average	38.03	419.62	0.00	44.36	0.00	759.00	945.92
	Test	37.00	409.00	0.00	45.00	0.00	760.00	943.00
	Relative error (%)	-2.78	-2.60	-	1.42	-	0.13	-0.31
F10N90-42	Simulated average	42.02	355.79	0.00	39.72	0.00	790.12	970.98
	Test	42.00	360.00	0.00	40.00	0.00	780.00	969.00
	Relative error (%)	-0.04	1.17	-	0.70	-	-1.30	-0.20
F10N90-47	Simulated average	44.66	320.56	0.00	35.84	0.00	814.83	920.71
	Test	47.00	321.00	0.00	36.00	0.00	832.00	952.00
	Relative error (%)	4.97	0.14	-	0.45	-	2.06	3.29
F20N80-37	Simulated average	37.81	372.11	0.00	90.96	0.00	728.95	938.20
	Test	37.00	363.00	0.00	91.00	0.00	752.00	934.00
	Relative error (%)	-2.18	-2.51	-	0.04	-	3.07	-0.45

Table 5 Continued

Mix case		*W/B* (%)	*C* (kg/m^3)	GGBFS (kg/m^3)	FA (kg/m^3)	SF (kg/m^3)	*S* (kg/m^3)	CA (kg/m^3)
F20N80-42	Simulated average	42.57	330.13	0.00	81.32	0.00	775.00	953.67
	Test	42.00	320.00	0.00	80.00	0.00	774.00	961.00
	Relative error (%)	-1.36	-3.17	-	-1.65	-	-0.13	0.76
F20N80-47	Simulated average	45.89	280.59	0.00	72.77	0.00	822.91	962.48
	Test	47.00	286.00	0.00	71.00	0.00	826.00	946.00
	Relative error (%)	2.37	1.89	-	-2.49	-	0.37	-1.74
F30N70-37	Simulated average	36.81	305.27	0.00	137.85	0.00	718.79	953.10
	Test	37.00	318.00	0.00	136.00	0.00	745.00	952.00
	Relative error (%)	0.52	4.00	-	-1.36	-	3.52	-0.12
F30N70-42	Simulated average	41.53	280.71	0.00	124.94	0.00	769.11	941.11
	Test	42.00	280.00	0.00	120.00	0.00	768.00	953.00
	Relative error (%)	1.12	-0.25	-	-4.12	-	-0.15	1.25
F30N70-47	Simulated average	46.12	249.50	0.00	104.67	0.00	850.94	936.23
	Test	47.00	250.00	0.00	107.00	0.00	820.00	939.00
	Relative error (%)	1.86	0.20	-	2.18	-	-3.77	0.30
F10S05-37	Simulated average	37.50	396.24	0.00	46.90	23.72	750.64	938.88
	Test	37.00	386.00	0.00	45.00	23.00	756.00	938.00
	Relative error (%)	-1.34	-2.65	-	-4.22	-3.11	0.71	-0.09
F10S05-42	Simulated average	42.91	352.63	0.00	40.06	20.73	787.75	982.08
	Test	42.00	340.00	0.00	40.00	20.00	777.00	965.00
	Relative error (%)	-2.16	-3.71	-	-0.14	-3.63	-1.38	-1.77
F10S05-47	Simulated average	47.89	313.22	0.00	35.11	17.77	823.00	947.44
	Test	47.00	303.00	0.00	36.00	18.00	829.00	950.00
	Relative error (%)	-1.90	-3.37	-	2.48	1.29	0.72	0.27
F20S05-37	Simulated average	37.85	339.24	0.00	90.02	22.14	755.25	959.02
	Test	37.00	340.00	0.00	91.00	23.00	749.00	929.00
	Relative error (%)	-2.31	0.22	-	1.07	3.72	-0.83	-3.23
F20S05-42	Simulated average	40.43	296.37	0.00	79.74	19.97	767.92	945.77
	Test	42.00	300.00	0.00	80.00	20.00	771.00	957.00
	Relative error (%)	3.74	1.21	-	0.33	0.17	0.40	1.17
F20S05-47	Simulated average	47.05	272.37	0.00	67.96	17.57	828.47	971.06
	Test	47.00	268.00	0.00	71.00	18.00	810.00	972.00
	Relative error (%)	-0.10	-1.63	-	4.28	2.40	-2.28	0.10
G30S05-37	Simulated average	35.73	296.94	140.24	0.00	22.84	775.06	929.79
	Test	37.00	295.00	136.00	0.00	23.00	759.00	942.00
	Relative error (%)	3.43	-0.66	-3.11	-	0.70	-2.12	1.30
G30S05-42	Simulated average	42.04	253.31	122.39	0.00	19.09	786.67	947.78
	Test	42.00	260.00	120.00	0.00	20.00	765.00	949.00
	Relative error (%)	-0.09	2.57	-2.00	-	4.55	-2.83	0.13

Table 5 Continued

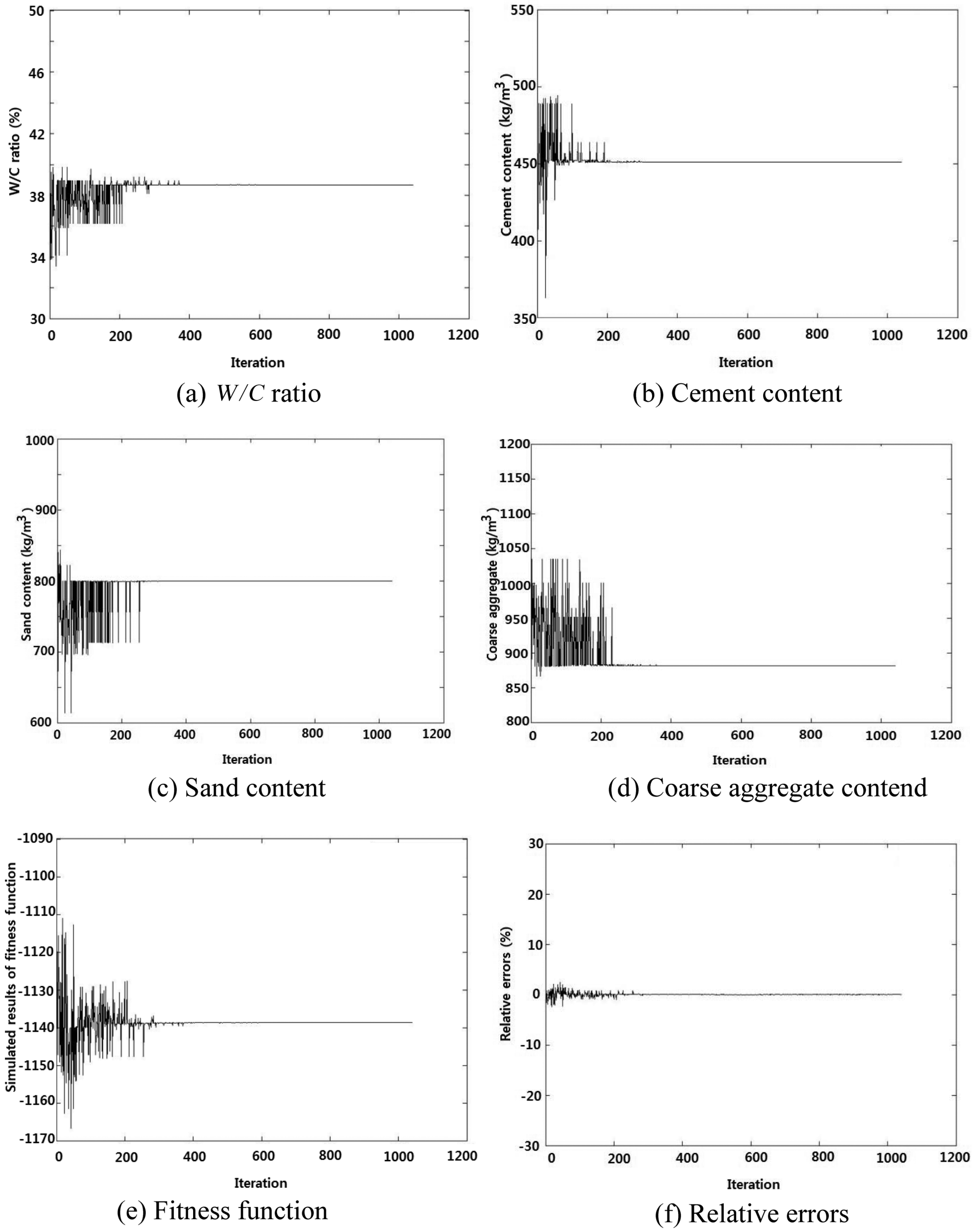
	Mix case	*W/B* (%)	*C* (kg/m^3)	GGBFS (kg/m^3)	FA (kg/m^3)	SF (kg/m^3)	*S* (kg/m^3)	CA (kg/m^3)
G30S05-47	Simulated average	47.04	240.40	108.24	0.00	17.53	831.75	965.90
	Test	47.00	232.00	107.00	0.00	18.00	832.00	952.00
	Relative error (%)	-0.09	-3.62	-1.15	-	2.61	0.03	-1.46
G35F15-37	Simulated average	36.91	228.31	155.78	68.82	0.00	773.93	902.47
	Test	37.00	227.00	159.00	68.00	0.00	751.00	932.00
	Relative error (%)	0.25	-0.58	2.03	-1.20	-	-3.05	3.17
G35F15-42	Simulated average	43.59	194.27	142.10	61.16	0.00	755.97	955.41
	Test	42.00	200.00	140.00	60.00	0.00	773.00	959.00
	Relative error (%)	-3.78	2.87	-1.50	-1.93	-	2.20	0.37
G35F15-47	Simulated average	47.62	182.64	125.75	54.84	0.00	802.37	937.84
	Test	47.00	178.00	125.00	54.00	0.00	804.00	951.00
	Relative error (%)	-1.32	-2.61	-0.60	-1.56	-	0.20	1.38

input boundary conditions for each mix component are ±20% of test results. Table 6 shows the results from 5 mix batch for verification with simulation results and relative errors. The mix components from GA are in good agreement with those from experiments, showing less than 5.0% of relative errors. However, the proposed technique has limitation like a great dependency on acquired data and fitness function. If diffusion coefficient is obtained from concrete with different type of cement or mineral admixtures like different fineness and properties, this may cause significant error. The fitness function is derived from diffusion coefficient data with the range of $1.4\sim7.3\times10^{-12}$ m^2/sec so data out of this range may lead unreasonable mix components.

4. Mix proportions for service life of RC structures

4.1 Scenario of durability design with intended diffusion coefficient

Assuming the exposure conditions and design parameters for RC structures, mix design which can satisfy service life is performed. Safety and load reduction factors can be considered (JSCE 2002, KCI 2004, RILEM 1994) however they are assumed as 1.0 for the convenience of design. Two RC structures (A and B type) with different conditions are assumed. Structure (A)-high strength RC column and (B)-normal strength concrete slab are assumed to have 100 and 75 years of intended service life, respectively. Critical chloride content at the steel location is determined as 1.2 kg/m^3, at which steel corrosion initiates (JSCE 2002, KCI 2004). Regarding the exterior conditions, structure (A) is assumed to be exposed to sea-splash condition with 10°C of temperature and 100% of R.H. Its surface chloride content is set as 13.0 kg/m^3 (splash zone) recommended in Concrete Specification (JSCE 2002, KCI 2004). 25°C of temperature and 85% of R.H. are assumed for structures (B) located in seashore with 9.0 kg/m^3 of surface chloride content. Structure (A) has 10 cm of cover depth and 30% of replacement of GGBFS is used in mix proportions. Structure (B) has 8 cm of cover depth and 100% of Ordinary Portland Cement (OPC) is used. For the derivation of intended



(a) W/C ratio (b) Cement content

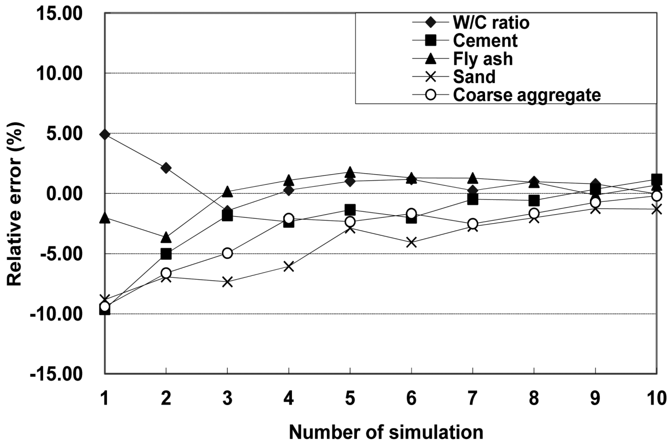
(c) Sand content (d) Coarse aggregate contend

(e) Fitness function (f) Relative errors

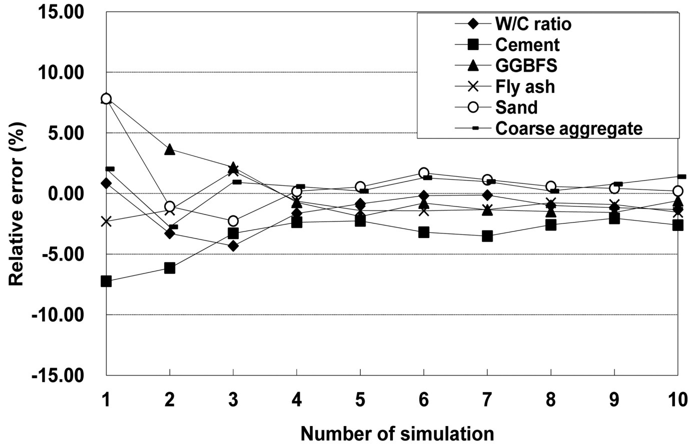
Fig. 4 Simulation of mix proportions for NPC100-37

diffusion coefficient, the effects of temperature and humidity on diffusion coefficient should be considered. Through the parameters for temperature (Thomas and Bentz 2002) and R.H. (Glasser *et al.* 2008, Saetta 1993), their effects on diffusion coefficient are considered like Eqs. (4) and (5).

$$F(T) = \exp\left[\frac{U}{R}\left(\frac{1}{T_{ref}} - \frac{1}{T}\right)\right] \tag{4}$$



(a) F10N90-42



(b) G35F15-47

Fig. 5 Relative errors with number of simulations

$$F(h) = \left[1 + \frac{(1-h)^4}{(1-h_c)^4}\right]^{-1} \tag{5}$$

where U is activation energy (35,000 J/mol), R is gas constant, T_{ref} is reference temperature (293K), h is relative humidity and h_c is threshold of R.H. (0.75). The governing equation for chloride diffusion can be determined based on Fick's 2nd law in Eq. (6). For considering decrease in diffusion with time, time effect on coefficient ($D(t)$) is employed as Eq. (7) (Thomas and Bentz 2002).

$$C(x,t) = C_S\left[1 - erf\left(\frac{x}{2\sqrt{D(t)t}}\right)\right] \tag{6}$$

$$D(t) = D_{ref}\left(\frac{t_{ref}}{t}\right)^m \tag{7}$$

Table 6 Mix proportions for verification of proposed technique

Items case names of Mix.	W/B (%)	S/a (%)	Unit weight (kg/m³)							Binder×%		Diffusion coefficient (m²/sec)
			W	Cementitious materials				S	CA	Admixture		
				C	GGBFS	FA	SF			SP	AE	
NPC100-40	40	44	168	420	-	-	-	775	973	0.98	0.017	
Simulation average (relative error%)	41.46 (-3.65)	-	-	415.98 (0.96)	-	-	-	803.80 (-3.72)	959.77 (1.36)	-	-	4.72
G30N70-40	40	45	168	294	126	-	-	778	961	0.78	0.017	
Simulation average (relative error%)	40.81 (-2.01)	-	-	294.37 (0.73)	130.09 (-3.25)	-	-	774.67 (0.04)	945.37 (1.63)	-	-	2.18
G50N50-40	40	45	168	210	210	-	-	770	962	0.75	0.015	
Simulation average (relative error%)	40.93 (-2.32)	-	-	218.77 (-4.18)	202.89 (3.39)	-	-	759.61 (1.35)	951.91 (1.05)	-	-	1.42
F20N80-45	45	46	168	300	-	75	-	802	954	0.77	0.018	
Simulation average (relative error%)	44.61 (0.86)	-	-	297.58 (0.81)	-	73.92 (1.44)	-	811.24 (-1.15)	948.27 (0.60)	-	-	5.35
F30N70-45	45	46	168	263	-	112	-	795	948	0.68	0.017	
Simulation average (relative error%)	46.19 (-2.65)	-	-	254.51 (3.23)	-	110.49 (1.35)	-	807.16 (-1.53)	962.27 (-1.51)	-	-	4.90

where C_s is surface chloride content (kg/m^3), D_{ref} is diffusion coefficient in reference time (t_{ref}), m is exponent which controls reduction of diffusion (Thomas and Bentz 2002). For the time effect in Eq. (7), averaged diffusion coefficient can be obtained as Eqs. 8(a) and (b) (Poulsen 1993). These equations can be rewritten as Eqs. 9(a) and (b) considering temperature and R.H. effect on diffusion.

$$\overline{D(t)} = \frac{1}{t}\int_0^t D_{ref}\left(\frac{t_{ref}}{\tau}\right)^m d\tau = D_{ref}\frac{t_{ref}^m}{t}\left[\frac{\tau^{1-m}}{1-m}\right]_0^t = \frac{D_{ref}}{1-m}\left(\frac{t_{ref}}{t}\right)^m,\ (t<t_R) \tag{8a}$$

$$\overline{D(t)} = D_{ref}\left[1+\frac{t_c}{t}\left(\frac{m}{1-m}\right)\right]\left(\frac{t_{ref}}{t_c}\right)^m,\ (t \ge t_R) \tag{8b}$$

$$\overline{D(t)} = \frac{1}{t}\int_0^t D_{ref}F(T)F(h)\left(\frac{t_{ref}}{\tau}\right)^m d\tau = \frac{D_{ref}}{1-m}F(T)F(h)\left(\frac{t_{ref}}{t}\right)^m,\ (t<t_R) \tag{9a}$$

$$\overline{D(t)} = D_{ref}F(T)F(h)\left[1+\frac{t_c}{t}\left(\frac{m}{1-m}\right)\right]\left(\frac{t_{ref}}{t_c}\right)^m,\ (t \ge t_R) \tag{9b}$$

where $D(t)$ is averaged diffusion coefficient considering time effect, t_R is the time when diffusion coefficient is changed to be constant, generally assumed as 30 years (Thomas and Bentz 2002). Time-exponent (m) can be obtained through Eq. (10) since replacement ratio of GGBFS is assumed as 30% (Thomas and Bentz 2002). Without replacement of cement, m is set as 0.2.

$$m = 0.2 + 0.4(FA/50 + SG/70) \tag{10}$$

where FA and SG denote replacement ratio of fly ash (%) and GGBFS (%).

Table 7 Assumptions for durability design parameters

Structure	Type A	Type B
Intended service life	100 years	75 years
Critical chloride content	1.2 kg/m^3	1.2 kg/m^3
Surface chloride content	13.0 kg/m^3	9.0 kg/m^3
Exterior conditions	Temp. 10°C, R.H. 100%	Temp. 20°C, R.H. 70%
Mineral admixture	GGBFS (30%)	OPC only
M-exponent	0.37	0.20
Cover depth	8.0 cm	12.0 cm
Required strength (MPa, 28 days)	45 MPa	30 Mpa
Target diffusion coefficient (6 months, 10^{-12} m^2/sec)	2.33	6.55
Mixture design	*M*1	*M*2

4.2 Optimization of mix proportions for service life

4.2.1 Application of proposed GA technique

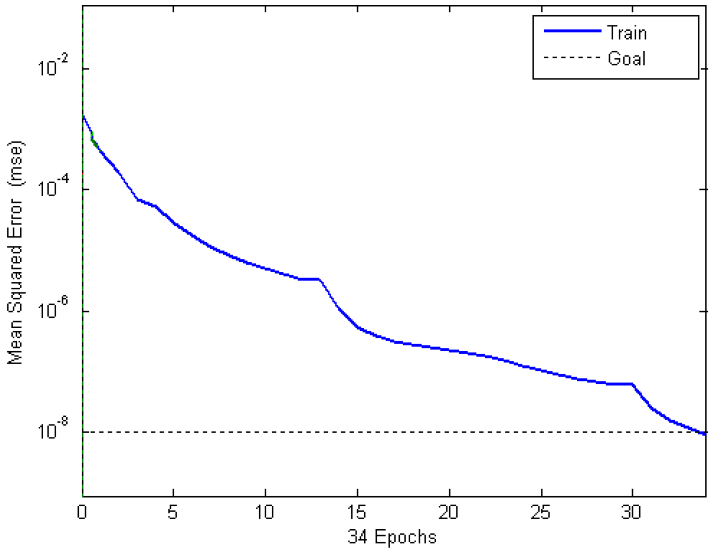
Derivation of intended diffusion coefficient is important, which controls the induced chloride content not to exceed critical threshold in given design parameters (cover depth, intended service life and time exponent) and exterior conditions (temperature and R.H.). Reference time in Eq. (7) is conventionally defined as 28 days (Thomas and Bentz 2002, Kwon *et al.* 2009) but it is determined as 6 months since diffusion coefficients from 6-month submerged condition are employed in this study. The summary of assumed design parameters in Section 4.1 is presented in Table 7, and 2 mix proportions (*M*1 and *M*2) which satisfy the intended service life will be obtained through the proposed technique considering the design parameters.

For one diffusion coefficient in Table 7, GA technique is applied 10 times and the averaged unit contents are listed in Table 8. For *M*1 mixture, totally 100 times simulations are performed and they are listed as *M*1-1~*M*1-10. In the same procedure, *M*2-1~*M*2-10 are obtained through averaging total 100 times simulations.

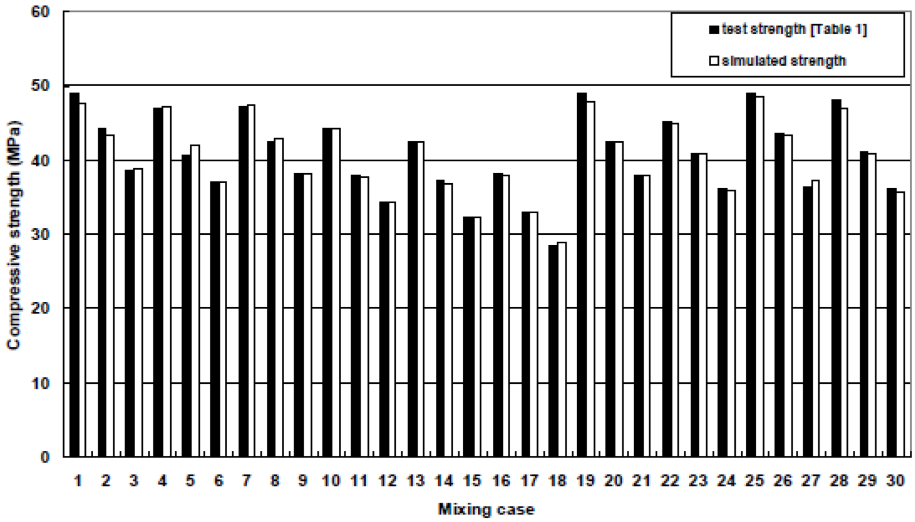
For the optimum mix proportions, various solutions can be generated. In order to select the fittest one among the feasible cases, another step for evaluation of required strength and cost is taken in the next section.

4.2.2 Evaluation of required strength and cost benefit

Regarding the design parameter in Table 7, required strength is assumed as 45 MPa for *M*1 mixture and 30 MPa for *M*2 mixture. NN algorithm is applied for the evaluation of concrete strength. NN technique is widely used for an evaluation of concrete characteristics (Dias and Pooliyadda 2001), and recently its application is developing for durability analysis through predicting the reasonable diffusion coefficient of chloride ion for chloride attack (Song and Kwon 2009) and carbon dioxide for carbonation (Kwon and Song 2010). The outline of NN is well explained in several references (Demuth and Beale 1997, Song and Kwon 2009, 2010). For the application of NN technique, it is necessary to set neurons and perform data processing since each input and output value has boundary limitation from 0.0 to 1.0. Data processing for input and output is described as Eq. (11).



(a) Error with repeating epochs



(b) Simulation results for training data

Fig. 6 Simulation process and results for NN for strength prediction

$$P_n = \frac{P_{acutal} - P_{\min}}{P_{\max} - P_{\min}} \tag{11}$$

where P_n is input value for training of learning, P_{acutal} is actual input neuron, $P_{\max}$ and $P_{\min}$ are maximum and minimum value of a set of input neuron. In this paper, 7 variables for input are set up as neurons like *w/b* ratio, unit content of cement, GGBFS, FA, SF, sand and coarse aggregate. Back propagation algorithm of NN is applied through Matlab program. Output value is determined as strength of concrete at the age of 28 days. For input values, $P_{\max}$ and $P_{\min}$ are assumed as 1000 and 0.0, respectively, and for output values, $P_{\max}$ and $P_{\min}$ are assumed as 50 and 0.0. Tansig

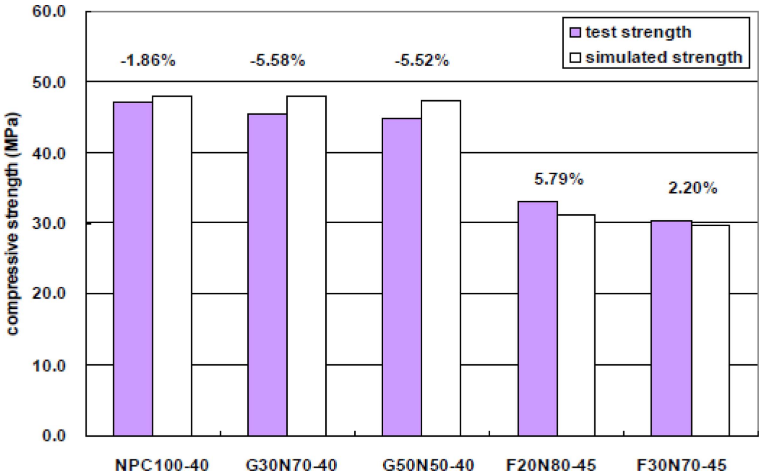


Fig. 7 Verification of NN for compressive strength

Table 8 Mixture proportions for intended diffusion coefficients (*M*1 and *M*2)

Mix	*w/b* (%)	*C* (kg/m^3)	GGBFS (kg/m^3)	FA (kg/m^3)	SF (kg/m^3)	*S* (kg/m^3)	CA (kg/m^3)	Replacement ratio (%)
*M*1-1	41.31	285.24	127.74	0.00	0.00	776.90	942.67	30.93
*M*1-2	40.21	291.61	126.03	0.00	0.00	744.14	986.86	30.20
*M*1-3	39.69	294.53	125.51	0.00	0.00	731.91	1001.31	29.90
*M*1-4	38.99	297.24	126.79	0.00	0.00	731.07	986.27	29.92
*M*1-5	40.06	291.83	125.75	0.00	0.00	731.07	986.27	29.92
*M*1-6	39.43	301.23	123.34	0.00	0.00	734.97	1003.40	29.12
*M*1-7	38.17	303.77	126.75	0.00	0.00	725.19	1001.09	29.45
*M*1-8	39.06	294.53	129.48	0.00	0.00	735.87	1000.10	30.55
*M*1-9	39.68	296.72	124.54	0.00	0.00	737.84	985.04	29.60
*M*1-10	39.26	296.64	124.92	0.00	0.00	723.02	999.64	29.66
*M*2-1	45.08	370.29	0.00	0.00	0.00	911.87	962.93	-
*M*2-2	44.23	380.60	0.00	0.00	0.00	849.42	972.93	-
*M*2-3	43.24	371.60	0.00	0.00	0.00	861.72	951.63	-
*M*2-4	44.47	369.93	0.00	0.00	0.00	860.30	978.67	-
*M*2-5	44.37	367.90	0.00	0.00	0.00	863.61	930.49	-
*M*2-6	44.41	377.15	0.00	0.00	0.00	841.35	991.96	-
*M*2-7	44.06	375.15	0.00	0.00	0.00	867.70	979.85	-
*M*2-8	43.30	375.07	0.00	0.00	0.00	836.86	976.82	-
*M*2-9	43.26	376.28	0.00	0.00	0.00	850.29	937.34	-
*M*2-10	44.49	373.52	0.00	0.00	0.00	867.21	981.90	-

function is used as transfer function, and target epochs with mean square error are assumed as 1000 with 10^{-8} respectively. The simulation process is shown in Fig. 6, which shows comparison with the strength results in Table 1. Figs. 6(a) and (b) show decreasing errors with epochs and simulation results, respectively. As shown in the Fig. 6, the results of strength are reasonably simulated through

Table 9 Unit and relative price for each mix component

	Cement	GGBFS	FA	SF	Sand	Coarse aggregate
Unit price (KW/ton)	67,500	48,000	15,000	700,000	4,580	3,540
Relative price	1.00	0.71	0.22	10.37	0.07	0.05

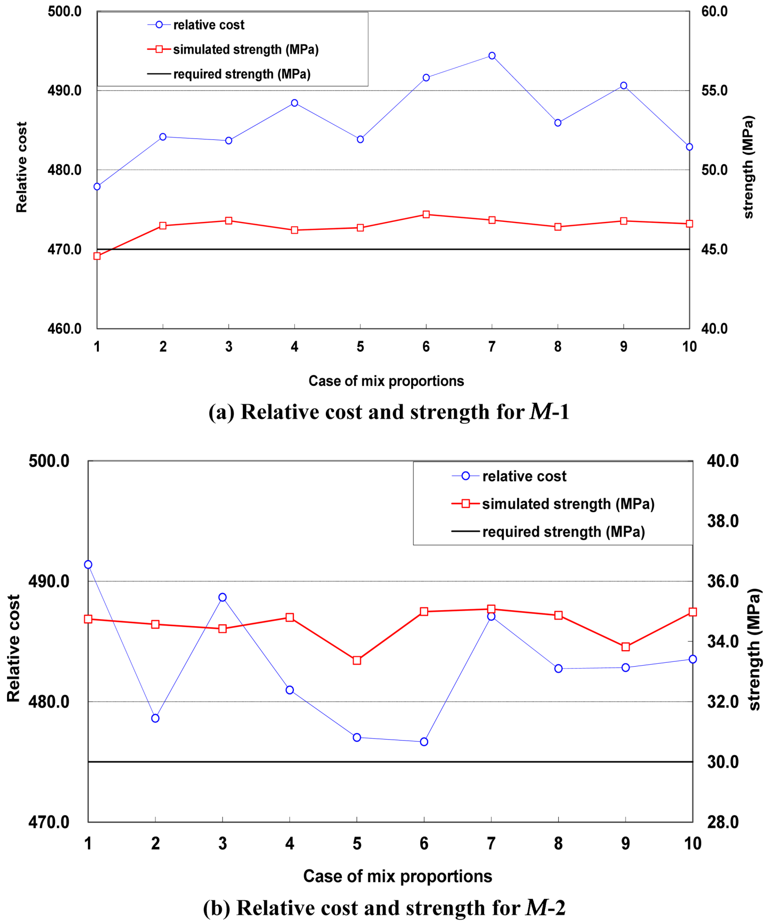


Fig. 8 Relative cost and estimated strength for selection of optimum mix design

NN technique with maximum error of 3.7%

For the verification of NN technique, results of compressive strength from Table 6 are compared with the simulation results. The simulated results are in a good agreement with experimental data with maximum error of 5.79%, which is shown in Fig. 7.

For evaluation of cost benefit, cost per unit weight of mix component is investigated for domestic products (http://www.n2i.co.kr/category/jajae/priceOn/). The relative price to cement is listed in Table 9.

Through NN technique and the unit cost in Table 9, required strength and cost of each mix proportions are evaluated. The results are shown in in Fig. 8 for optimum mix proportions which satisfy both required strength and minimum cost.

From the Fig. 8, case 10 for *M*-1 and case 6 for *M*-2 are selected since they show the least relative cost of 482.90 and 476.67, satisfying the required strength. Compared with the most expensive case, the selected mix proportions cost 97.7% in *M*-1 and 97.0% in *M*-2, respectively.

In this paper, concrete mix design for RC structures under chloride attack is studied through GA technique considering several design parameters such as cover depth, exterior conditions and intended diffusion coefficient. The technique utilizing GA can provide reasonable mix components, however it still has numerous local solutions. Boundary conditions for output (mix component) depend on both user's experience and data-sets for fitness function. For the verification of mix proportions, 20% variations for input boundary condition can show reasonable results but further research is still needed for arbitrary diffusion coefficient with user's least effort on determination of boundary condition. For improving the technique, data-sets with more comprehensive range of diffusion coefficient including various replacement ratio and fineness of mineral admixtures are necessary. This technique can be applied to providing trial mix proportions but dosage of chemical admixtures for workability and air content should be considered in batch plant.

5. Conclusions

The conclusions mixture design optimization for service life of RC structures exposed to chloride attack through genetic algorithm and neural network are as follows.

(1) Based on the previous thirty mix proportions and related diffusion coefficients, logarithmic fitness function is derived. Through GA technique, mix proportions are simulated and its applicability to durability design is verified with test results. The averaged mix proportions from 10 times simulation of GA show reasonable content of mix components below 5.0% of relative errors.

(2) For durability design of RC structures under chloride attack, several design parameters like cover depth, exterior conditions and intended diffusion coefficients are assumed and optimum mix proportions are derived. Among the 10 averaged mix proportions for one target diffusion coefficient, compressive strength and their costs are evaluated through NN technique, through which optimum mix proportions with satisfying service life, required strength and least cost are selected. The selected mix proportions show 2.3% of cost saving for *M*1 mixture and 3.0% for *M*2 mixture.

(3) This technique would be improved through obtaining more comprehensive data-sets and related diffusion coefficients containing various replacement ratio and fineness of mineral admixtures.

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