GENETIC-ALGORITHM-BASED MIX PROPORTION DESIGN METHOD FOR RECYCLED AGGREGATE CONCRETE

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ABSTRACT

Several desirable characteristics of concrete, such as strength, slump, durability and low CO_2 emission, cannot always be obtained by current conventional mix proportion design methods for recycled aggregate concrete (RAC), because Recycled aggregate generally has lower quality than natural aggregate owing to residual cement paste and various impurities. We treat optimal concrete mix proportioning as a multi-criteria problem, and suggest a new method based on genetic algorithms (GAs) to solve the mix proportion design problem for RAC through a simulated biological evolutionary process. In this method, several fitness functions for the desired properties of concrete, i.e., slump, strength, carbonation speed coefficient, price, and emission of CO_2, were considered based on conventional data or adopted from previous studies. We thus arrived at optimal mix proportions for RAC that meet the desired performance criteria.

Keywords: recycled aggregate concrete; mix proportion design; genetic algorithm.

ALGORITHME GÉNÉTIQUE BASÉ SUR LA MÉTHODE DE DOSAGE PROPORTIONEL POUR LE MÉLANGE DE GRANULATS DE BÉTON RECYCLÉ

RÉSUMÉ

Plusieurs caractéristiques souhaitables du béton, telles que la résistance, la consistance, la durabilité et une émission de CO_2, réduite, ne peuvent pas toujours être obtenues par la méthode conventionnelle actuelle de dosage proportionnel pour les granulats de béton recyclé (GBR). La cause étant que la qualité des granulats de béton recyclés est inférieure, par rapport aux granulats naturels, dû à la pâte de ciment résiduel et à différentes impuretés. Nous étudions le dosage optimal du mélange de béton comme un problème à multiples critères, et suggérons une nouvelle méthode basée sur les algorithmes génétiques (AG) pour résoudre le problème du dosage proportionnel du mélange pour les GBR, à travers un procédé biologique évolutif simulé. Dans cette méthode, plusieurs fonctions adaptées pour les propriétés souhaitées du béton, c'est-à-dire la consistance, la résistance, le coefficient de gazéification carbonique, le coût, et l'émission de CO_2, ont été considérées en se basant sur des données conventionnelles ou des données adoptées d'études précédentes. Ainsi, nous obtenons les dosages proportionnels optimaux pour les GBR, qui satisfont le critère de performance souhaité.

Mots-clés : granulats de béton recyclé ; dosage proportionnel ; algorithme génétique.

NOMENCLATURE

W_{slump}	slump (cm)
$D(t,t_0)$	dry shrinkage strain when curing age is (t_0) ($\times 10^{-6}$)
W	unit water content (kg/m^3)
C	cement content per unit volume of concrete (kg/m^3)
G	weight of coarse aggregate per unit volume of concrete (kg/m^3)
W_{Ra}	weight of recycled aggregate (kg)
h	relative humidity (%) ($40\% \leq h \leq 100\%$)
V/S	ratio of volume to exposed surface area (mm) (V/S $\leq$ 300 mm)
C_c	cost of cement (Yen/t)
C_{ca}	cost of coarse aggregate (Yen/t)
C_{fa}	cost of fine aggregate (Yen/t)
C_{Ad}	cost of admixture (Yen/t)
C_{ad}	cost of chemical agent (Yen/t)
$C_{\text{CO}_2-\text{C}}$	carbon dioxide (CO_2) emissions for producing cement (kg/t)
$C_{\text{CO}_2-\text{CA}}$	carbon dioxide (CO_2) emissions for producing coarse aggregate (kg/t)
$C_{\text{CO}_2-\text{FA}}$	carbon dioxide (CO_2) emissions for producing fine aggregate (kg/t)
$C_{\text{CO}_2-\text{Ad}}$	carbon dioxide (CO_2) emissions for producing admixture (kg/t)
$C_{\text{CO}_2-\text{ad}}$	carbon dioxide (CO_2) emissions for producing chemical agent (kg/t)
$f(x),x$	fitness value and fitness function
u	parameter representing the desired performance
T	parameter that determines fitness function
W/B	water to binder ratio
τ_p	yield value of cement paste
Γ	relative thickness of excess paste
τ_c	yield value of fresh concrete
a,b,K	material parameters
W_{RA}	surface water content per unit weight
B/W	binder to water ratio
c,d,e	material constants
E_c	modulus of elasticity of concrete
E_m	modulus of elasticity of mortar
E_p	modulus of elasticity of paste
V_{ca}	volume of coarse aggregate
V_{fa}	volume of fine aggregate
$D_{\text{CO}_2,\text{t}}$	carbonation depth (D_{CO_2}) and time
R_1	factors of cement affecting carbonation depth
R_2	factors of admixture affecting carbonation depth
R_3	factors of chemical agent affecting carbonation depth
R_4	impact factors of aggregate types

1. INTRODUCTION

The recycling of demolished construction waste, such as recycled aggregate (RA), has gained importance in recent years because the RA obtained from concrete waste can be reused as a construction material, called recycled aggregate concrete (RAC), instead of being utilized as roadbed gravel and backfilling material. However, the desirable characteristics of concrete, such as strength, workability, and durability, cannot always be attained by the current general mixture design methods for RAC, because RA generally has poorer quality than natural aggregate as a result of the residual cement paste attached to it. In addition, it is difficult to ensure a consistent quality of RA, because it is produced by various methods. To attain characteristics that cannot be attained using conventional concrete or by the current mix proportion method,

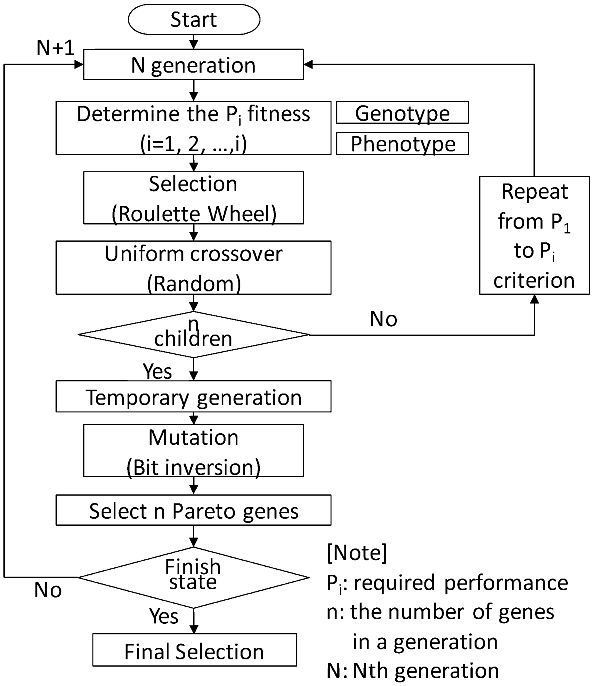

Fig. 1. GA procedure.

a large number of trial mixes are required [1, 2]. The optimization of the concrete mix proportion to attain the desired performance characteristics can be framed as a multi-criteria problem [3–6]. In this study, we use genetic algorithms (GAs), which are typically used for combination problems, to solve this multi-criteria problem.

2. GA-BASED DESIGN

2.1. GA Procedure

GAs are widely used in various engineering fields. They are based on natural selection and natural genetics [7]. The general form of GA uses three major genetic operators: selection, crossover, and mutation. The evolutionary calculation associated with GA is illustrated in Fig. 1. In applying GA to a mix proportion design, the genotype represents the components and mixture proportions, whereas the phenotype represents the properties and performance characteristics of the resulting RAC. Figure 2 shows the schematic of a GA applied to RAC proportioning.

The GA process involves the generation of random population of n chromosomes representing solutions to the mix proportion problem for concrete, as discussed in [8]. We evaluate the fitness (P_i) of each chromosome x in the population by repeating the process of selection, crossover, and mutation. Mutation of genes is carried out by reversing arbitrary loci with a constant probability of 5%. We select individual Pareto-optimal genes from the mutated generation and then create the next generation, which consists of N individuals. When the fitness criterion is satisfied, the repeating process is terminated and the optimal solution is reached. The mix proportion for RAC can be solved as a multi-objective problem (MOP) [9–13]. The purpose of a multi-objective optimization is to simultaneously optimize multiple conflicting objectives such as various desirable characteristics. To compare the different solutions in an MOP and determine the superiority of a solution, Pareto optimality is usually used, as shown in [5–6]. Therefore, the proportioning problem for RAC can be applied to the MOP. The concept of Pareto optimality is illustrated in Fig. 3.

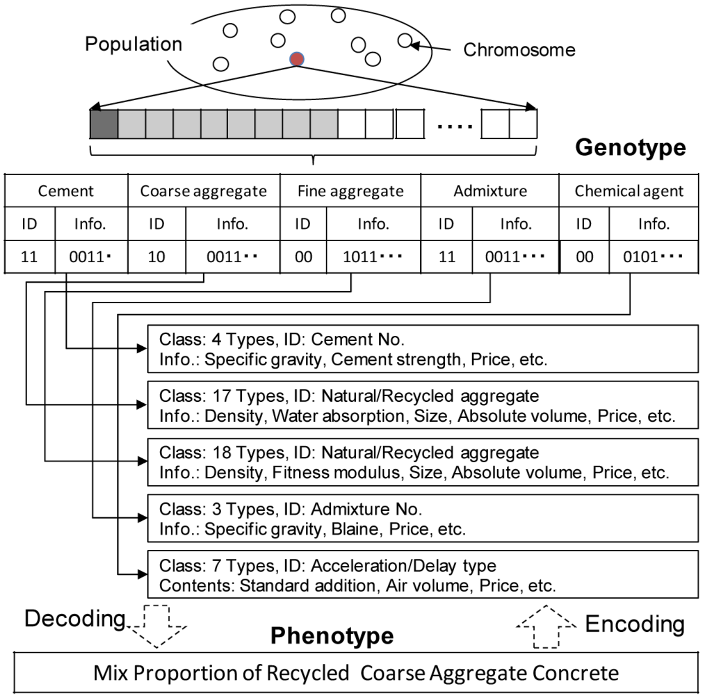

Fig. 2. Schematic coding in GA.

To apply the GA to the MOP, it is assumed that there are P criteria and N individuals, as shown in Fig. 1. The genotypes consist of two parts: a coded binary string and a database containing components such as cement, aggregate, and admixture. The algorithm derives a phenotype from each genotype and calculates a fitness value for the phenotype, as seen in Figs. 1 and 2. The fitness of each phenotype is calculated, and used to determine the individuals' ability to reproduce and pass their genotype to the next generation, much like natural selection. Thus, when the fitness is satisfied, the individuals approach the optimal solution. The following parameters express the allowable range of performance requirements as shown in [6, 11, 14]:

$$f_1(x) = \frac{1.0}{1.0 + e^{-(x-u_1)^n/T_1}}, \tag{1}$$

$$f_2(x) = \frac{2.0}{1.0 + e^{-(x-u_2)^{2n}/T_2}}. \tag{2}$$

The method described above is characterized by an evolving population having evaluated genes and Pareto conditions. We should note, however, that a Pareto-optimal set is a set of noninferior points. This definition implies that the evolving population has individuals that have an outstanding performance according to a certain performance criterion. The Pareto set conditions do not provide a single exact solution but help to search for an optimal set. Because some undesirable elements still remain, we have to select individuals that satisfy the desired performance criteria from among the final population returned by the GA [14, 15].

2.2. Set of Fitness Functions

The slump of RAC can be determined by the relation between the relative thickness of excess paste and the rheological parameters of fresh concrete as given by Eqs. (3) and (4) and proved in [11, 15].

$$W_{\text{slump}} = a \times \text{Log}(\tau_c) \times \frac{1}{1 + W/B} + b, \tag{3}$$

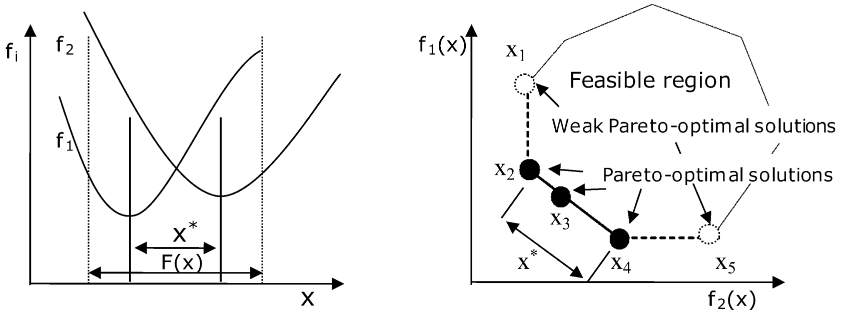

Fig. 3. Concept of Pareto-optimal solution.

$$\tau_c = \tau_p \times (1 + 0.075 \cdot \Gamma^{-2.22}) \tag{4}$$

The dry shrinkage strain of RAC can be calculated using Eq. (5), as proposed by AIJ [16].

$$D_{\text{shrinkage}}(t, t_0) = k \cdot t_0^{-0.08} \cdot \left(1 - \left(\frac{h}{100}\right)^3\right) \cdot \left(\frac{(t - t_0)}{0.16 \cdot (V/S)^{1.8} + (t - t_0)}\right)^{1.4(V/S) - 0.18}. \tag{5}$$

$$k = (11 \cdot W - 1.0 \cdot C - 0.82 \cdot G + 404) \cdot \gamma_1 \cdot \gamma_2 \cdot \gamma_3. \tag{6}$$

The factors affecting compressive strength (F_c) are mortar strength (F_m) and the impact factors of coarse aggregates (R_{CA}), fine aggregate (R_{FA}), admixture (R_{ad}), and air content (R_{air}). In this study, we formulate the basic fitness function of compressive strength as shown in Eq. (7) below and as proved in [15, 17, 18].

$$F_c = F_m \times R_{\text{CA}} \times R_{\text{FA}} \times R_{\text{ad}} \times R_{\text{air}}. \tag{7}$$

The mortar strength (F_m) can be calculated using Eq. (8) [17, 18].

$$F_m = (a(B/W) + b) \cdot K. \tag{8}$$

The impact factor of coarse aggregate is given by Eq. (9) [14, 15].

$$R_{\text{CA}} = \left(1 - \left(c\left(\frac{1}{W/B + 1}\right) \cdot \frac{V}{1000}\right)\right) \times (1 - (d \cdot B/W + e) \cdot (\log C - \log A). \tag{9}$$

The impact factor of fine aggregate (R_{FA}) is given by Eq. (7) [15]. k_1 is the material parameter of fine aggregate, which is taken to be 1.0 for silicate aggregate and 0.89 for other aggregates.

$$R_{\text{FA}} = k_1 \tag{10}$$

The impact factors (R_{FA}) are considered in Eq. (11).

$$\left.\begin{matrix} R_{\text{CA}} \\ R_{\text{FA}} \end{matrix}\right\} = -0.0242 \times W_{\text{RA}} + 1. \tag{11}$$

To estimate the modulus of elasticity of concrete, this study used Hashin's [20] model, which relates the modulus of elasticity of concrete to the elastic modulus of composite models of the two phases (mortar matrix and aggregates) [19–21] as shown in Eq. (12).

$$E_c = \left[\frac{(1 - V_{\text{ca}})E_m + (1 + V_{\text{ca}})E_{\text{ca}}}{(1 + V_{\text{ca}})E_m + (1 - V_{\text{ca}})E_{\text{ca}}}\right] E_m. \tag{12}$$

Table 1. Standard of recycled coarse aggregate in Japan.

Classification	Recycled coarse aggregate		
	Class H	Class M	Class L
Oven-dried density (t/m^3)	More than 2.5	More than 2.3	–
Absorption ratio (%)	Less than 3.0	Less than 5.0	Less than 7.0
JIS No.	A5021	A5022	A5023

Table 2. Set of case studies.

	Class of RCA (Table 1)	Use of RAC	Desired performances for RAC
Case A	Class H	Structural concrete	Workability, strength, durability, cost
Case B	Class M Class L	Concrete block cast-in-place concrete pile, under-bed concrete	Workability, strength, durability, cost, low CO_2

The factors affecting the carbonation depth (D_{CO_2}) are the cement (R_1), admixture (R_2), chemical agent (R_3), and aggregate type (R_4). The estimated carbonation speed coefficient can be calculated using Eq. (13) [22, 23].

$$D_{CO_2} = 0.354 \cdot R_1 \cdot R_2 \cdot R_3 \cdot R_4 \cdot \sqrt{t} \tag{13}$$

The cost (E_{cost}) and CO_2 emission (E_{CO_2}) functions are calculated using Eqs. (14) and (**??**), respectively. The expressions are combinations of parameters for producing 1 m^3 of concrete with an RAC mix proportion as shown in [24, 25].

$$E_{\mathrm{cos}t} = C_c \times W_c + C_{\mathrm{ca}} \times W_{\mathrm{ca}} + C_{\mathrm{fa}} \times W_{\mathrm{fa}} + C_{\mathrm{Ad}} \times W_{\mathrm{Ad}} + C_{\mathrm{ad}} \times W_{\mathrm{ad}} \tag{14}$$

$$E_{CO_2} = C_{CO_2\_C} \times W_c + C_{CO_2\_CA} \times W_{\mathrm{ca}} + C_{CO_2\_FA} \times W_{\mathrm{fa}} + C_{CO_2\_Ad} \times W_{\mathrm{Ad}} + C_{CO_2\_ad} \times W_{\mathrm{ad}}. \tag{15}$$

3. CASE STUDIES AND RESULTS

3.1. Set of Case Studies

The quality of RCA used in this study corresponds to the Japanese Industrial Standards (JIS) as shown in Table 1. We consider various uses of RAC and their corresponding requirements, as presented in Table 2 [26–28]. We consider two cases as listed in Table 3.

Table 3. Desired properties and performances.

Property or performance	Unit	Case A	Case B
Slump	cm	15	15
Setting time	hour	8	8
Dry shrinkage strain	μ	500	500
Specific gravity	t/m^3	2.3	2.2
Strength	MPa	36	24
Modulus of elasticity	GPa	24	21
Carbonation speed coefficient	cm/$\sqrt{\ }$Year	0.27	0.27
Cost*	Yen/m^3	13000	10000
CO_2 emission	kg/m^3	330	250

* is assumed for ready-mixed concrete in Japan.

Table 4. Selected optimal mix proportions (Case A).

Mix No.	W/B	Unit weight (kg/m^3) Water	Cement	Sand	Aggregate	Additive	Admixture (%/C) 1	2
1	0.59	191.0	319(OC)	659(M)	1047(M)	3.13	–	0.2
2	0.59	170.6	289(OC)	713	1065(M)	–	0.4	–
3	0.49	154.4	263(EC)	1040	795(H)	50.6(SF)	0.1	–
4	0.47	151.6	313(OC)	878	909(M)	7.6(SF)	0.1	0.2
5	0.56	178.6	305(OC)	573	1210(M)	14.8(SF)	0.2	0.2
6	0.59	178.1	302(OC)	845(M)	876(M)	–	–	0.1

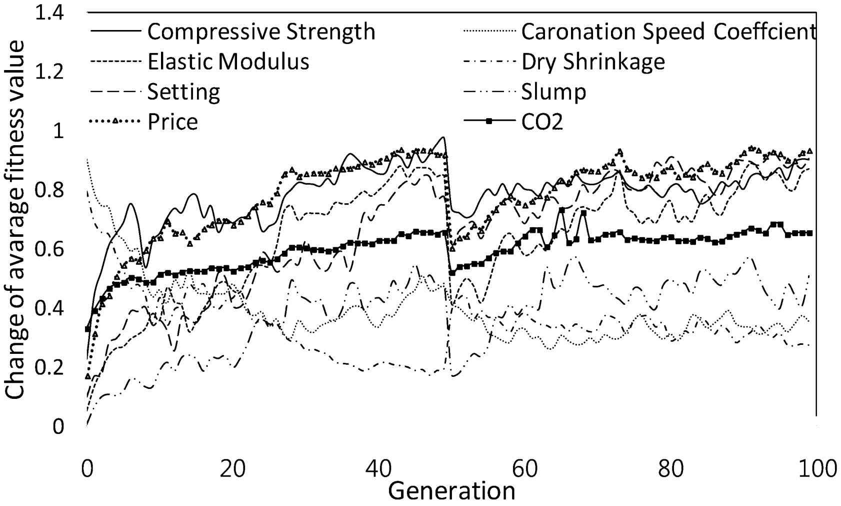

Fig. 4. Change of maximum and average fitness value according to generation.

3.2. Results

As discussed in Section 2, it is necessary to select individuals that satisfy the desired performance criteria from among the GA results. After running the system with 200 individuals over 100 generations, we select individuals that best meet the criteria presented in Table 3. The changes in the average fitness value over 100 generations are presented in Fig. 4. The candidate proportions for Case A and Case B are listed in Tables 4 and 5, respectively. The ratios of the expected to the desired properties for these candidate proportions are shown in Figs. 5 and 6.

The average fitness value of case A and case B, which is the average fitness values for target properties including strength, setting time, slump and so on, is shown in Figs. 5 and 6. Increase of the average fitness value indicates that GA derives a better mix proportion (Pareto optimal set) from generation to generation. Both lowering the water to binder ratio and using additive have retarding effect for drying shrinkage and carbonation speed of concrete.

4. CONCLUSIONS

In this study, a GA-based system using the concept of Pareto optimality was developed to solve the multi-criteria optimization problem for the desired properties of RAC. GA-based system integrating the concept of Pareto optimality in this study was developed for solving the multi-criteria optimization problem in recycled aggregate concrete mix proportioning. A GA-based system can derive the appropriate mix proportions from

Table 5. Selected optimal mix proportions (Case B).

		Unit weight (kg/m^3)						
Mix No.	W/B	Water	Cement	Sand	Aggregate	Additive	Admixture (%/C)	
							1	2
1	0.48	149.1	221(EC)	760	1044(L)	87.8(FA)	–	0.1
2	0.64	191.5	300(MC)	765	985(L)	0	0.1	–
3	0.56	163.1	290(OP)	739	1067(M)	0	1.1	–
4	0.62	171.2	277(EC)	720	1083(M)	0	1.1	0.1

EC, OC, and MC denote early strength cement, ordinary Portland cement, and moderate heat cement, respectively; N is natural aggregate; H, M, and L are RA classes; SF and FA denote silica fume and fly ash, respectively; and admixtures 1 and 2 are air-entrained agent and superplasticizer, respectively.

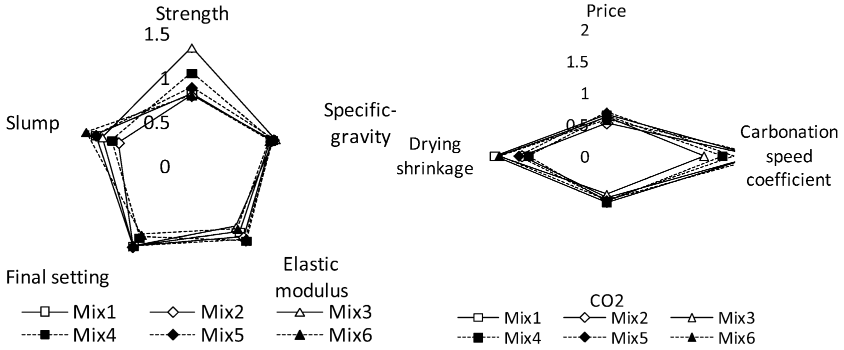

Fig. 5. Ratio of expected and desired properties in Case A.

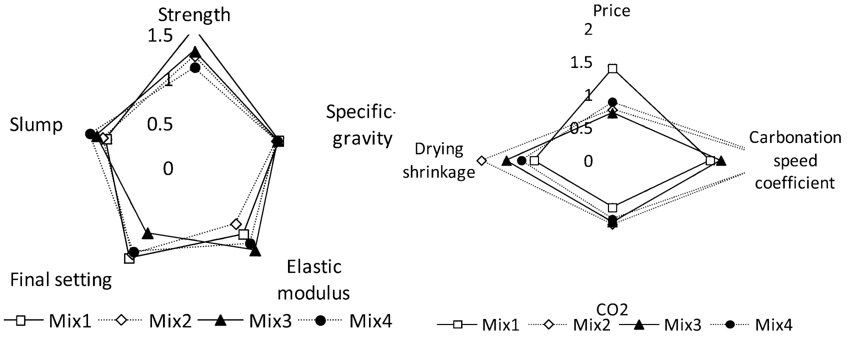

Fig. 6. Ratio of expected and desired properties in Case B.

a variety of mixture proportions and contents. This system requires a suitable fitness evaluation, reasonable reproduction, and accurate prediction formulas. Using GAs, we obtained several optimum mix proportions for RAC that met the desired performance criteria. The utility of a GA-based system in increasing the applicability of RAC was confirmed by studying various uses of RAC. Future work to obtain more reliable mix proportions for RAC could involve improving the prediction formulas to take into account the effect of RA. By precisely modeling the effect of admixtures on RAC performances, GA-based mix proportioning can find more efficient mix proportions.

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