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OPTIMAL DESIGN OF LOW-CARBON CONCRETE CONTAINING FLY ASH AND LIMESTONE POWDER

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Fly ash and limestone powder are common admixtures in environmentally friendly concrete production. This paper proposes an optimal design method for low-carbon concrete containing fly ash and limestone powder. This design method considers the influence of strength (30, 40, and 50 MPa) and carbonization service life (50 and 100 years). The genetic algorithm was utilized to determine the optimal global solution, which satisfies different constraints and can find the decisive factor of the concrete mixture design. The analytical results are as follows: When the carbonization service life is 50 years, for ordinary-strength concrete (30 MPa), carbonation durability is the decisive factor in the mixture design, while for medium- (40 MPa) and high-strength (50 MPa) concrete, strength is the decisive factor. When the carbonation service life is 100 years, for ordinary- (30 MPa) and medium-strength (40 MPa) concrete, carbonation durability is the decisive factor for the mixture design, while for high-strength (50 MPa) concrete, compressive strength is the decisive factor. Furthermore, the CO2 emissions, compressive strength, and water–binder ratio of the optimized concrete design results are in line with the actual project, which proves the effectiveness of the proposed method.

INTRODUCTION

Fly ash and limestone powder are common concrete admixtures. The long-term chemical reaction of fly ash can increase the later strength of concrete and improve the impermeability of concrete and the resistance of chloride penetration [1-3]. The early nucleation effect of limestone powder can improve the early strength of concrete. Moreover, when fly ash and limestone powder are utilized together to produce concrete, a synergistic effect can be achieved as the aluminates in fly ash can chemically react with limestone powder to form carboaluminate, which can improve the concrete's strength and make the pore structures of concrete much finer [4]. In summary, composite concrete containing both fly ash and limestone powder is a new type of concrete and provides a feasible way to develop CO_2 neutrality in the concrete industry.

The mixture design of concrete is among the fundamental problems in concrete engineering. Previous works on the mixture design of concrete containing fly ash or limestone powder are summarized. Yeh [5] produced a cost-efficient composite concrete mixture design with fly ash and slag and considered the desirable slump and compressive strength. Jiao et al. [6] developed an optimal design of the rheological properties of slag–fly ash blended concrete using the simplex centroid design method. Yong et al. [7] devised a mixture design of high-performance concrete using the packing density theory, considering workability, mechanical properties, and durability (such as shrinkage, chloride ingression, and freeze–thaw). Venkatesan et al. [8] used the D-optimal mixture design method to find the optimal fly ash and waste foundry sand content for geopolymer concrete. The 7- and 28-day strengths were set as the targets of optimization. Junaid et al. [9] produced a mix design of fly ash-based alkali-activated concrete, considering strength and workability. Santos et al. [10] assessed the optimal rheology design of cement paste with limestone and metakaolin based on an analysis of variance of yield stress, viscosity, and thixotropy. Jafari et al. [11] developed an optimal design of polymer concrete using Taguchi and ANOVA methods and considered types of strength, such as compressive, flexural, and splitting tensile strength. Liu et al. [12] optimized the rheological properties (static and dynamic yield stress) of 3D printing concrete using an analysis of variance (ANOVA) of the design of the experiment (DOE). Naghizadeh and Ekolu [13] produced a mixture design of fly ash geopolymer mortars, considering specified compressive strength and workability. Attia et al. [14] used a mixture design method to optimize blended concrete, considering compressive strength and flexural strength. Meskini et al. [15] used a statistical mixture design approach to optimize fly ash–

lime–gypsum composite, considering compressive and weight loss durability.

Although many models have been proposed for the mixture design of blended concrete, these models show some limitations. First, most previous models have focused on strength and workability [5, 6] [8-15]. The durability aspect, including the service life of carbonation durability, is seldom considered. The late age reaction of the mineral admixture effectively improves the concrete strength, while the carbonation resistance is impaired due to the utilization of the mineral admixture [16, 17]. Hence, the carbonation service life should be considered for the design of blended concrete. Second, most previous models have assumed that strength is the decisive factor of the concrete mixture design [8-15]. This assumption is valid for concrete of high strength; however, for concrete of ordinary and medium strength, the mixture design may be dominated by durability. In other words, for concrete of high and ordinary strength, the control factor of the mixture design may be different. Moreover, there is a threshold strength that can separate strength control and durability control for the mixture design of composite concrete. Previous models have not successfully found this threshold strength. Third, previous models have mainly focused on traditional composite concrete [5, 6] [8-15], while ternary concrete incorporating fly ash and limestone powder is an emerging material [18, 19]. To achieve carbon neutrality in the concrete industry, ternary composite concrete with fly ash and limestone powder is increasingly used. Therefore, concrete factories have been aiming to find a general method for the mixture design of ternary composite concrete with fly ash and limestone powder.

This paper proposes an optimal design method for low-carbon concrete containing fly ash and limestone powder to overcome the flaws of previous study works. This design method considers the influence of various strength classes (30, 40, and 50 MPa) and carbonization service life durations (50 and 100 years). The genetic algorithm was utilized to determine the optimal solution that satisfies different constraints. The proposed method can determine the decisive factor of the concrete mixture design, such as strength control and durability control, and determine the threshold strength of the concrete which differentiates strength control from durability control. Moreover, the CO_2 emissions, compressive strength, and water–binder ratio of the optimized concrete design results are in line with the actual project, proving the proposed method's effectiveness.

EXPERIMENTAL

Optimization Design

Aim of the Design

The objective of our optimal design is to reduce the embodied CO_2 in concrete. The embodied CO_2 can be established as follows:

$$C_F = \sum_{i=1}^{i=7} \left(M_i \times CO_{2i} \right) \quad (1)$$

where C_F is the embodied CO_2 in concrete, CO_{2i} is the embodied CO_2 from a unit mass of a component of concrete (shown in Table 1) [20], and M_i is the individual mass of a concrete component. The components of sustainable concrete include water, cement, fly ash, limestone powder, coarse aggregate, sand (fine aggregate), and superplasticizer.

Constraints of the Low-Carbon Concrete Optimal Design

The constraints of the optimal design concern the component contents of concrete; the component ratios in concrete; the absolute volume of concrete; and the strength, slump, and durability of carbonation. The details of the various constraints are summarized below.

(1) Component content constraint

The constraint of the components' contents concerns the necessary lower and upper limits of the values for the elements of concrete. This constraint can be written as follows:

$$\text{lower limit} \leq \text{component} \leq \text{upper limit}. \quad (2)$$

The upper and lower boundaries of concrete components' contents are shown in Table 2 [5, 21].

Table 2. Upper and lower limits of the contents of concrete components (kg·m^{-3}).

	Lower limit	Upper limit
Water	120	250
Cement	50	540
Fly ash	0	300
Limestone powder	0	300
Coarse aggregate	600	1100
Fine aggregate	600	1000

Table 1. Embodied CO_2 and density of the components of concrete [20].

	Water	Fly ash	Cement	Limestone powder	Coarse aggregate	Fine aggregate	Superplasticizer
Embodied CO_2 (kg·kg^{-1})	0.000196	0.04	0.86	0.008	0.0075	0.0026	0.25
Density (kg·m^{-3})	1000	2200	3150	2700	2540	2600	1200

(2) Component ratio constraint

The constraint of the component ratios concerns the necessary lower and upper limits of the ratios of elements in the concrete. These include the fly ash–binder, limestone powder–binder, water–binder, sand–aggregate, water–solid, and aggregate–binder ratios. This constraint can be written as follows:

$$\text{lower limit} \leq \text{component ratio} \leq \text{upper limit}. \quad (3)$$

The upper and lower limits of the component ratios are shown in Table 3 [5, 21].

Table 3. Lower and upper limits of the component ratios.

	Lower limit	Upper limit
Water–binder ratio	0.20	0.75
Fly ash–binder ratio	0	0.25
Limestone–binder ratio	0	0.25
Sand–aggregate ratio	0.40	0.52
Aggregate–binder ratio	2.0	6.4
Water–solid ratio	0.08	0.12

(3) Absolute volume constraint

The constraint of the absolute amount of concrete is that the volumetric sum of elements in the concrete must be equal to 1 m^3. This constraint can be written as follows:

$$\sum_{i=1}^{i=7}\left(\frac{M_i}{\rho_i}\right)=1-V_{air} \quad (4)$$

where V_{air} denotes the volume of entrapped air, and ρ is the density of the components of the concrete.

(4) Strength constraint

The constraint of strength is that the real strength must be greater than the necessary strength. This constraint can be written as follows:

$$\text{real strength} \geq \text{required strength}. \quad (5)$$

The 28-day strength of sustainable concrete with fly ash and limestone powder can be determined using Abram's law, as follows [5, 21]:

$$f_c=\frac{15.727}{\left(\dfrac{W}{C+0.435FA+0.265LS}\right)^{1.194}} \quad (6)$$

where W denotes the mass of water, and C, FA, and LS denote the cement mass, fly ash mass, and limestone powder mass in the concrete mixture, respectively. The unit of strength in Equation 6 is MPa.

(5) Slump constraint

The constraint of the slump means that the actual slump must be greater than the necessary slump. This constraint can be written as follows:

$$\text{real slump} \geq \text{required slump}. \quad (7)$$

The slump of sustainable concrete with fly ash and limestone powder can be established by the following [5, 21, 22]:

$$slump=0.088\times W-250.9\times\frac{W}{C+FA+LS}-146.2\times\frac{S}{S+G}+36.8\times\frac{FA}{C+FA+LS}+0.199\times SP+341 \quad (8)$$

where S and G denote the mass of fine aggregate and mass of coarse aggregate, respectively; SP is the mass of superplasticizer in the mixture; $\frac{W}{C+FA+LS}$ and $\frac{FA}{C+FA+LS}$ are the water–binder and fly ash–binder ratios, respectively; and $\frac{S}{S+G}$ is the sand ratio of the concrete. The unit of slump is mm.

The mass of the superplasticizer can be determined as follows [5, 21]:

$$SP=9.198-7.74\times\frac{W}{C+FA+LS} \quad (9)$$

This equation indicates that with an increase in the water–binder ratio, the mass of the superplasticizer decreases.

(6) Constraint of service life of carbonation

The constraint of carbonation durability dictates that the carbonation depth must be lower than the cover depth. Therefore, the constraint of carbonation durability may be written as follows:

$$\text{carbonation depth} \leq \text{cover depth}. \quad (10)$$

The carbonation depth can be calculated as follows [23, 24]:

$$x_c=\sqrt{\frac{2D[CO_2]_0 t}{0.218\times(C+0.5\times FA+0.6\times LS)\times\alpha_H}} \quad (11)$$

$$D=6.1\times10^{-6}\left(\frac{[W-0.267\times(C+0.5\times FA+0.6\times LS)\times\alpha_H]/1000}{\dfrac{C+0.5\times FA+0.6\times LS}{\rho_c}+\dfrac{W}{\rho_w}}\right)^3\left(1-\frac{RH}{100}\right)^{2.2}\exp\left[\beta\left(\frac{1}{T_{ref}}-\frac{1}{T}\right)\right] \quad (12)$$

where x_c is the concrete carbonation depth; D is the diffusivity of CO_2, which is a function of concrete material and environmental conditions (shown in Equation 12); $[CO_2]_0$ is the concentration of CO_2; t is time; α_H is the degree of hydration, which can be determined as $\alpha_H=1-\exp(-3.38\frac{W}{C+0.5\times FA+0.6\times LS})$ [25]; RH denotes the relative humidity; β is the temperature sensitivity factor of CO_2 diffusion (β = 4300) [25]; T_{ref} is a reference temperature (T_{ref} = 293 K); and T is the temperature of the exposure environment. In Equation 12, the item

$$\left(\frac{[W-0.267\times(C+0.5\times FA+0.6\times LS)\times\alpha_H]/1000}{\dfrac{C+0.5\times FA+0.6\times LS}{\rho_c}+\dfrac{W}{\rho_w}}\right)^3$$

denotes the concrete material [23], and the items $(1-RH/100)^{22}$ and $\exp[\beta(1/T_{ref} - 1/T)]$ denote environmental relative humidity and environmental temperature, respectively [23].

Algorithm of optimal design

When the desired function and constraints are confirmed, the optimal mixtures of sustainable concrete can be discovered using the genetic algorithm. The genetic algorithm is an optimization search method based on natural selection and genetic principles. It simulates the evolution process of organisms and the operation of genes on a computer. It does not require specific knowledge of the object, nor does the search space of the object need to be continuous and differentiable. Moreover, the genetic algorithm has the ability of global optimization [22]. The main procedures of the genetic algorithm are (1) initialization; (2) selection based on fitness function value; (3) genetic operators, such as crossover and mutation; (4) heuristics, which make the calculation faster; and (5) termination once the terminating conditions are met [22]. The MATLAB program features a toolbox that includes the genetic algorithm. In this study, the genetic algorithm toolbox in MATLAB was used as the optimal mixture design. Figure 1 shows a flowchart of the calculation. The starting point was to confirm the desired function, i.e., the embodied CO_2 in concrete. The second step was to confirm the various constraints, including component content, component ratio, absolute volume, strength, slump, and durability. The final step was the resolution of the optimal mixtures using the genetic algorithm.

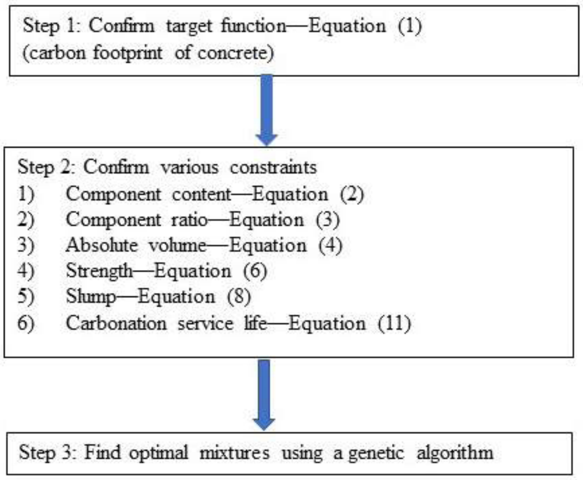


Figure 1. Flowchart of the calculation.

Illustrative examples

This section presents illustrative examples of the optimal mixture design. The concentration of CO_2 was set at 0.04 %, and the temperature of the exposure atmosphere was 20 °C. The required slump was assumed to be 150 mm. The amount of entrapped air in the concrete was placed at 2 %. The service life for sustainable concrete with fly ash and limestone is intended to be 50 or 100 years. According to the design code [26], the required 28-day strength was categorized into three classes at 30 (ordinary strength), 40 (medium strength), and 50 MPa (high strength), and the cover depth of concrete was assumed to be 25 mm. The constraints of the component content and component ratio are shown in Table 2 and Table 3, respectively.

As shown in Table 4, three design cases were considered. Case 1 included mixture designs without considering carbonation durability (the 28-day strengths of Mix 1, Mix 2, and Mix 3 were 30, 40, and 50 MPa, respectively). Case 2 included mixture designs with a carbonation service life of 50 years (the 28-day strengths of Mix 4, Mix 5, and Mix 6 were 30, 40, and 50 MPa, respectively). Case 3 included mixture designs with a carbonation service life of 100 years (the 28-day strengths of Mix 7, Mix 8, and Mix 9 were 30, 40, and 50 MPa, respectively). Here, using the comparison between Mix 1 and Mix 3, the effect of strength on mixture design can be determined. Using the comparison between Case 1 and Case 2, the effect of a 50-year carbonation service life on mixture design can be determined. Using the comparison between Case 1 and Case 3, the effect of a 100-year carbonation service life on mixture design can be determined.

Case 1: Mixture designs without considering carbonation durability

The mixture design without considering carbonation is described in this section. Based on the flowchart shown in Figure 1, the optimal mixtures of Mix 1, Mix 2,

Table 4. Summary of the illustrative examples.

Cases	Constraints	Mixtures	Design strength (MPa)	Comparisons	Clarification points
Case 1	No carbonation	Mix 1 Mix 2 Mix 3	30 40 50	Between Mix 1, Mix 2, and Mix 3	Effect of strength on mixture design
Case 2	50-year carbonation service life	Mix 4 Mix 5 Mix 6	30 40 50	Between Case 1 and Case 2	Effect of 50-year carbonation service life on mixture design
Case 3	100-year carbonation service life	Mix 7 Mix 8 Mix 9	30 40 50	Between Case 1 and Case 3	Effect of 100-year carbonation service life on mixture design

Table 5. Optimal mixtures ($kg \cdot m^{-3}$).

Cases	Mixtures	Water	Cement	Fly ash	Limestone powder	Fine aggregate	Coarse aggregate	Superplasticizer
Case 1	Mix 1	168.05	213.80	106.90	106.90	869.97	803.05	6.16
	Mix 2	168.44	272.68	136.34	136.34	811.27	748.86	6.81
	Mix 3	168.85	329.51	164.75	164.75	754.82	696.75	7.22
Case 2	Mix 4	168.13	226.58	113.29	113.29	857.20	791.26	6.33
	Mix 5	168.44	272.68	136.34	136.34	811.27	748.86	6.81
	Mix 6	168.85	329.51	164.75	164.75	754.82	696.75	7.22
Case 3	Mix 7	168.49	279.41	139.71	139.71	804.57	742.68	6.87
	Mix 8	168.49	279.41	139.71	139.71	804.57	742.68	6.87
	Mix 9	168.85	329.51	164.75	164.75	754.82	696.75	7.22

and Mix 3 were determined (shown in Table 5). The performances of Mix 1, Mix 2, and Mix 3 at 50 years in terms of embodied CO_2, 28-day strength, slump, and carbonation depth were calculated using Equation 1, Equation 6, Equation 8, and Equation 11, respectively. Mix 1, Mix 2, and Mix 3 were set without carbonation consideration. The aim of calculating the carbonation depth of Mix 1, Mix 2, and Mix 3 was to check whether the constraint of carbonation should be considered or not. Generally, after a 50-year service life, if the carbonation depth is lower than the cover depth, the constraint of carbonation is not necessary to consider because the durability of carbonation can be satisfied. However, if the carbonation depth is greater than the cover depth, the constraint of carbonation should be considered because the durability of carbonation cannot be satisfied.

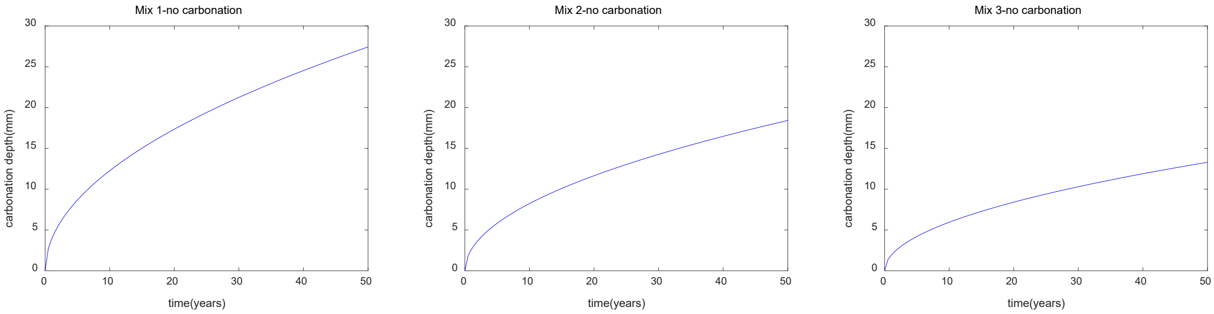
Table 5 shows that the water contents of Mix 1, Mix 2, and Mix 3 were similar. This is due to the fact that the water–solid ratio was equal to the lower limit of constraints for all three mixes. Moreover, Table 6 shows that the fly ash–binder and limestone–binder ratios for these three mixes were equal to the upper limit of constraints. This is due to the fact that the fly ash and limestone presented much lower CO_2 emissions than cement. When the target of the optimal design is low CO_2 emissions, the contents of fly ash and limestone will be at the maximum. In addition, Figure 2a shows that after a service life of 50 years, the carbonation depth of Mix 1 was higher than the cover depth. Cover depth is the cover thickness for the reinforcement of a steel rebar. Regarding durability design, the cover depth of concrete is required to protect reinforcements against corrosion in aggressive environments. Hence, Mix 1 could not satisfy the requirement of carbonation durability. On the other hand, Mix 2 and Mix 3 could satisfy the requirement of carbonation durability as shown in Figure 2b,c, as the carbonation depth of Mix 2 and Mix 3 after a service life of 50 years was lower than the concrete cover depth. This is due to the fact that Mix 2 and Mix 3 contained much higher binder contents than Mix 1, and the carbonation resistance of Mix 2 and Mix 3 was stronger than that of Mix 1.

Case 2: design of mixture considering 50-year carbonation service life

Section "Case 1" does not consider carbonation durability. The results of Section "case 1" show that for ordinary-strength concrete (30 MPa), after a service

Table 6. Performance of optimal mixtures.

Cases	Mixtures	Strength (MPa)	Slump (mm)	Embodied CO_2 ($kg \cdot m^{-3}$)	Carbonation depth (mm)	Water–binder ratio	Limestone–binder ratio	Fly ash–binder ratio
Case 1	Mix 1	30.00	191.58	198.86	27.43	0.39	0.25	0.25
	Mix 2	40.00	212.86	250.51	18.42	0.31	0.25	0.25
	Mix 3	50.00	226.19	300.31	13.30	0.26	0.25	0.25
Case 2	Mix 4	32.14	197.14	210.08	25.00	0.37	0.25	0.25
	Mix 5	40.00	212.86	250.51	18.42	0.31	0.25	0.25
	Mix 6	50.00	226.19	300.31	13.30	0.26	0.25	0.25
Case 3	Mix 7	41.17	214.72	256.41	25.00	0.30	0.25	0.25
	Mix 8	41.17	214.72	256.41	25.00	0.30	0.25	0.25
	Mix 9	50.00	226.19	300.31	18.81	0.26	0.25	0.25



a) Carbonation depth of Mix 1. b) Carbonation depth of Mix 2. c) Carbonation depth of Mix 3.

Figure 2. Carbonation depth versus time of mixtures of Case 1 (Mix 1, Mix 2, and Mix 3).

life of 50 years, the carbonation depth is higher than the cover depth. Hence, this section added carbonation service life as a constraint of the mixture design and considers carbonation durability. The durability service life was assumed as 50 years.

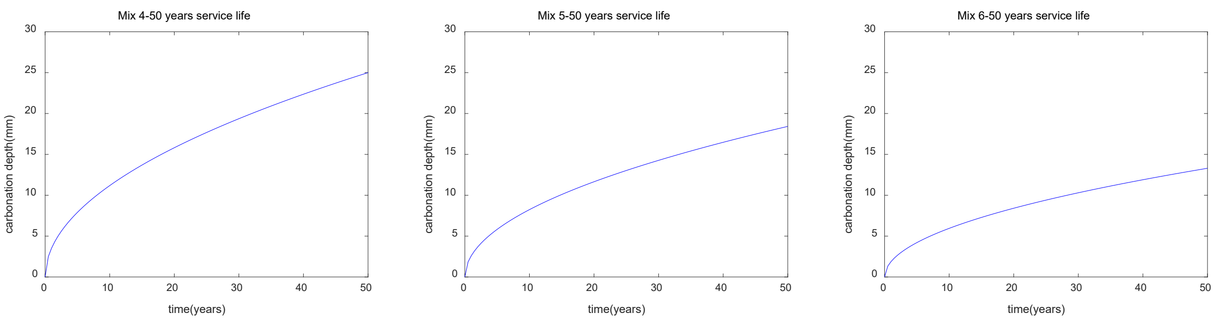
The optimal mixtures of Case 2 are shown in Table 5. Table 6 shows the performance of the optimal mixtures. For Mix 4, the real strength was 32.14 MPa, which was higher than the design strength of 30 MPa. Figure 3a shows that after a service life of 50 years, the carbonation depth of Mix 4 was equal to the cover depth (25 mm). In other words, for the concrete of ordinary strength (30 MPa), carbonation durability was the decisive factor of the mixture design. Moreover, for Mix 5 and Mix 6, the real strength was the same as the design strength. Figure 3b,c show that after a service life of 50 years, the carbonation depths of Mix 5 and Mix 6 were lower than the cover depth (25 mm). Hence, for the concrete of medium (40 MPa) and high strength (50 MPa), strength was the decisive factor of the mixture design. In summary, when the service life is 50 years, 32.14 MPa is the threshold strength of the mixture design. When the design strength is lower than this threshold strength, the durability of carbonation dominates the mixture design. In contrast, when the design strength is higher than the threshold strength, strength dominates the mixture design.

The differences between Figure 2 and Figure 3 are summarized as follows. Figure 2a is different from Figure 3a as the strengths of Figure 2a and Figure 3a are 30 and 32.14 MPa, respectively. After a service life of 50 years, the carbonation depth in Figure 2a is 27.43 mm, while the carbonation depth in Figure 3a is 25.00 mm. This is because the mixture of Figure 2a does not consider carbonation durability while the mixture of Figure 3a does. Additionally, Figure 2b,c are the same as Figure 3b,c, respectively. The strengths in Figure 2b, c are 40 and 50 MPa, respectively, which are higher than the strength in Figure 2a (30 MPa). After a service life of 50 years, the carbonation depths of the 40 and 50 MPa concrete were lower than the cover depth of 25 mm, and the durability of carbonation could be satisfied. Hence, after considering the constraint of the durability of carbonation, the mixtures of Figure 2b,c do not change.

Case 3: design of mixture considering 100-year carbonation service life

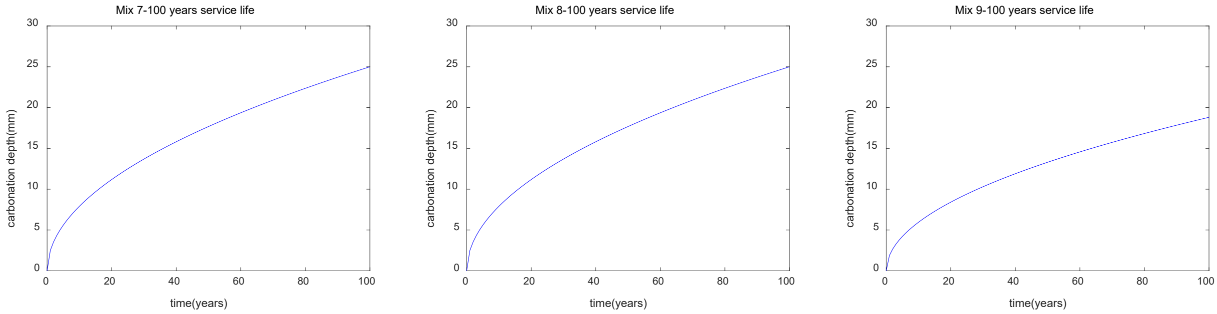
Section 3.2 shows a mixture design of concrete with a service life of 50 years. However, for some important infrastructures, the service life may be much longer, e.g., 100 years. Hence, this section considers a mixture design for concrete with a service life of 100 years, while the other items are the same as the previous section. The methodology serves to design concrete with a 100-year carbonation service life separately from that with a 50-year carbonation service life.

Table 5 shows the optimal mixtures of Case 3. Table 6 shows the performance of the optimal mixtures of Case 3. For Mix 7 and Mix 8, the design strengths were 30 and 40 MPa, respectively, while the real strengths of Mix 7



a) Carbonation depth of Mix 4. b) Carbonation depth of Mix 5. c) Carbonation depth of Mix 6.

Figure 3. Carbonation depth versus time of mixtures of Case 2 (Mix 4, Mix 5, and Mix 6).



a) Carbonation depth of Mix 7.   b) Carbonation depth of Mix 8.   c) Carbonation depth of Mix 9.

Figure 4. Carbonation depth versus time of mixtures of Case 3 (Mix 7, Mix 8, and Mix 9).

and Mix 8 were the same, i.e., 41.17 MPa, which is higher than their design strengths. Figure 4a, b show that after a service life of 100 years, the carbonation depths of Mix 7 and Mix 8 were equal to the cover depth (25 mm). In other words, for the ordinary-strength concrete (30 MPa) and medium-strength concrete (40 MPa), when the carbonation service life was 100 years, durability of carbonation was the decisive factor of the mixture design. Moreover, for Mix 9, the real strength was the same as the design strength. Figure 4c shows that after a service life of 100 years, the carbonation depth of Mix 9 was lower than the cover depth (25 mm). Hence, for the high-strength concrete (50 MPa), strength was the decisive factor of the mixture design. In summary, when the service life is 100 years, the threshold strength of the mixture design is 41.17 MPa. When the design strength is lower than this, carbonation durability dominates the mixture design. In contrast, when the design strength is higher than 41.17 MPa, strength dominates the mixture design.

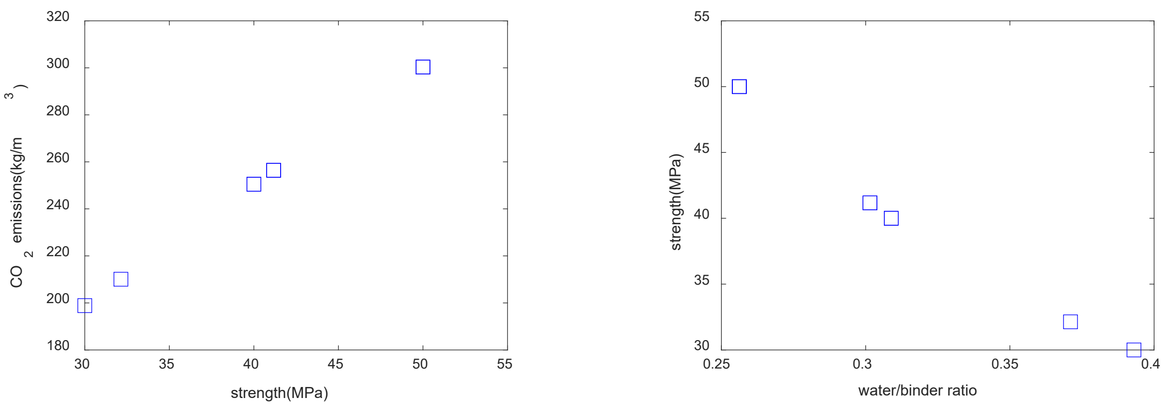
Figure 5a shows that for Mixes 1–9, as the strength of the concrete increased, the embodied CO_2 increased. This is in accordance with the study of Long et al. [27]. In addition, Figure 5b shows that as the water–binder ratio increased, the strength of the concrete decreased. This concurs with Abram’s law [5]. In summary, the CO_2 emissions, compressive strength, and water–binder ratio of the optimized concrete design results are in line with those of the actual project [28], which proves the effectiveness of the proposed method.

DISCUSSION

An optimal design method for sustainable concrete with fly ash and limestone powder was proposed which considers various carbonation service lives. As opposed to previous studies, this study shows some advantages.

(1) Traditional mixture design methods do not consider carbonation durability. Conventional methods assume that when the strength matches the need, the durability criterion will probably be instantly satisfied [5]. However, due to the lower carbonation resistance of fly ash and limestone powder composite concrete of ordinary and medium design strength, this mixture design may be controlled by carbonation, not strength [24]. This study showed a design method that can distinguish the control factors, for instance, carbonation control or strength control. In addition, the optimal mixtures corresponding to various control factors can be acquired using the genetic algorithm.

(2) For several design codes, the specific equations might not be the same as the equations presented in this research, such as the calculation equations of strength, slump, and carbonation depth [19, 21-23, 29-31]. However, the genetic algorithm is a common and universal means which is flexible and can use different equations. Although the specific format and content of the equations may be different, the fundamental concepts and steps of the optimal mixture design might be similar.



a) CO_2 emission versus strength.   b) Strength versus water–binder ratio.

Figure 5. Relations among CO_2 emission, strength, and water–binder ratio.

The proposed method may consider general types of sustainable concrete production based on different design codes.

(3) European Standard EN 206-1 considers the material design of concrete with various types of binders, such as Portland cement (CEM I), silica fume cement (CEM II/A-D), Portland limestone cement (CEM II/A-LL or L), Portland fly ash cement (CEM II/B-V), blast furnace slag cement (CEM III/A-B), and pozzolanic cement (CEM IV/B-V) [32]. In this study, the cementitious material was a ternary composite binder with fly ash, limestone, and cement. The binder used in this study is a new type of cementitious material which is not considered in the European Standard EN 206-1.

(4) This study only shows the qualitative verification of the optimal results. The trends of results, such as the relation between CO_2 emissions and strength and the relation between water-to-binder ratio and strength, show agreement with engineering practices (shown in Figures 5a and 5b). In future studies, more quantitative verifications should be carried out involving other factors, such as the strength, slump, and carbonation depth of optimal mixtures.

CONCLUSIONS

This study showed an integrated mixture design method covering the embodied CO_2 in concrete and the 28-day strength, slump, and durability of carbonation. In addition, the influence of carbonation durability with different service lives on the optimal mixture was clarified.

First, the goal of the optimal design to reduce the embodied CO_2 in concrete was established. We considered the various constraints, such as component content, component ratio, absolute volume, strength, slump, and carbonation durability. The carbonation model considered environmental conditions (i.e., relative humidity and temperature) and material compositions.

Second, the optimal mixtures were acquired using the genetic algorithm, which considered the desired functions along with other constraints. The design strengths of each case included three classes: 30 (ordinary strength), 40 (medium strength), and 50 MPa (high strength). The case study results are summarized in the following.

(1) Case 1 (does not consider carbonation durability): For Mix 1, Mix 2, and Mix 3, the fly ash–binder and limestone–binder ratios were equal to the upper limit of constraints. This is because fly ash and limestone powder presented much lower CO_2 emissions than cement. The water contents of Mix 1, Mix 2, and Mix 3 were similar as the water–solid ratio was equal to the lower limit of constraints.

(2) Case 2 (carbonation service life of 50 years): For Mix 4, the design strength was 30 MPa, while the real strength was 32.14 MPa. After a service life of 50 years, the carbonation depth of Mix 4 was equal to the cover depth (25mm). Meanwhile, for Mix 5 and Mix 6, the real strength was the same as the design strength. In summary, when the design strength was lower than the threshold strength (32.14 MPa), the durability of carbonation dominated the mixture design. In contrast, when the design strength was higher than the threshold strength (32.14 MPa), strength dominated the mixture design.

(3) Case 3 (carbonation service life of 100 years): For Mix 7 and Mix 8, the design strengths were 30 and 40 MPa, respectively, while the real strength was the same, 41.17 MPa. After a service life of 100 years, the carbonation depth of Mix 7 and Mix 8 was equal to the cover depth (25 mm). Moreover, for Mix 9, the real strength was the same as the design strength. In summary, as the service life increased from 50 to 100 years, the threshold strength increased from 32.14 to 41.17 MPa.

(4) The results of Mix 1 to Mix 9 showed that as the strength of concrete increased, the embodied CO_2 increased. With the increase in the water–binder ratio, the strength of the concrete decreased. In summary, the CO_2 emissions, compressive strength, and water–binder ratio of the optimized concrete design results are in line with the actual project, which proves the effectiveness of the proposed method.

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