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Design Method for Low-Carbon Fly Ash Concrete Considering Strength, Form Removal Time, and Carbonation Durability Life

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Abstract: Low-carbon fly ash concrete is one of the hottest research topics in the concrete industry. This study proposes a design method for low-carbon fly ash concrete that systematically considers strength, form removal time, and carbonation durability life. The basic steps of this method are as follows: First, based on the experimental results, the strength development formula of fly ash concrete using different mix ratios and different aging periods is obtained through regression. The adopted carbonation depth calculation formula can be used to consider the influence of the curing time and mix ratio on carbonation depth. Second, through the analysis of design cases, the dominant factors in the design of low-carbon fly ash concrete are clarified. For example, strength dominates, demolding time dominates, or carbonation durability dominates. If the concrete is removed from the formwork early, the carbonation resistance is very weak, and a large amount of cementitious material is required in order to meet the carbonation durability requirements. Appropriately extending the removal time of the concrete form can enhance the carbonation durability, reduce the content of cementitious materials, and achieve the goal of low-carbon design. In short, the method proposed in this study can be used as a general method for low-carbon fly ash concrete design, and this method can be extended for use in different countries and regions.

Keywords: fly ash; concrete; carbonation; form removal time; carbon emissions

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1. Introduction

Fly ash is one of the most commonly used concrete mineral admixtures [1–3]. Incorporating fly ash into concrete can bring many advantages, such as better resistance to chloride ion erosion, lower material prices, and lower CO_2 emissions [4,5]. However, it must be acknowledged that it also brings negative factors, such as lower early strength and weaker carbonation resistance [6]. When using fly ash concrete, it is necessary to consider the positive and negative effects of fly ash on concrete and to use it with caution [7]. Mineral admixtures such as fly ash have been found to prolong the setting time and to reduce the early concrete strength, which, in turn, increases the form pressure and delays the form removal time [8].

Strength is an important indicator of concrete quality [9]. Recently, many researchers have proposed models to predict the strength of fly ash concrete. Han proposed a strength model of fly ash concrete based on activation energy theory and found that the activation energy changed with the water–binder ratio [10]. The model proposed by Hwang et al. was used to consider the effects of age, fly ash particle size, and mix ratio on the strength of fly ash concrete [11]. Based on the content of calcium silicate hydrate, Wang and Park proposed a hydration model that was used to systematically consider the effects of material properties, curing conditions, and mix ratio on the early and late strengths of fly ash concrete [6]. Krishnya et al. simulated the generation and strength development processes of the hydration products of fly ash concrete [12]. In addition to the models based on the hydration mechanism [6,10–12], some researchers have proposed strength models based on machine learning. Yeh used the neural network method to estimate the strength of fly ash concrete [13], and Sevim et al. used artificial neural network (ANN) and adaptive network-based fuzzy inference system (ANFIS) methods to estimate the strength of fly ash concrete with different components. It was found that ANFIS combined with genetic algorithms could achieve better prediction results [14]. Roshani et al. used neural networks to predict the mechanical properties of fly ash concrete, such as compressive strength, tensile strength, and elastic modulus [15]. Song et al. used the machine learning method of gene expression programming to predict strength. Compared with other machine learning methods, gene expression programming can obtain specific regression equations [16].

The technology that is used to predict the strength of concrete is important. Along with prediction, the industry is also concerned with the material design of low-carbon fly ash concrete. Material design is equivalent to the inverse of the problem of strength prediction. At present, most researchers in the field of concrete material design mainly consider strength and workability [17–20]. Few researchers have observed that for fly ash concrete, carbonation durability may become a decisive factor in the material design, and one which is related to the strength [20]. When the strength is the same, the carbonation durability of fly ash concrete is worse than that of plain cement [21,22]. Carbonation durability is mainly related to the material design, curing conditions, and the environment of the concrete.

Regarding the material design of low-carbon fly ash, the main shortcomings of the previous research are as follows. Firstly, strength and working performance were considered, but the limiting factors of carbonation durability were not [17,18]. Secondly, although the 28-day design strength was considered, the development process of the strength was not. It is necessary to design concrete materials for simultaneous 7-day and 28-day strength tests [19,20]. In Reference [8], the requirements for form removal, which are typically 70% of the 28 days strength for the horizontal members and 5 MPa for the vertical members, are presented. Thirdly, carbonation durability is closely related to the curing age of concrete. When carbonation durability becomes the dominant factor in the mix design, the curing age of concrete may also affect the material design of the low-carbon concrete.

In order to overcome the shortcomings of the current research, this study proposes a design method for low-carbon fly ash concrete that systematically considers strength, form removal time, and carbonation durability life. Through the analysis of design cases, the dominant factors in the design of low-carbon fly ash concrete in different design scenarios are clarified. The method proposed in this study can be used as a general method for low-carbon concrete design.

2. Evaluation and Parameters Analysis for Strength

2.1. Methods and Materials

Lam conducted experimental studies on the strength development of fly ash blended concrete, using various mixtures and test ages [23]. The water–binder ratio, substitution amount, and test age included in this study covered the ranges commonly used in engineering. The fly ash substitution amount ranged from 0 to 55%, the water–binder ratio ranged from 0.3 to 0.5, and the test age ranged from 3 days in the early stage to 180 days in the long term. Regarding the completeness of the experimental results, the experimental data used in this study is taken from the study by Lam [23].

2.2. Regression and Parameter Analysis for Compressive Strength

After collecting the experimental results of the compressive strength tests of the fly ash blended concrete, a commercial software package was used to perform regression [24]. The independent variables in the regression were the water–binder ratio, fly ash replacement amount, and age. The water–binder ratio is defined as $x1$ = W/(C + FA), where W, C, and FA represent, respectively, the mass of water, cement, and fly ash in 1 cubic meter of concrete. The replacement amount of fly ash is defined as $x2$ = FA/(C + FA), where $x1$ and

$x2$ are dimensionless variables, and the test age is defined as $x3$; the time unit is a day. The strength is used as the dependent variable fc(t); the unit is MPa. The strength prediction Equation (1) was obtained using regression and the coefficients of Equation (1) are shown in Table 1. The comparison between the regression results and the test results is shown in Figure 1. In this figure, it can be seen that the regression results are basically consistent with the experimental results; the correlation coefficient between the two is 0.9818.

$$fc(\mathrm{t}) = (((1+\ x3)^{0.5}) \times ((\mathrm{p1} - x1)^{3}))/(((1 + \mathrm{p2} \times x2 + \mathrm{p3} \times x1 + \mathrm{p4} \times x3)/(\mathrm{p5} + \mathrm{p6} \times x2 + \mathrm{p7} \times x1 + \mathrm{p8} \times x3))/(1/\mathrm{p9} - x3))) \quad (1)$$

Table 1. Coefficients of the regression equation.

Coefficients	Values
p1	6.35297417900102
p2	116,952,873.38987
p3	−1,050,245,908.58601
p4	−991,527.590492115
p5	1,107,321,066.20182
p6	−1,181,907,559.08431
p7	−512,788,823.508165
p8	12,880,913.9775729
p9	−20.5249682079566

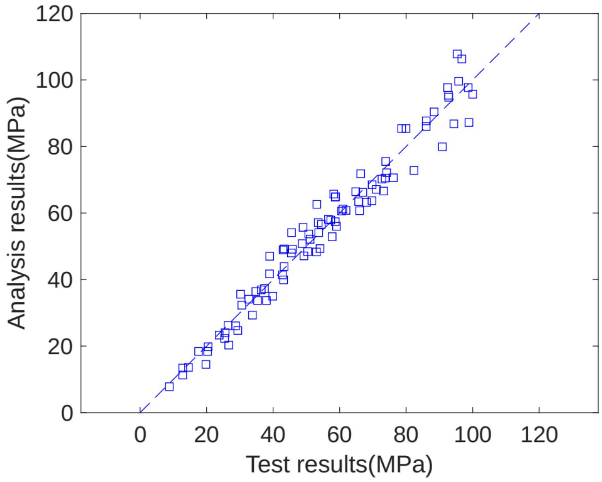

Figure 1. Experimental results and strength test results.

After obtaining the regression equation, we used it to conduct the parameter analysis of the variables. The effect of the water–binder ratio on strength is shown in Figure 2. In this analysis, we assumed that the variation range of the fly ash was 0 to 0.55, the test age was 90 days, and the water–binder ratios were 0.30 and 0.50 in the two cases. This figure illustrates that as the amount of fly ash substitution increases, the strength of the concrete decreases because fly ash is less reactive than cement. In addition, when the fly ash substitution rate is given, the strength of the concrete increases as the water–binder ratio decreases. This is because the reduction in initial porosity causes a reduction in concrete porosity during hardening, thereby increasing the strength.

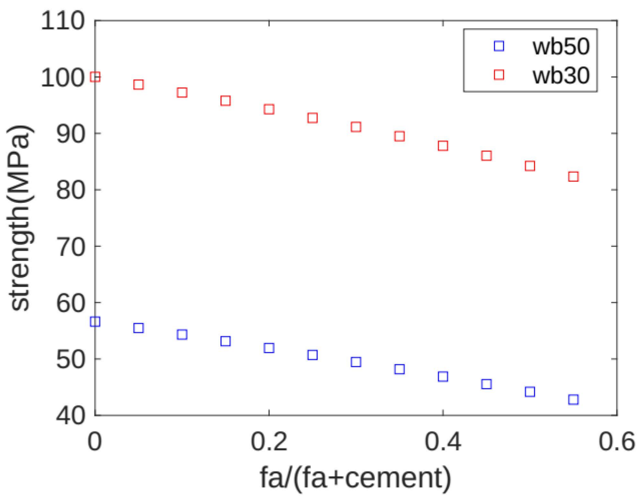

Figure 2. Effects of water/binder ratio and fly ash/binder ratio on strength.

The effect of the water–binder ratio on the relative strength of the materials is shown in Figure 3. In this analysis, we assume that the strength of the plain concrete without fly ash is 1 and that the relative strengths of the material are equal to the strength of the concrete with fly ash divided by the strength of the plain concrete without fly ash. It can be seen that the relative strengths of the materials are different with the different water–binder ratios. As the water–binder ratio of the concrete decreases from 0.5 to 0.3, the relative strength of the concrete increases. This is because fly ash has a dilution effect after being incorporated into concrete with a low water–binder ratio [25]. This results in an increase in the mass ratio between the cement and water, which increases the hydration degree of the cement and also increases the strength [6]. For concrete with a high water–binder ratio, the dilution effect is not significant.

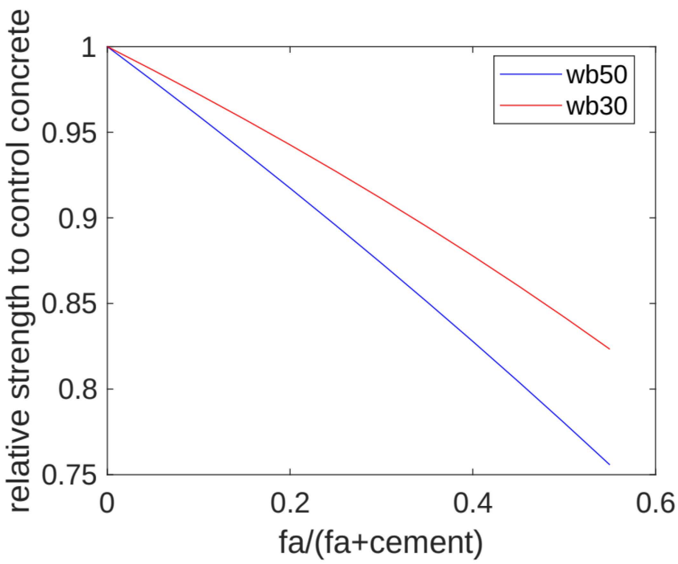

Figure 3. Effects of water/binder ratio and fly ash/binder ratio on relative strength of material.

The effect of age on strength is shown in Figure 4. In this analysis, we assume that the replacement rate of fly ash is 25% and that the age range is from 3 days to 180 days. We can see that as age increases, the strength also increases. In addition, as the water–binder ratio decreases, the strength increases, which is similar to the conclusion given in Figure 2. The influence of age on the age-related strength is shown in Figure 5. The age-related strength is defined as the ratio of the strength at a given age to the 180-day strength. We can see that as the water–binder ratio decreases, the age-related strength increases. This is similar to the conclusion given in Figure 3.

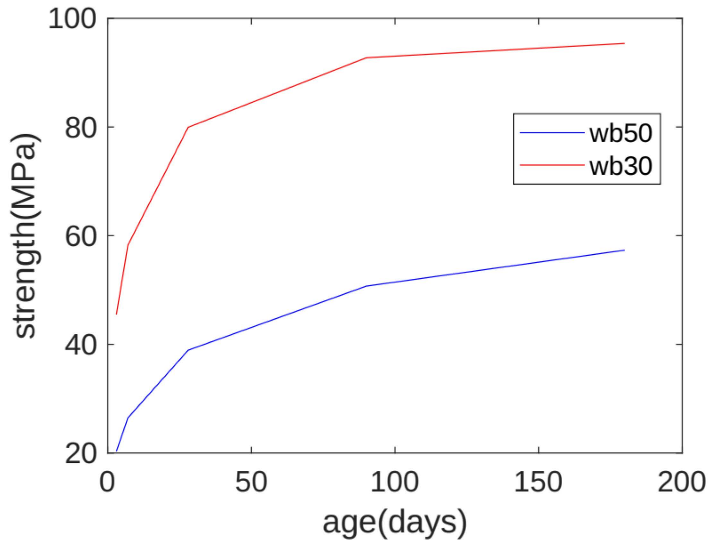

Figure 4. Effects of water/binder ratio and age on strength.

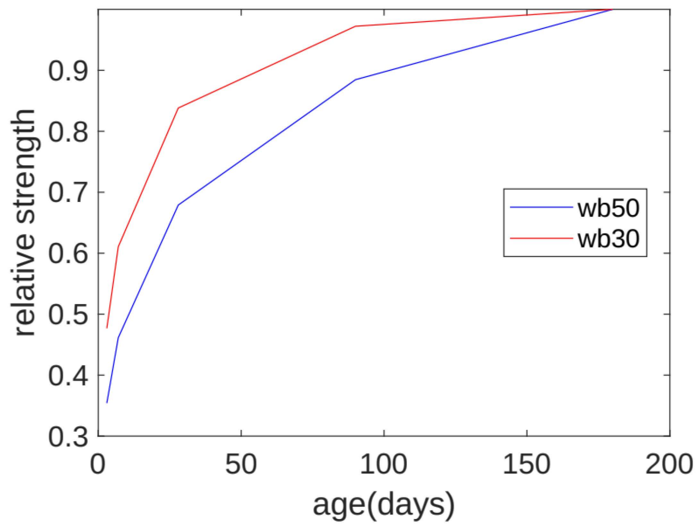

Figure 5. Effects of water/binder ratio and age on age-related strength.

3. Low-CO_2 Optimal Design of Fly Ash Blended Concrete

3.1. Goal of Optimization Design

The material composition of concrete mainly includes cementitious materials, water, and aggregates. The carbon emissions of concrete mainly come from cementitious materials. When optimizing the carbon emissions design, we assume that the optimization target measures the carbon emissions of the cementitious materials; these emissions are equal to the carbon emissions of the cement plus the carbon emissions of the fly ash, that is, min($0.931 \times C + 0.0196 \times FA$), where the coefficients 0.931 and 0.0196 are the CO_2 emissions from 1 kg of cement and 1 kg of fly ash, respectively [19,20].

3.2. Constraints on Optimal Design

The conditions for the optimized design are shown in Table 2; they mainly include water content, range of component proportions, carbonation durability, and strength when removing the formwork.

Table 2. Constraints of optimal design.

Water content	170 kg/m^3
Water/binder ratio	[0.3, 0.5]
Fly ash/binder ratio	[0, 0.55]
Carbonation depth at 50 years	≤cover depth
Strength at concrete formwork removal time	≥design strength 70%

3.2.1. Water Content

According to reference [26], the unit water consumption of concrete mainly depends on the maximum particle size of the coarse aggregate. The range of the unit water consumption is roughly between 150 and 200 kg [26]. In this analysis, we assume that the unit water consumption is constant, at 170 kg/m^3.

3.2.2. Range of Ingredient Ratios

In our optimization design, we assume that the water–binder ratio should range from 0.3 to 0.5 and that the fly ash substitution amount should range from 0 to 0.55. The latter range is taken from Lam's experiment [23] and covers most of the engineering scenarios using fly ash concrete.

3.2.3. Carbonation Durability

After adding fly ash, the carbonation durability of concrete decreases. Even at the same strength, the carbonation depth of concrete containing fly ash is higher than that of Portland concrete; thus, the carbonation service life of the structure is reduced [19,20]. Therefore, for fly ash concrete, carbonation durability is an issue that cannot be ignored. The carbonation depth can be calculated according to the following formula [21,22,27].

$$x_c = \sqrt{\frac{2D[\mathrm{CO_2}]_0 t_c}{0.218 \times (C + 0.5 \times FA) \times \alpha}} \quad (2)$$

$$D = 6.1 \times 10^{-6} \left(\frac{[W - 0.267 \times (C + 0.5 \times FA) \times \alpha]/1000}{\frac{C+0.5\times FA}{\rho_c} + \frac{W}{\rho_w}} \right)^3 \left(1 - \frac{RH}{100}\right)^{2.2} \quad (3)$$

$$\alpha = \alpha_{max} \frac{\mathrm{fc(t)}}{\mathrm{fc(180)}} \quad (4)$$

$$\alpha_{max} = 1.0 - \exp(-3.38 * W/(C + 0.5 * FA)) \quad (5)$$

In the above equation, x_c represents the depth of carbonation, D represents the diffusion coefficient of carbon dioxide, $[\mathrm{CO_2}]_0$ represents the concentration of carbon dioxide in the air, t_c represents the carbonation durability service life, and the denominator $0.218 \times (C + 0.5 \times FA) \times \alpha$ represents the consumption capacity of carbonizable substances for CO_2, where α represents the start of the reaction degree of the cementitious material when carbonation starts. As shown in Formula (4), the reaction degree of the cementitious material can be calculated from the development of the maximum reactivity, α_{max}, and the age-related strength, $\frac{\mathrm{fc(t)}}{\mathrm{fc(180)}}$ [28], in which fc(t) is the strength at the age of t days (which can be calculated using Equation (1); fc(180) is the strength at 180 days of age; RH represents the relative humidity of the environment; and ρ_c and ρ_w represent the densities of cement and water, respectively.

As shown in Formula (5), as the water–binder ratio increases, the maximum reactivity of the cementitious material, α_{max}, decreases, which is consistent with the experimental results of the hydration reaction [20]. As the curing age increases, the hydration degree α increases, the diffusion coefficient D decreases, the content of carbonizable substances increases, and the carbonation depth decreases; these findings are consistent with the results of the carbonation experiment [29].

3.2.4. Construction Requirements

According to the construction specifications, the concrete strength must have reached 70% of the design strength when the formwork is removed [18,20,26].

3.3. Algorithm for Optimal Design

This study uses a genetic algorithm to optimize the design. The aim of the optimized design is related to the quality of the cement and the quality of the fly ash. The objective function of the optimal design is related to the carbon emissions of the binder in the concrete. The constraints of the optimized design are the water–binder ratio, fly ash substitution amount, carbonation durability, and construction requirements. Using MATLAB's 2024a genetic algorithm toolbox [30], the optimal design can be achieved [19,20].

4. Case Analysis of Optimized Design

4.1. Design Cases

We conducted four case analyses. For these four design cases, in accordance with the concrete design specifications, the 28-day design strength of the concrete was 30 MPa, and the thickness of the protective layer was 25 mm [31]. In accordance with the concrete construction specifications, in order to meet the construction requirements and achieve a 7-day formwork removal, we assumed that the 7-day design strength was 21 MPa, that is, that the concrete had reached 70% of the design strength when the formwork was removed [18,20,26]. For concrete mixed with fly ash, carbonation durability cannot be ignored. At the end of the 50-year service life, the carbonation depth should be no greater than the thickness of the protective layer. Carbonation is related to the material properties of concrete and the environmental factors to which it is exposed. The content of the cementitious material is the optimization target of this study; it can be obtained through the optimization toolbox. In terms of environmental factors, the concrete carbonation mainly includes two processes: the diffusion of CO_2 and the reaction of CO_2. Carbonation proceeds fastest in a relative humidity range of 0.5 to 0.7. When the relative humidity is lower than 0.5, the CO_2 reaction proceeds very slowly due to insufficient water, which slows down the carbonation rate; when the relative humidity is higher than 0.7, the diffusion of CO_2 is hindered due to the high water content, which also slows down the carbonation process. Therefore, in this study, it was assumed that the relative humidity of the environment was 0.6. Carbon dioxide is a colorless and odorless gas. It is one of the components of air. The concentration of carbon dioxide in natural air is 0.04%. As the local environment changes, the CO_2 concentration may also change.

We assumed that the relative humidity of the environment was 0.6 (the carbonation reaction proceeds at its fastest speed in a relative humidity range between 0.5 and 0.7, so we assumed that the relative humidity was 0.6) and that the carbon dioxide concentration was 0.04%.

As shown in Table 3, Design Case 1 assumes that the 28-day design strength of concrete is 30 MPa, and does not consider the requirements for construction and carbonation durability. Design Case 2 assumes that the 28-day design strength is 30 MPa and that the 7-day design strength is 21 MPa. It takes into account the construction requirements but ignores the durability requirements. Design Case 3 assumes that the 28-day design strength is 30 MPa and that the 7-day design strength is 21 MPa. After the formwork is removed at 7 days, the material is exposed to the surrounding environment and carbonation starts. Design Case 4 assumes that the 28-day design strength is 30 MPa and that the 7-day design strength is 21 MPa. After the formwork is removed at 28 days, the material is exposed to the surrounding environment and carbonation starts.

Table 3. Optimal design cases.

	28-Day Design Strength (MPa)	7-Day Design Strength (MPa)	Curing Time before Carbonation (Days)
Mix 1	30	-	-
Mix 2	30	21	-
Mix 3	30	21	7
Mix 4	30	21	28

By comparing these cases, we can clarify the following effects. Firstly, by comparing Case 1 and Case 2, we can clarify the impact of mold removal time on the mix-ratio optimization. Secondly, by comparing Case 2 and Case 3, the impact of carbonation on the mix design can be clarified. Thirdly, by comparing Case 3 and Case 4, the impact of the curing time before the start of carbonation on the mix design can be clarified.

4.2. Results and Analysis of Design Cases

The results of the design cases are shown in Table 4. For Case 1, the optimized design result is Mix 1. Its cement and fly ash masses are 167.70 and 204.84 kg/m^3, respectively, and the water–binder ratio of Mix 1 is 0.45 (which is located in the studied range of the water–binder ratio between 0.3 and 0.5). The mass ratio of the fly ash to the binder is 0.55 (reaching the upper limit of the fly ash replacement). This design example shows that using concrete with a high fly ash content can indeed reduce CO_2 emissions.

Table 4. Results of optimal design.

	Water (kg/m^3)	Cement (kg/m^3)	Fly Ash (kg/m^3)	Water/Binder Ratio	Fly Ash/Binder Ratio
Mix 1	170	167.60	204.84	0.45	0.55
Mix 2	170	193.82	236.89	0.39	0.55
Mix 3	170	428.09	138.56	0.30	0.24
Mix 4	170	221.34	270.53	0.34	0.55

For Case 2, the result of the optimized design is Mix 2. Its cement and fly ash masses are 193.82 and 236.89 kg/m^3, respectively. The water–binder ratio of Mix 2 is 0.39 (which is located in the studied water–binder ratio range between 0.3 and 0.5). The mass ratio of the fly ash to the binder is 0.55 (reaching the upper limit of the fly ash substitution). As shown in Table 5, the 7-day strength of Mix 2 is 21 MPa, which is equal to the design strength, but its 28-day real strength is 41.43 MPa, which is higher than the design strength of 30 MPa. This shows that the early strength development is slow due to the low reactivity of fly ash. When early formwork removal is required, the strength needs to be increased for 28 days to meet the construction requirements.

The strength requirements for concrete formwork removal are derived from the construction specifications [8]. The main purpose of this provision is to specify a more reasonable construction plan. When the formwork is removed too early, the strength of the concrete is insufficient to support its own weight and the load during the construction process, resulting in reduced safety; when the formwork is removed too late, the efficiency of the formwork recycling is reduced and the construction cost increases.

Table 5. Material properties of optimal design.

	28-Day Real Strength (MPa)	CO_2 Emissions (kg/m^3)	7-Day Real Strength (MPa)	Carbonation Depth at 50 Years (mm)
Mix 1	30.00	160.05	15.64	38.55
Mix 2	41.43	185.09	21.00	62.94
Mix 3	80.29	401.27	58.61	25.00
Mix 4	47.22	211.37	26.98	25.00

As shown in Figures 6 and 7, after fifty years of use, the carbonation depths of Mix 1 and Mix 2 are higher than the thickness of the protective layer. Thus, they do not meet the durability requirements. In order to meet the carbonation durability requirements, we designed Case 3 and Case 4. Case 3 and Case 4 had different demolding times for the concrete; these were 7 days and 28 days, respectively. Previous studies have shown that as the form removal time increases, the content of generated hydration products increases, the porosity decreases, and the carbonation ability of the concrete also increases [29].

For Case 3, the optimized design result is Mix 3. Its cement and fly ash masses are 428.09 and 138.56 kg/m^3, respectively; the water–binder ratio of Mix 3 is 0.30 (reaching the lower limit of the water–binder ratio); the fly ash and mass binder ratio is 0.24 (which is located between the upper and lower limits of the fly ash replacement rate). As for Mix 3, its 7-day and 28-day real strengths are 58.61 and 80.29 MPa, respectively, which are much higher than the design requirements of 21 and 30 MPa. This is due to the carbonation durability requirements. As shown in Figure 7, for Mix 2, after 50 years of use, the carbonation depth is 62.94 mm, which is much higher than the protective layer thickness of 25 mm. As shown in Figure 8, for Mix 3, after 50 years of use, the carbonation depth is 25 mm, which is equal to the thickness of the protective layer.

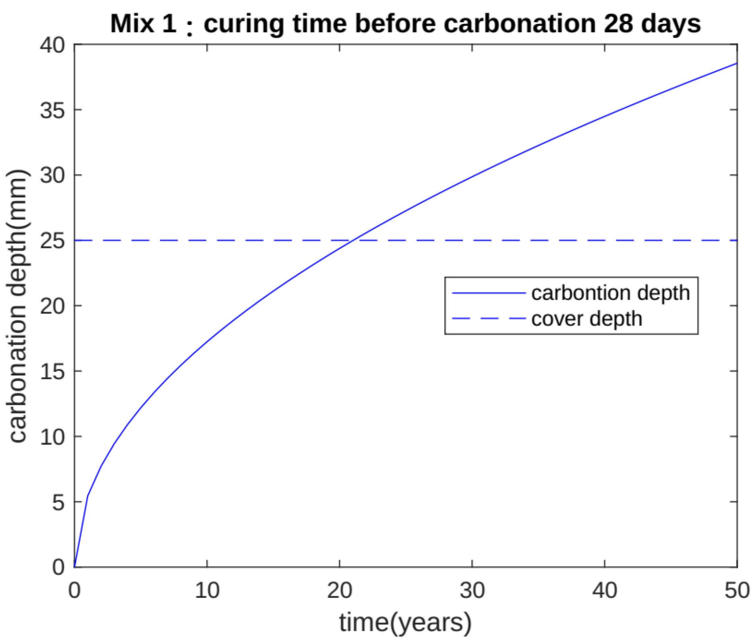

Figure 6. Carbonation depth curve of Mix 1.

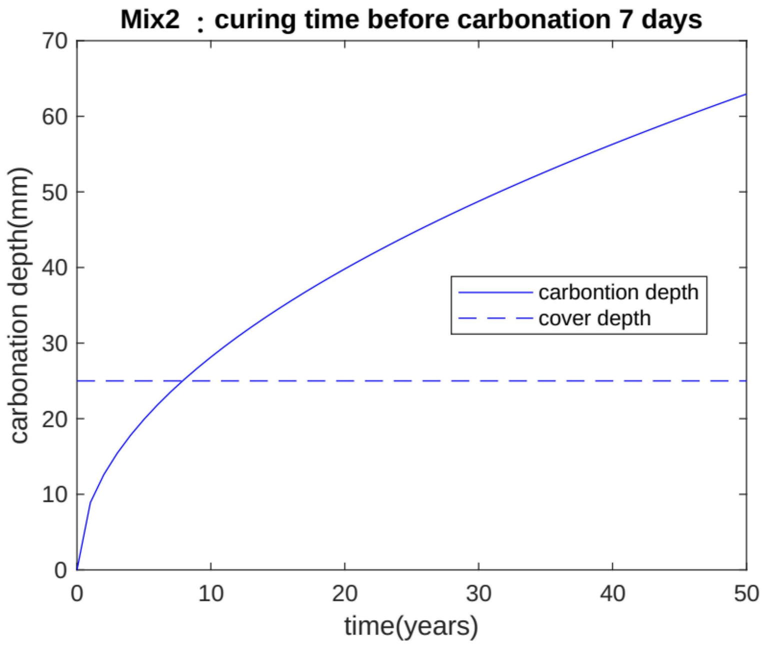

Figure 7. Carbonation depth curve of Mix 2.

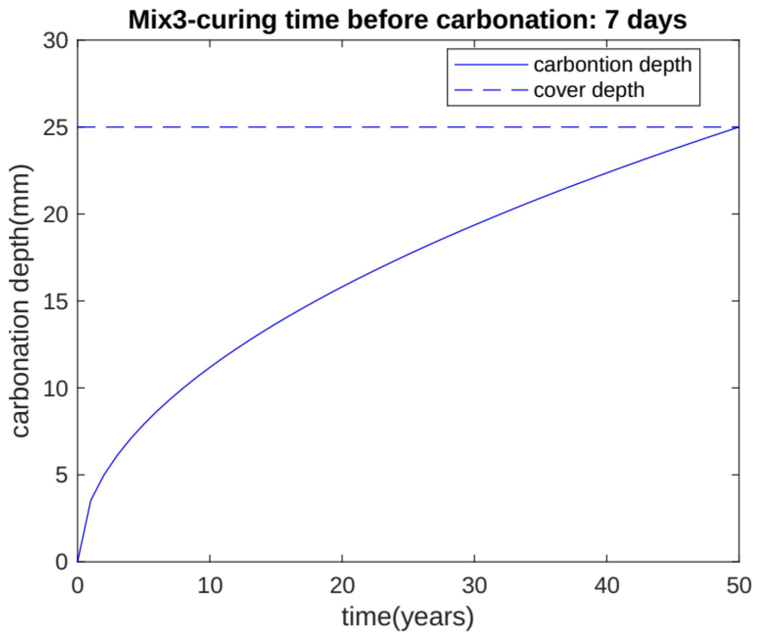

Figure 8. Carbonation depth curve of Mix 3.

For Case 4, the result of the optimized design is Mix 4. Its cement and fly ash masses are 221.34 and 270.53 kg/m^3, respectively. The water–binder ratio of Mix 4 is 0.34 (which is between the upper and lower limits), and the fly ash/binder ratio of the materials is 0.55 (which is equal to the upper limit). For Mix 4, its 7-day and 28-day real strengths are 26.98 and 47.22 MPa, respectively, which are higher than the design requirements of 21 and 30 MPa. This is also due to the carbonation durability requirements. For Mix 4, as shown in Figure 9, after 50 years of use the carbonation depth is 25 mm, which is also equal to the thickness of the protective layer. This shows that for Mix 3 and Mix 4, carbonation durability is the dominant factor in the design and that the 28-day strength and 7-day strength are not the dominant factors in the design.

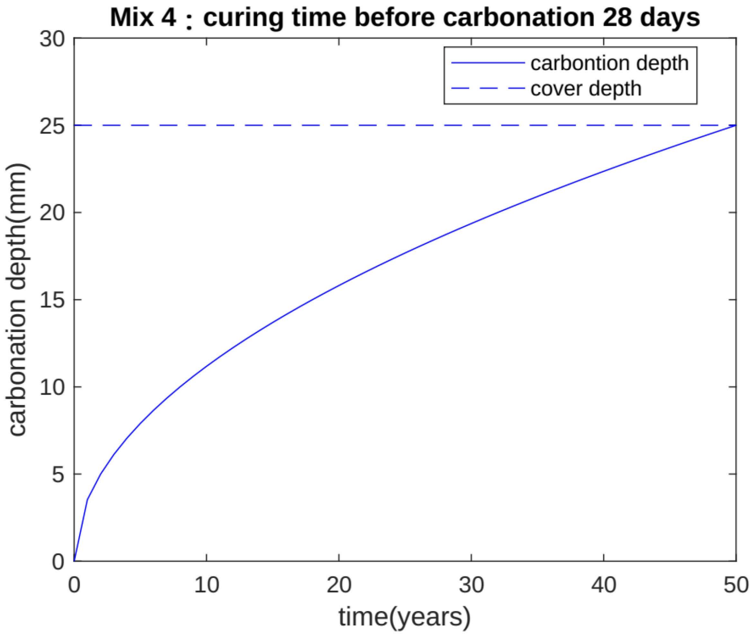

Figure 9. Carbonation depth curve of Mix 4.

As shown in Table 2, the carbonation depth constraint is one of the constraints in concrete mix design. As the age of concrete increases, its strength gradually increases, the degree of hydration gradually increases, the content of carbonatable substances gradually increases, the diffusion coefficient of CO_2 gradually decreases, and the anti-carbonation ability gradually becomes stronger. As shown in Table 3, the difference between the third and fourth examples is that the curing period before carbonation is different; the other factors are the same. For both examples, carbonation durability was the decisive factor in the mix design. By optimizing the design results, we can enhance carbonation durability as an effective way to design low-carbon concrete when carbonation durability becomes the dominant factor in the design.

The curing mechanisms of carbonation are as follows. As shown in Equation (4), with the increase in curing time before carbonation, the strength of the concrete fc(t) increases, the degree of hydration α increases, the CO_2 diffusion coefficient decreases, and the content of carbonatable substances $0.218 \times (C + 0.5 \times FA) \times \alpha$ increases. In Equation (2), both decreasing the numerator and increasing the denominator lead to a decrease in carbonation depth. As shown in Table 2, carbonation durability life is one of the constraints of the mix design. The curing time before the concrete is removed from the formwork affects carbonation, which affects the results of the mix design. The main purpose of this method is to enhance the carbonation durability of concrete by extending the curing time before carbonation begins, to meet the carbonation durability design requirements of low-carbon concrete, and to achieve the sustainable development of the concrete materials. In addition, although extending the curing time of concrete increases the durability, it increases the use time of the formwork and reduces the efficiency of formwork recycling; thus, it increases the cost of construction. Therefore, in actual engineering, the positive and negative effects of this method need to be comprehensively considered.

Compared with the low-carbon concrete design method in the reference literature, the originality of this study lies in its consideration of the impact of carbonation durability on mix design, especially the impact of concrete demolding time on low-carbon design. While most of the previous studies only focused on the material level, this study found that construction factors are also important. For low-carbon concrete, both the material and construction aspects need to be comprehensively considered.

The relationship between the calculated carbon emissions and the strength of concrete is shown in Figure 10. As the strength increases, the amount of carbon emissions also increases. The optimized design results of this study are consistent with those of previous research [19,20].

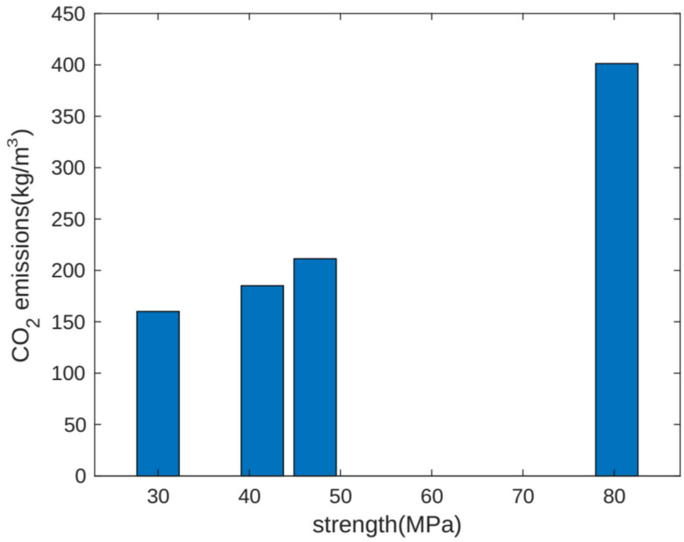

Figure 10. The relationship between strength and carbon emissions.

5. Discussion

In previous optimization designs, most of the research focused on the material composition of the concrete and rarely considered durability [17,18]. The main originality of this study was its systematic consideration of the requirements of three aspects: 28-day strength, construction (7-day strength), and durability. It was found that in different design scenarios, the optimal design had different dominant factors. Case 1 was dominated by 28-day strength, Case 2 was dominated by 7-day strength, and Cases 3 and 4 were dominated by carbonation durability. From Case 3 to Case 4, we found that increasing the curing time before carbonation was one of the effective methods of producing low-carbon concrete. Previous researchers have ignored this point [17–20]. In this study, the authors were the first to propose a design method for low-carbon fly ash concrete that considered curing time before carbonation.

In addition, it should be noted that the specific format of the strength formula and the coefficients of the formula proposed in this study are mainly based on the experimental results of the study's references and are not applicable to all concretes [10,11,26]. However, the steps of the method proposed in this study can be regarded as a general method. That is, the first step uses the regression method to obtain the strength prediction formula; then, the second step uses the genetic algorithm to optimize the mix ratio. The reliability of this two-step method has been proven in previous studies [13,17,19,20].

There are many methods that are used for the regression analysis of the experimental results. For example, the regression analysis that considers the basic mechanism and pre-formatting equations mainly uses the undetermined coefficient method. There are also regression methods that do not consider the basic mechanism, such as machine learning methods.

The genetic algorithm is a global optimization algorithm that has wide applicability. It mainly includes optimization design objectives and optimization design constraints. The optimization design goal of this study is to consider the carbon emissions of cementitious materials. The constraints of the optimization design are shown in Table 2. The optimization design of this study comprehensively considers both the material and the construction aspects.

There are certain limitations to the main hypothesis of this study. Firstly, it was assumed that the carbon emissions of concrete mainly come from cementitious materials, ignoring the carbon emissions that occur during transportation. Secondly, it was assumed that the carbon dioxide concentration was a constant value. As climate changes, CO_2 concentrations may increase. Finally, no consideration was given to repair works during use. When repair work is carried out, the durability of the concrete may be enhanced.

Another shortcoming of this study is that the method proposed is an algorithm, not a specific formula. By now, most engineering designers are probably more accustomed to using specific calculation formulas. However, if the algorithm proposed in this study is compiled using software or integrated into existing engineering software packages, then engineers can easily use the algorithm proposed in this study to design low-carbon concrete materials.

6. Conclusions

This study conducted a design analysis of low-carbon concrete mixed with fly ash concrete and took into account the three requirements of 28-day strength, construction sequence (7-day strength), and carbonation durability. The unit water consumption of the concrete was 170 kg/m^3; the 28-day design strength was 30 MPa; the 7-day design strength was 21 MPa; the protective layer thickness was 25 mm; and the carbonation durability life was 50 years. The results of the design cases are as follows:

(1) Design Case 1 assumes that the 28-day design strength of concrete is 30 MPa and does not consider the requirements for construction and carbonation durability. The optimized design result is that the masses of cement and fly ash are 167.70 and 204.84 kg/m^3, respectively. In Case 1, the water–binder ratio is 0.45 (which is located in the studied water–binder ratio range between 0.3 and 0.5), and the mass ratio of the fly ash to binder is 0.55 (reaching the upper limit of fly ash substitution). This design example illustrates that the use of concrete with a high level of fly ash can indeed reduce CO_2 emissions.

(2) Design Case 2 assumes that the 28-day design strength is 30 MPa and that the 7-day design strength is 21 MPa. The construction requirements are considered, but the durability requirements are ignored. The result of the optimized design is that the masses of cement and fly ash are 193.82 and 236.89 kg/m^3, respectively; the water–binder ratio of Mix 2 is 0.39 (which is located in the studied range of the water–binder ratio between 0.3 and 0.5), and the mass ratio of the fly ash to binder is 0.55 (reaching the upper limit of the fly ash replacement amount). For Mix 2, its 7-day strength is 21 MPa, which is equal to the design strength, but its 28-day real strength is 41.43 MPa, which is higher than the design strength of 30 MPa. This shows that the early strength development is slow due to the low reactivity of fly ash. When early formwork removal is required, the strength needs to be increased for 28 days to meet the construction requirements.

(3) Case 3 assumes that the 28-day design strength is 30 MPa and that the 7-day design strength is 21 MPa. After the formwork is removed at seven days, the material is exposed to the surrounding environment. For Case 3, the result of the optimized design is that the masses of cement and fly ash are 428.09 and 138.56 kg/m^3, respectively; the water–binder ratio of Mix 3 is 0.30 (reaching the lower limit of the studied water–binder ratio), and the mass ratio between the fly ash and binder is 0.24 (which is located between the upper and lower limits of the fly ash substitution rate). For Mix 3, its 7-day and 28-day real strengths are 58.61 and 80.29 MPa, respectively, which are higher than the design requirements of 21 and 30 MPa, respectively. This is because of the carbonation durability requirements. After 50 years of use, the carbonation depth is 25 mm, which is equal to the thickness of the protective layer.

(4) Case 4 assumes that the 28-day design strength is 30 MPa and that the 7-day design strength is 21 MPa. The material is only exposed to the surrounding environment after the formwork is removed at 28 days. For Case 4, the optimized design result is that the masses of cement and fly ash are 221.34 and 270.53 kg/m^3, respectively; the water–binder ratio is 0.34 (which is between the upper and lower limits), and the mass ratio of the fly ash to binder is 0.55 (which is equal to the upper limit). For Mix 4, its 7-day and 28-day real strengths are 26.98 and 47.22 MPa, respectively, which

are higher than the design requirements of 21 and 30 MPa, respectively. This is also due to the carbonation durability requirements. After 50 years of use, the carbonation depth is 25 mm, which is also equal to the thickness of the protective layer. From Case 3 to Case 4, it is shown that increasing the curing time before carbonation is one of the effective methods that can be used to produce low-carbon fly ash concrete.

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