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Energy Optimization Design of Limestone Hybrid Concrete in Consideration of Stress Levels and Carbonation Resistance

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Abstract: This research describes a genetic algorithm-based process for the optimization design of sustainable concrete with limestone powder. The objective of the optimization design was set as the embodied energy. The restraints of the optimization design consist of strength, workability, and carbonation resistance along with stress. The result of the research is shown as follows: (1) for low-strength concrete, carbonation dominates the mixture design of limestone hybrid concrete. Furthermore, the levels of stress and stress types modify the carbonation and optimization mixtures. The influence of tensile stress on optimization mixtures was much more apparent than compressive stress. (2) For concrete with high strength, strength dominates the mixture design of limestone hybrid concrete. (3) The optimization mixtures with low carbon footprints overlapped with those with low embodied energy. In addition, the new knowledge of the research is shown as follows: (1) find the decisive factor of concrete mixture design, (2) show a material design method considering structural stress, and (3) validate for various aims of optimal material design. In summary, the proposed model can be regarded as a common approach for the design of concrete mixture in consideration of strength, workability, carbonation resistance, and structural stress.

Keywords: embodied energy; carbon footprint; limestone; optimization mixtures design; carbonation resistance

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1. Introduction

Limestone powder is widely utilized to produce concrete. Limestone confers many advantages, such as low hydration heat, good workability, low-cost materials, and low environmental impact [1]. On the other hand, limestone hybrid concrete has several weak points; it presents lower carbonation resistance and late-age compressive strength compared with plain concrete [2,3]. Moreover, when the strength of limestone hybrid concrete is the same as control concrete, limestone hybrid concrete presents a lower resistance of carbonation than control concrete [2,4]. Strength cannot ensure the carbonation resistance of limestone hybrid concrete [2,4]. Summarily, when using limestone in the concrete industry, the negative aspect and positive aspect should be integrally considered.

Concrete mixtures design is a fundamental aspect of concrete manufacturing techniques. Fundamental studies have been conducted regarding mixing design methods.

First, the workability of fresh concrete, the strength of hardened concrete, and possibly low cost or low environmental impact are the main aims of mixture design. Yeh [5] proposed a mixture design procedure based on a simplex-centroid method and neural networks that considered strength and workability. Silva et al. [6] designed self-consolidating concrete that considered the rheology of fresh concrete and the 28-day compressive strength.

Zahiri and Naddaf [7] determined the optimization combination of micro silica fume, nano silica fume, and polymer fibers for different design strength classes. Zaitri et al. [8] designed high-performance concrete containing dune sand and limestone rock that considered slump flow and strength. Gao et al. [9] designed a mixture of concrete containing steel fiber and recycled coarse aggregate in consideration of the target strength and workability. Abouhussien and Hassan [10] designed metakaolin-hybrid self-consolidating concrete using statistical analysis regarding fresh properties and compressive strength under different curing regimes. Meng et al. [11] devised an optimization design for ultra-high performance concrete based on an approach of the factorial design with fresh properties, rheological properties, autogenous shrinkage, and compressive strength. Kim and Tae [12] and Kim et al. [13] evaluated the emissions of the life cycle of CO_2 and proposed a method for optimum design of concrete based on an evolutionary algorithm [14].

Second, besides workability, strength, and cost or environmental impact, some mixture design methods are proposed in consideration of various durability aspects. Nunes et al. [15] developed a statistical factorial design for a self-compacting mortar, taking into account the targeted strength and workability while maximizing the resistivity and minimizing the carbonation depth. Shi et al. [16] designed a high-performance concrete that accounted for workability, strength, and durability aspects such as the drying shrinkage, permeability, alkali-aggregate reaction, and carbonation resistance. Gil et al. [17] designed self-consolidating concrete that took into account slump-flow, segregation resistance, strength, and chloride ingress resistance. Chen et al. [18] replaced fine aggregate using glass sand and designed concrete that considered a strength, elastic modulus, workability, and surface electrical resistance. Sharifi et al. [19] developed an optimization design for high-strength, high-performance concrete based on the Taguchi method, which considered various items, such as slump, strength, cost, and water absorption.

Although much research has been conducted on the mixture styles of concrete materials, these studies have some flaws. First, the majority of the previous studies concentrated on strength, workability, material cost, and durability. However, it ought to be observed that certain aspects of concrete's structure sustain various stresses, for example, compressive or tensile stress. These stresses can impact porosity and cracks in the concrete. In addition, they can affect the performance of durability and the mixture style of concrete. Previous mixture design methods did not consider the aftereffects of sustained stress on the durability and mixtures of concrete. Second, there's a threshold strength for hybrid concrete. If the design strength is less than the threshold strength, the carbonation resistance can be a critical problem. Many researchers and building proprietors are curious about threshold strength. However, previous methods cannot distinguish the dominant factor in mixture design, for example, whether durability or strength is dominant. Furthermore, threshold strength cannot be found according to previous methods. Third, design methods in the previous studies mainly concentrated on cost and CO_2 emissions, and the research on embodied energy was extremely bound. Because embodied energy is a vital index of sustainability, the optimization design, when it comes to embodied energy, is useful for sustainable growth and development in the concrete industry.

To overcome the flaws found in the literature, this work presents a procedure for the optimization design of sustainable limestone hybrid concrete that considers stress types, stress levels, and carbonation. The objective of optimization design is positioned as embodied energy. The different restraints, for example, strength (mechanical property), slump (workability), and carbonation (durability), are considered. The carbonation model considers the effects of stress conditions (i.e., the stress levels and types), surrounding conditions (i.e., environmental relative humidity and environmental temperature), and concrete compositions. The optimization mixtures are found based on a genetic formula that heeds the goal functions along with other restraints. The proposed model can be a common approach for mixture design that considers mechanical property, workability, the durability of carbonation, and sustained stress.

2. Procedure of Optimization Design

2.1. Goal Function of Optimization Design

The goal of the optimization design was set as the embodied energy of hybrid concrete. Embodied energy is the energy associated with the manufacturing of a product or service. The embodied energy C_E can be discovered in the following:

$$C_E = \sum_{i=1}^{i=6}(M_i * E_i) \tag{1}$$

where M_i and E_i are mass and the embodied energy from a concrete constituent with a unit of mass [20,21], respectively (Table 1). The constituents of sustainable concrete consist of water, limestone, cement, coarse aggregate, fine aggregate (sand), and superplasticizer. The cement belonged to Portland cement with a compressive strength grade of 42.5 MPa. The CO_2 emission of cement consists of two components. The primary component is from the calcination of calcium carbonate, and the minor component is from the combustion of fossil fuels. The value of the CO_2 emission of cement in Table 1 is the sum of two components. For different types of binders, such as CEMI (Portland cement) or CEM III (slag cement), the CO_2 emission of a 1 kg binder is different. Slag cement has a lower CO_2 emission than Portland cement. Limestone powder, which originated from grounded quarry waste-limestone chips, was used as filler. The CO_2 emission of limestone powder mainly depends on grind quality. Fine aggregate was river sand with a fineness modulus of 2.86. Mined aggregate shows different embodied energy and CO_2 emissions from crushed aggregate because of the differences from cradle to gate steps of the production process. The coarse aggregate in Table 1 is crushed limestone with a size of 5–20 mm. Tap water was used as the mixing water. Polycarboxylate superplasticizer had a water-reducing rate of 26%. Based on the life cycle assessment approach, the embodied CO_2 emissions and embodied energy consumption are calculated by considering all major emissions or consumptions during the extraction of raw materials, transportation to the site, construction processes, and so on [21].

Table 1. Embodied energy, CO_2 emission, and density of constituent of concrete [21].

	Water	Cement	Limestone	Coarse Aggregate	Sand (Fine Aggregate)	Superplasticizer
Embodied energy (MJ/kg)	0.006	4.727	0.35	0.113	0.022	18.3
CO_2 emission (kg/kg)	0.0003	0.83	0.017	0.007	0.001	0.72
Density (kg/m^3)	1000	3150	2710	2540	2600	1200

2.2. Restraints of Optimization Design

Concrete mixture design subjects to various restraints, such as constituent content and constituent content ratio restraint, absolute volume restraint, and performance (strength, workability, and durability) restraint. The details of these restraints are shown as follows.

(1) Constituent content restraint

The constituent content restraint means the constituent of concrete data should come between the lower bound and upper bound. The restraint of the constituent content might be written as:

$$\text{lower bound} \leq \text{constituent} \leq \text{upper bound} \tag{2}$$

The lower and upper bounds of the constituent restraint content are shown in Table 2. These lower bound and upper bound were selected from references [5,22].

Table 2. Restraint of constituent contents (kg/m^3).

Bounds	Water	Cement	Limestone Powder	Coarse Aggregate	Fine Aggregate
Lower bound	120	50	0	700	600
Upper bound	250	540	300	1100	1000

(2) Restraint of the constituent ratio

The restraint of the constituent ratio means that the ratios among the constituents of concrete should come between the upper bound and lower bound. The constituent ratios consist of the ratios of limestone/binder, aggregate/binder, water/binder, sand/aggregate, and water/solid. The restraint of the constituent ratio might be written as:

$$\text{lower bound} \leq \text{constituent ratio} \leq \text{upper bound} \tag{3}$$

Table 3 shows the lower bound and upper bound of the restraint of the constituent ratios. These lower and upper bounds were selected from references [5,22].

Table 3. Restraint of constituent ratios.

Bounds	Water/Binder	Limestone/Binder	Sand/Aggregate	Aggregate/Binder	Water/Solid
Lower bound	0.25	0	0.40	2.5	0.08
Upper bound	0.75	0.20	0.52	6.4	0.12

(3) Restraint of absolute volume

For concrete, the volumetric sum of the constituent needs to be one cubic volume, which is the restraint of the absolute volume. The restraint of absolute volume may be written the following:

$$\sum_{i=1}^{i=6}\left(\frac{M_i}{\rho_i}\right) = 1 - V_{air} \tag{4}$$

where V_{air} means the volume of entrapped air and ρ_i is the density of the constituent of concrete.

(4) Restraint of compressive strength

The actual compressive strength must be higher than the needed compressive strength, which is the restraint of compressive strength. The restraint of compressive strength may be written as the following:

$$\text{real strength} \geq \text{required strength} \tag{5}$$

Yeh [22] measured the compressive strength of various types of concrete, such as Portland cement concrete, fly ash blended concrete, and slag blended concrete. Meddah [23] measured the compressive strength of cement-limestone binary concrete. Based on the experimental data shown in references [22,23], regressions were made and the strength evaluation equation (Formula (6)) was obtained. In other words, references [22,23] do not directly show the Formula (6). Formula (6) is obtained based on the regressions using experimental data shown in references [22,23]. For limestone hybrid concrete, the 28 days compressive strength can be determined based on the law of Abram as follows [22,23]:

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

where C, LS, and W denote the mass of cement, limestone, and water in concrete mixtures, respectively.

(5) Slump restraint

The restraint of slump means the real slump must be higher than the required slump. The restraint of slump may be written as the following:

$$\text{real slump} \geq \text{required slump} \tag{7}$$

The slump of limestone hybrid concrete can be established in the following [21,24]:

$$slump = 0.088 * W - 250.9 * \frac{W}{C + LS} - 146.2 * \frac{S}{S + G} + 18.4 * \frac{LS}{C + LS} + 0.199 * SP + 341 \tag{8}$$

where G, S, and SP are the masses of coarse aggregate, fine aggregate(sand), and superplasticizer, respectively. $\frac{W}{C+LS}$, $\frac{LS}{C+LS}$, and $\frac{S}{S+G}$ are the ratios of water/binder, limestone powder/binder, and sand/aggregate, respectively.

Yeh [22] and Lim [24]showed some concrete mixtures for various strength levels and aimed slumps. Based on the experimental data shown in references [22,24], such as water-to-binder ratios and superplasticizer contents, regressions were made and the superplasticizer evaluation equation (Formula (9)) was obtained. In other words, references [22,24] do not directly show the Formula (9). Formula (9) is obtained based on regressions using the experimental data shown in references [22,24]. The mass of the superplasticizer can be established by the following [22,24]:

$$SP = 9.198 - 7.74 * \frac{W}{C + LS} \tag{9}$$

This equation means that, with the ratio of water/binder increasing, the mass of the superplasticizer in concrete should decrease.

(6) Restraint of carbonation service life

The restraint of carbonation resistance dictates that cover depth should be higher than the depth of carbonation at the end of service life. The restraint of carbonation service life may be written as the following:

$$\text{cover depth} \geq \text{carbonation depth} \tag{10}$$

The carbonation depth of concrete relates to concrete materials, surrounding environments, and stress levels. Depth of carbonation can be calculated as follows [25,26]:

$$x_c = \lambda_{\text{stress}} * x_{c0} \tag{11}$$

$$L = \frac{stress}{strength} \tag{12}$$

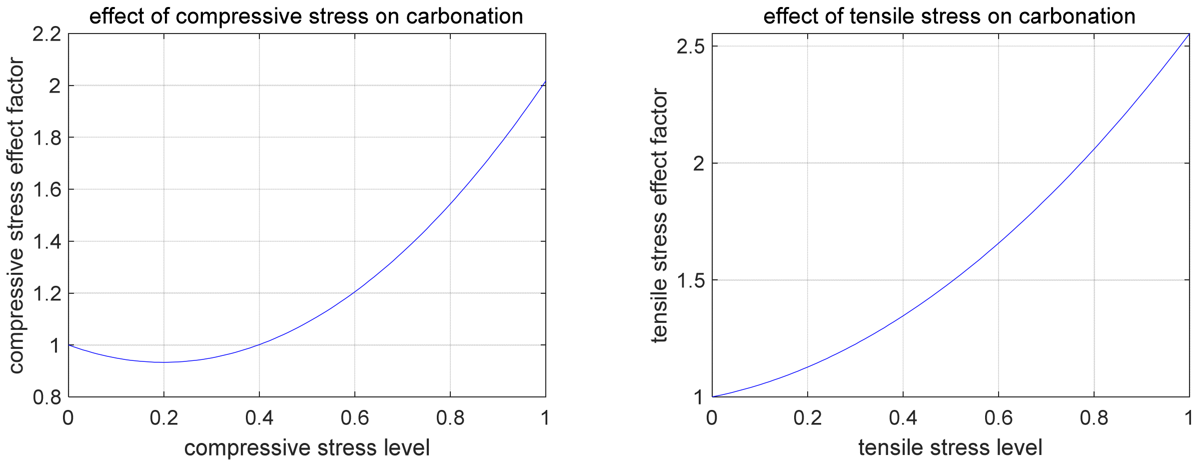
$$\lambda_{compression} = 1 - 0.672 * L + 1.69 * L^2 \tag{13}$$

$$\lambda_{tension} = 1 + 0.410 * L + 1.144 * L^2 \tag{14}$$

$$x_{c0} = \sqrt{\frac{2D[CO_2]_0 t}{0.218 * (C + 0.4 * LS) * \alpha_H}} \tag{15}$$

$$D = 6.1 * 10^{-6} \left(\frac{[W - 0.267 * (C + 0.4 * LS) * \alpha_H]/1000}{\frac{C+0.4*LS}{\rho_c} + \frac{W}{\rho_w}} \right)^3 \left(1 - \frac{RH}{100}\right)^{2.2} \exp\left[\beta\left(\frac{1}{T_{ref}} - \frac{1}{T}\right)\right] \tag{16}$$

where x_c and x_{c0} are the carbonation depth with the stress effect and without stress effect, respectively, λ_{stress} and L are the stress effect factor and stress level, respectively, and stress level L equals the ratio of stress to strength, and L ranges from 0 to 1. Stress effect factor λ_{stress} was found using measurement results of the depth of carbonation with multiple stress types and stress levels. Equation (13) and Figure 1a show that, when concrete is subjected to compressive stress, the value of λ_{stress} first decreased and then increased. The decreasing of carbonation depth is because of the compaction of concrete porosity at a low level of compressive stress. The increase of carbonation depth is because of the occurrences of cracks and damage at high levels of compressive stress. Equation (14) and Figure 1b show that when concrete is subjected to tensile stress, with the stress level increasing, λ_{stress} increases. This is because of the occurrence of damage and cracks. D is the diffusivity of CO_2. Equation (16) shows that CO_2 diffusivity relates to concrete compositions and surrounding conditions. $[CO_2]_0$ is the concentration of CO_2, t is time, α_H is the degree of concrete binder hydration ($\alpha_H = 1 - \exp(-3.38\frac{W}{C+0.4*LS})$) [27], RH is the relative humidity, β is the temperature influencing factor of CO_2 diffusion (β = 4300) [28], T_{ref} is a reference temperature (T_{ref} = 293 K), and T means the temperature of the exposure environment. Item $\left(\frac{[W-0.267*(C+0.4*LS)*\alpha_H]/1000}{\frac{C+0.4*LS}{\rho c}+\frac{W}{\rho w}}\right)^3$ considers the influence of concrete material on CO_2 diffusivity [26], and items $\left(1-\frac{RH}{100}\right)^{2.2}$ and $\exp\left[\beta(\frac{1}{T_{ref}}-\frac{1}{T})\right]$ consider the influences of surrounding relative humidity and temperature on CO_2 diffusivity, respectively [26].



(**a**) compressive stress (**b**) tensile stress

Figure 1. Effect of stress levels and stress types on depth of carbonation.

2.3. Optimization Algorithm and Flowchart

After the confirmations of goal function and restraints, the optimization mixtures can be discovered based on numerical methods, such as a genetic algorithm. Based on biologically inspired operators, the genetic algorithm can search for the optimal solutions to problems [24]. The main procedures of the genetic algorithm are (1) initialization, (2) selection based on fitness function value, (3) genetic operators, for instance, crossover and mutation, (4) heuristics that make the calculation faster, and (5) termination once the terminating conditions are met [24]. The MATLAB commercial program features a global optimization toolbox that includes the genetic algorithm. This study used the global optimization toolbox in the MATLAB commercial program to find the optimization mixture. Figure 2 shows a flowchart of the calculation. The starting point was confirming the goal function, i.e., the embodied energy of concrete. The second step was to confirm the various restraints, for instance, constituent ratio, constituent content, absolute volume, slump (workability), compressive strength, and durability of carbonation together with multiple stress types and stress levels. The next step was the resolution of the optimization mixtures based on the genetic algorithm.

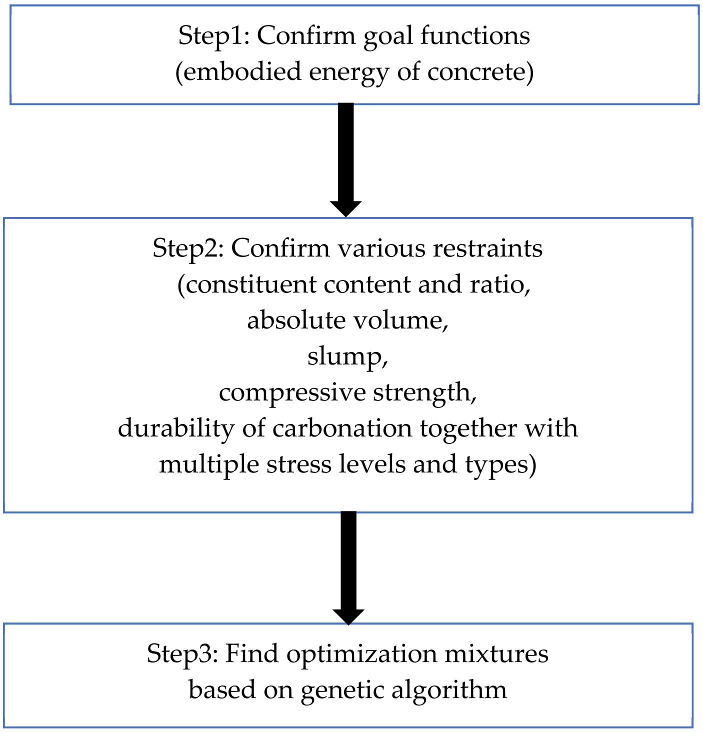


Figure 2. Flowchart of the calculation.

3. Case Studies

This section presents case studies of the optimization mixture design. The concentration of CO_2 was set at 0.04%, and the temperature of the exposure atmosphere was 20 °C. The aimed slump of hybrid concrete was assumed as 150 mm. The entrapped air content was placed at 2%. The service life for limestone hybrid concrete is intended to be fifty years. According to the regulations of the design code [29], the aimed 28-day strength consists of two different levels, 30 MPa (low level) and 55 MPa (high level), and the cover depth of concrete was 25 mm. The restraints of the constituent content and constituent ratio are shown in Tables 2 and 3, respectively.

Table 4 shows four case studies. Case 1, Case 2, and Case 3 have the same design strength, i.e., 30 MPa. Case 1 presented mixture designs free of stress (Mix 1 and Mix 2 had no carbonation restraint and one carbonation restraint, respectively). Case 2 presented mixture designs in consideration of carbonation durability together with multiple levels of compressive stress. Mix 3, Mix 4, and Mix 5 were suitable for compressive stresses of 25%, 50%, and 75% fc (fc, compressive strength), respectively. Case 3 presented mixture designs in consideration of carbonation durability together with multiple levels of tensile stress. Mix 6, Mix 7, and Mix 8 were appropriate for tensile stresses of 25%, 50%, and 75% ft (ft, tensile strength), respectively. Case 4 was a mixture design that considered the high strength of concrete and carbonation durability together with high-stress levels (75% fc or 75% ft). Mix 9 has a design strength of 55 MPa.

Table 4. Summary of case studies.

Cases	Goal Strength	Restraints		Mixtures	Comparisons	Clarify Points
Case 1	30 MPa	Free of stress	No carbonation	Mix 1	Mix 1 and Mix 2	carbonation
			Carbonation	Mix 2		
Case 2		Carbonation with compressive stress	0.25 fc	Mix 3	Mix 3, Mix 4, and Mix 5	compressive stress
			0.50 fc	Mix 4		
			0.75 fc	Mix 5		
Case 3		Carbonation with tensile stress	0.25 ft	Mix 6	Mix 6, Mix 7, and Mix 8	tensile stress
			0.50 ft	Mix 7		
			0.75 ft	Mix 8		
Case 4	55 MPa	Carbonation with high level stress	0.75 fc	Mix 9	Cases 1, 2, 3, and Case 4	Goal strength
			0.75 ft			

Table 4 showed the carbonation effect may be illustrated using the contrast between Mix 1 and Mix 2. The compressive stress effect may be illustrated using the contrast from Mix 3, Mix 4, to Mix 5. The tensile stress influence may be illustrated using the contrast from Mix 6, Mix 7, to Mix 8. In addition, the goal design strength may be illustrated using the contrast between Case 1, Case 2, Case 3 (30 MPa design strength), and Case 4 (55 MPa design strength).

3.1. Case 1: Style of Mixture Free of Stress

In this section, we perform mixture designs free of stress. Table 4 presents two subcases: (1) a sub-scenario of a mixture design without carbonation and (2) a sub-scenario of a mixture design in consideration of the durability of carbonation service life.

3.1.1. Mix 1: Design of the Mixture without Consideration of Durability of Carbonation

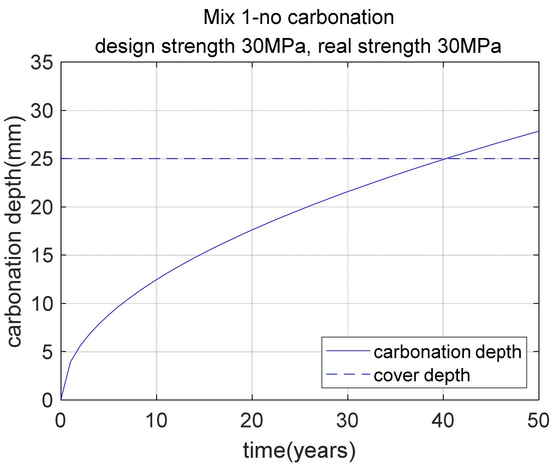
In this section, we determine the optimization mixture of limestone hybrid concrete of a design strength of 30 MPa without consideration of the durability of carbonation. After input goal functions along with other restraints (except carbonation), the optimization mixture of sub-Case 1 (Mix 1) is determined. Tables 5 and 6 show the mixtures and performance of concrete, respectively. The results given in Table 6 are the calculated results based on the properties evaluation equations in Section 2.2 and the optimization mixtures in Table 5. Because the properties evaluation equations for strength, slump, and carbonation resistance have been verified by various experimental tests [21–26], we believe that the calculation results from the properties evaluation equations are reliable. The limestone/binder ratio was 0.20, i.e., the surface of the bound limestone/binder ratio. This is because limestone has a significantly lower embodied energy than cement. Mix 1 has a real strength of 30 MPa, which equaled the design strength (30 MPa). Figure 3a shows the depth of the carbonation of Mix 1. After 50 years of service existence, cover depth is less than the depth of carbonation. Essentially, the carbonation resistance of Mix 1 could not be satisfied.

Table 5. Optimization mixtures of case studies (kg/m^3).

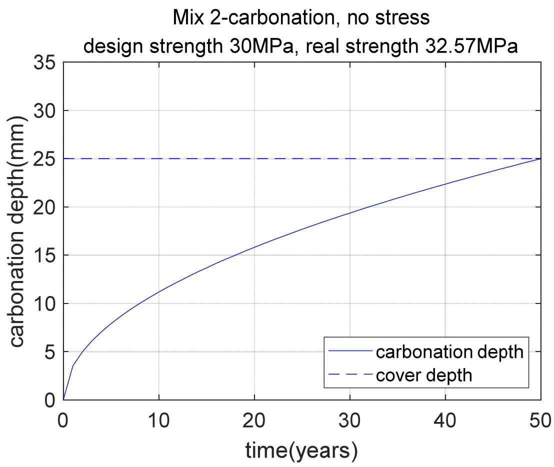
Cases	Mixtures	Cement	Limestone Powder	Water	Coarse Aggregate	Fine Aggregate	Superplasticizer
Case 1	Mix 1	273.81	68.45	169.99	855.62	926.92	5.35
	Mix 2	293.71	73.43	170.21	845.02	915.44	5.61
Case 2	Mix 3	281.73	70.43	170.07	851.40	922.35	5.46
	Mix 4	309.69	77.42	170.39	836.53	906.25	5.79
	Mix 5	369.86	92.46	171.10	804.68	871.74	6.33
Case 3	Mix 6	325.18	81.29	170.57	828.32	897.34	5.95
	Mix 7	376.69	94.17	171.18	801.07	867.83	6.38
	Mix 8	442.04	110.51	171.98	766.64	830.52	6.79
Case 4	Mix 9	460.86	115.22	172.21	756.74	819.80	6.88

Table 6. Concrete performance of results of case studies.

Cases	Mixtures	Compressive Strength (MPa)	Slump (mm)	Depth of Carbonation (mm)	Embodied Energy (MJ/m^3)	CO_2 Emission (kg/m^3)	Limestone Powder /Binder	Water /Binder
Case 1	Mix 1	30.00	160.07	27.85	1534.35	239.25	0.20	0.50
	Mix 2	32.57	168.43	25.00	1633.37	255.95	0.20	0.46
Case 2	Mix 3	31.02	163.54	25.00	1573.82	245.90	0.20	0.48
	Mix 4	34.65	174.37	25.00	1712.46	269.34	0.20	0.44
	Mix 5	42.62	192.12	25.00	2007.71	319.67	0.20	0.37
Case 3	Mix 6	36.68	179.56	25.00	1788.82	282.31	0.20	0.42
	Mix 7	43.54	193.78	25.00	2041.06	325.38	0.20	0.36
	Mix8	52.41	207.05	25.00	2358.36	379.91	0.20	0.31
Case 4	Mix 9	55.00	210.18	17.26 (0.75 fc) 23.30 (0.75 ft)	2449.38	395.60	0.20	0.30



(**a**) Depth of carbonation of Mix 1—without carbonation



(**b**) Depth of carbonation of Mix 2—with carbonation

Figure 3. Depth of carbonation of case study 1 (free of stress): Mix 1 and Mix 2.

3.1.2. Sub-Case 2: The Style of Mixture with the Effect of the Durability of Carbonation

This section shows that the carbonation restraint is important for the material design of limestone hybrid concrete. Carbonation resistance was added, becoming an additional restraint of the optimized design. The primary distinction between Sections 3.1.1 and 3.1.2. is that the carbonation restraint was considered in the latter; the other restraints remained the same. Using the genetic algorithm, the optimization mixtures were acquired and labeled Mix 2. As shown in Figure 3b, after 50 years of service existence, the depth of carbonation reaches the concrete cover depth. The real strength of Mix 2 (32.57 MPa) was much greater than the goal strength of 30 MPa. Essentially, to satisfy carbonation resistance, and especially the binder mix, a higher compressive strength must be used. In addition, the water contents in Mix 1 and Mix 2 were similar. Mix 1 and Mix 2 have the same water/solid ratio, i.e., 0.08, which was the lower bound of the restraint of water/solid ratio.

3.2. Case 2: Design in Consideration of Carbonation with Multiple Levels of Compressive Stress

In this section, we determine the optimization mixture of design with a 30 MPa strength, in consideration of concrete carbonation together with multiple levels of compressive stress. Table 4 shows three levels of compressive stress are considered, i.e., 25%, 50%, and 75% fc (fc, concrete compressive strength). The optimization mixtures Mix 3, Mix 4, and Mix 5 matched 25% fc, 50% fc, and 75% fc, respectively. For the mixture of Mix 3 (25% fc), the binder content and real strength were under zero stress case (Mix 2). Basically, low-level compressive stress, such as 25% fc, can boost the carbonation resistance. For mixtures of Mix 4 and Mix 5 (50% and 75% fc), the binder content is greater than the stress-free condition (Mix 2). Essentially, a greater level of compressive stress, such as 50% and 75% fc, lowers the resistance of the carbonation. To satisfy carbonation resistance together with greater levels of compressive stress (50% and 75% fc), binder mix is even more important. In addition, Table 6 showed for Mix 3 to Mix 5, the depth of carbonation reaches the cover depth after 50 years of service existence (the same as Figure 3b). This means that the longevity of carbonation was the control factor for Mix 3 to Mix 5.

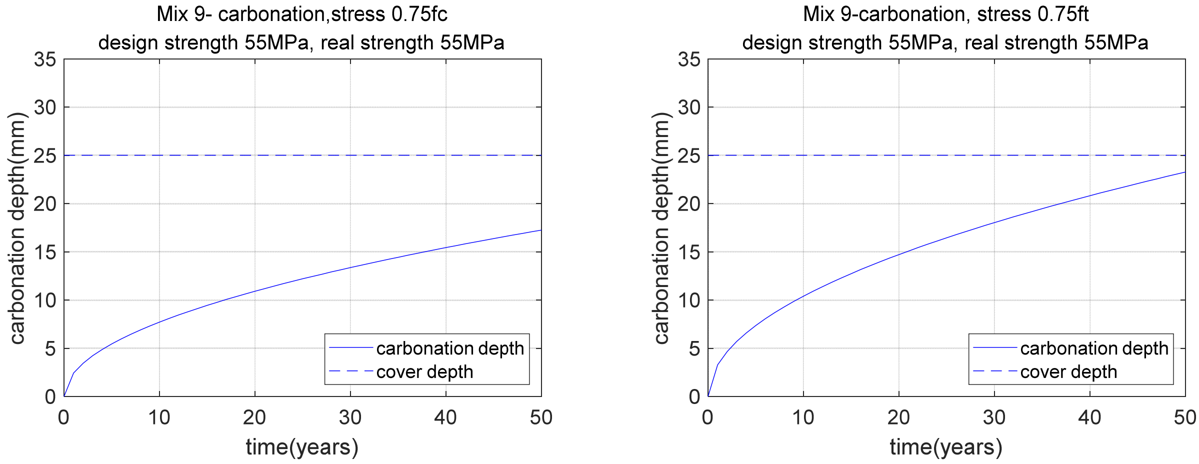
3.3. Case 3: Design in Consideration of Carbonation with Multiple Levels of Tensile Stress

In this section, we determine the optimization mixture of the design strength at 30 MPa in consideration of carbonation together with multiple levels of tensile stress. Table 4 shows that three levels of stress are considered, i.e., 25%, 50%, and 75% ft (ft, concrete tensile strength). The optimization mixtures Mix 6, Mix 7, and Mix 8 matched 25%, 50%, and 75% ft, respectively. From Mix 6 to Mix 8, the tensile stress level increased from 25% to 75% ft; the binder content and strength also increased, and thus, there was more than a zero-stress condition (Mix 2). Especially for the mixture of Mix 8 (corresponds to 75% ft), the actual strength of 52.41 MPa is much higher than the design strength of 30 MPa. Basically, tensile stress can reduce the carbonation durability service life. To fulfill carbonation resistance with tensile stress, a far more potent mix having greater binder content constituents are necessary. Furthermore, as shown in Table 6, for Mix 6 to Mix 8, the depth of carbonation reached the cover depth after 50 years of service existence (the same as Figure 3b). This means that the longevity of the carbonation was the control factor for Mix 6 to Mix 8.

Mixes 2–8 showed the same design strength. Meanwhile, as shown inside Table 6, after taking into consideration the restraint of carbonation durability, Mixes 2–8 presents the actual strengths more than the design strength of 30 MPa. Basically, for Mixes 2–8, carbonation, not compressive strength, controls this mixture type. Furthermore, for Mixes 2–8, the real strengths might be treated as the threshold strengths. When the design strength is lower than the threshold strength, carbonation controls this mix design; however, if the design strength is higher than the threshold strength, strength controls this mix design.

3.4. Case 4: Design of Mixture for Concrete with High Strength

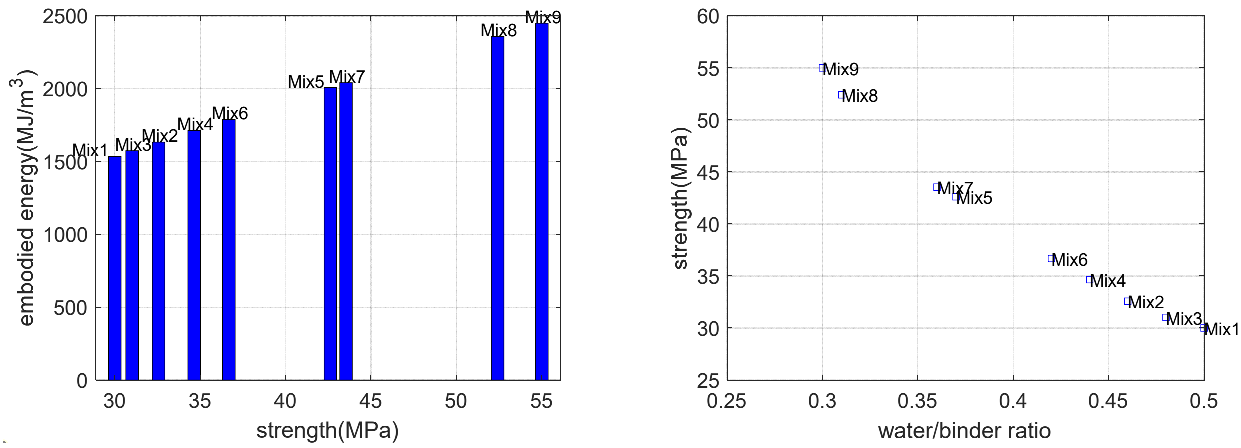
As described in Section 3.1 to Section 3.3, the goal strength was 30 MPa. In this section, the goal strength is positioned as 55 MPa to demonstrate the mix design for high-strength concrete. Table 4 showed the stresses applied to Case 4 were 75% ft and 75% fc. Through the use of the genetic algorithm, the optimization mixture was determined as Mix 9. The real strength of Mix 9 was the same as the design strength. Figure 4a,b presented the situation of when the levels of compressive and tensile stress were 75%, where the depth of carbonation was leaner than the cover depth after 50 years of service existence. Carbonation resistance was satisfied. Essentially, for concrete high in strength, strength controls this mix design. Carbonation is not a controlled restraint for the mixture design of concrete with high strength.



(**a**) Carbonation depth of Mix 9 coupled with 75% fc (**b**) Carbonation depth of Mix 9 coupled with 75% ft

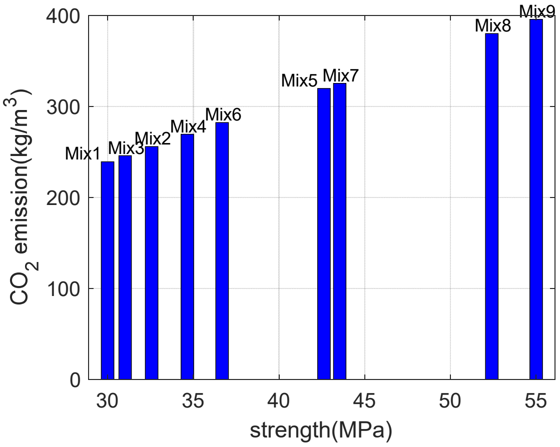
Figure 4. Carbonation depth of case study 4: design for concrete with high strength (Mix 9).

Figure 5 shows the general trends of strength versus embodied energy and strength versus water/binder ratio, respectively. Figure 5a shows that for Mix 1 to Mix 9, as concrete's strength grows, the embodied energy increases. This is in accordance with Long et al.'s study [21]. In addition, Figure 5b shows that while using a growing water-to-binder ratio, concrete compressive strength decreased. This concurs with Abram's law[22].



(**a**) Embodied energy (**b**) Relation between strength and water/binder ratio

Figure 5. *Cont.*



(**c**) CO_2 emission

Figure 5. Overall tendency of optimization mixtures.

3.5. Optimization Design in Consideration of Carbon Footprint

From Sections 3.1–3.4 the aim of the optimization design was embodied energy. Sustainability includes many sub-aims. In addition to low embodied energy, a low carbon footprint may be another important purpose for sustainable development. Much like embodied energy, the carbon footprint of concrete can be established in line with the mass and unit carbon footprints of the concrete constituents (provided in Table 1). According to similar methods in Sections 3.1–3.4, designs of optimization mixtures with low carbon footprints are performed. We discovered that the perfect mixtures with carbon footprints are the same as those of low embodied energy. This is because the carbon footprint and embodied energy of limestone tend to be lower than those of cement. Additionally, fine aggregate has a lower carbon footprint and less embodied energy than coarse aggregate. Quite simply, the individual mass within the optimization mixture relies upon the relative embodied energy and carbon footprint from the concrete constituent. Figure 5c shows the strength versus carbon footprint of optimization mixtures. As concrete strength increases, the carbon footprint also increased. The trends in the carbon footprint act like those of embodied energy.

The new knowledge and approach in the choice of the recipe are shown as follows: (1) the proposed method can find the decisive factor of concrete mixture design, such as strength control or carbonation durability control. Contrastingly, the previous methods could not distinguish between strength control and carbonation durability control [22,24]. (2) The proposed method covers both material aspects and structural aspects because it considers the effect of structural stress on carbonation durability and material design. Contrastingly, the previous methods only considered the material aspect and ignored the structural aspect [22,24]. (3) The proposed method considers various aims of sustainability, such as embodied energy and embodied CO_2. Contrastingly, the previous methods only considered a single aim [22,24].

4. Discussion

The traditional mixture design method generally can be used for plain Portland cement concrete without limestone powder. The traditional mixture design method assumes when the strength matches the need, durability will be instantly satisfied. However, even though limestone hybrid concrete has the same strength as control concrete, limestone hybrid concrete has a weaker resistance of carbonation than plain concrete [2,4]. Hence, this study selects carbonation as the key factor of the mixture design of limestone hybrid concrete. Moreover, this study considers the influences of various stress types and levels on carbonation and mixture design. As opposed to previous studies, this study shows some advantages.

(1) This study showed a design method that can distinguish the control factors, for instance, carbonation control (Mix 2 of Case 1, Mix 3, Mix4, and Mix 5 of Case 2, Mix 6, Mix7, and Mix 8 of Case 3) or strength control (Case 4). The optimization mixtures with different control factors might be acquired based on the genetic algorithm. Contrastingly, traditional mixture design methods do not consider carbonation resistance. Conventional methods assume that strength is the control factor of mixture design. This means that when the strength matches the need, durability will be instantly satisfied [22]. However, for limestone concrete with low and ordinary design strength, due to the fact of its lower carbonation resistance, the mixture design may be controlled by carbonation, not strength [2].

(2) This study showed an integrated design method covering structural stress (Case 2, Case 3, and Case 4) and optimization material design. Contrastingly, previous studies mainly focused on material design and neglected the influence of stress on mixture design [5–19]. All the structural elements bore stress due to the structural loading and environmental factors. The structural stress could affect micro-cracks, concrete durability, and the mixture design of concrete [25,30]. In other words, the influence of stress cannot be neglected regarding material design.

(3) This study used a genetic algorithm to determine the optimization mixtures (Case 1 to Case 4). A genetic algorithm is a universal means that is flexible to make use of different equations [31,32]. For several design codes, the calculation formulas of concrete strength, concrete slump, and concrete carbonation depth might be not the same as the equations present in this research [26,33]. Although the details of calculation equations may be not the same, the fundamental process of the genetic algorithm might be similar [34,35]. Hence, the suggested method might be a general technique of the production of sustainable concrete for different design codes.

(4) Wang showed optimal mixture designs of limestone blended concrete with low CO_2 emissions [36]. Compared with Wang [36], the main improvements of this study are (1) considering the effects of stress types and levels on mixture design, (2) considering various design aims, such as embodied energy and embodied CO_2, and (3) clarifying the similarities and differences between low-CO_2 concrete and low energy concrete. In addition, Wang [37] showed optimal mixture designs of fly ash hybrid concrete. Compared with Wang [37], the main difference is that this study focused on limestone blended concrete, while Wang [37] focused on fly ash hybrid concrete. In other words, the research objects in this study and Wang are different [37].

5. Conclusions

This work showed a genetic algorithm-based process for the optimization design of sustainable limestone hybrid concrete. The objective of the optimization design was set as the embodied energy. The restraints of the optimization design consist of compressive strength, slump, and carbonation resistance along with stress.

Four case studies were performed. Case 1 consisted of mixture designs free of stress, Case 2 consisted of mixture designs with the effect of compressive stress, Case 3 consisted of mixture designs with the effect of tensile stress, and Case 4 consisted of mixture designs for concrete with high strength. Case 1, Case 2, and Case 3 had a design strength of 30 MPa, and Case 4 had a much higher design strength of 55 MPa. The case study results are summarized next.

(1) Case 1 (free of stress): When the restraint of carbonation was not taken into account, the real strength (30 MPa) of Mix 1 was the same as the design strength (30 MPa). The depth of carbonation was much greater than the cover depth after 50 years of service existence. In addition, to fulfill the carbonation resistance, Mix 2 has a richer binder and a greater strength (32.57 MPa). When the design strength is 30 MPa, carbonation dominates the mixture design.

(2) Case 2 (multiple levels of compressive stress): For the situation of 25% fc, Mix 3 has a real strength (31.02 MPa) less than stress-free conditions (32.57 MPa). This is because 25% fc can boost the resistance of carbonation. Conversely, for the situations of 50% and 75% fc, Mix 4 and Mix 5 have real strengths of 34.65 MPa and 42.62 MPa, respectively, which were greater than the stress-free condition (32.57 MPa). To satisfy the carbonation resistance with higher compressive stress 50% and 75% fc, more binder mix is necessary.

(3) Case 3 (multiple levels of tensile stress): when the tensile stress level increased from 25% to 50% ft, Mix 6 and Mix 7 have the real strength of increased 36.68 to 43.54 MPa, respectively, which was much greater than that in the zero-stress condition (32.57 MPa). In addition, for the situation of 75% ft, the real strength of Mix 8 becomes much greater, i.e., 52.41 MPa. Compared to compressive stress, tensile stress presents a much more significant impact on the mixture design.

(4) Case 4 (high-strength concrete): For concrete of a high strength (design strength 55 MPa) with stresses of 75% fc or 75% ft, the real strength of Mix 9 was 55 MPa, which is the same as the design strength. For concrete high in strength, cover depth was higher than carbonation depth after fifty years of service life, and strength was a dominant restraint for the design of the mixture.

(5) When the purpose of the optimization design is set as the carbon footprint, the optimization mixtures with carbon footprints overlap with individuals of low embodied energy. The individual mass within the optimization mixture relies upon the relative ratios of CO_2 emissions and embodied energy from the concrete constituent.

(6) This study only shows the qualitative verifications of the proposed approach. The trends of optimal mixtures, such as the relations between strength and embodied energy, between strength and water/binder ratio, and between strength and CO_2 emissions, show agreement with that of engineering practices. In future studies, more quantitative verifications, such as the results of strength, carbonation depth, and slump, should be carried out.

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