Optimal mix design of air-entrained slag blended concrete considering durability and sustainability

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Abstract. Slag blended concrete is widely used as a mineral admixture in the modern concrete industry. This study shows an optimization process that determines the optimal mixture of air-entrained slag blended concrete considering carbonation durability, frost durability, CO2 emission, and materials cost. First, the aim of optimization is set as total cost, which equals material cost plus CO2 emission cost. The constraints of optimization consist of strength, workability, carbonation durability with climate change, frost durability, range of components and component ratio, and absolute volume. A genetic algorithm is used to determine optimal mixtures considering aim function and various constraints. Second, mixture design examples are shown considering four different cases, namely, mixtures without considering carbonation (Case 1), mixtures considering carbonation (Case 2), mixtures considering carbonation coupled with climate change (Case 3), and mixtures of high strength concrete (Case 4). The results show that the carbonization is the controlling factor of the mixture design of the concrete with ordinary strength (the designed strength is 30MPa). To meet the challenge of climate change, stronger concrete must be used. For high-strength slag blended concrete (design strength is 55MPa), strength is the control factor of mixture design.

Keywords: slag; carbonation; frost; service life; durability; low-CO2 concrete; sustainability; optimal design

1. Introduction

Slag is a by-product of the steel making industry. After the drying and grounding operations, the ground granulated slag can be used to replace partial cement for concrete productions. The slag-blended concrete has many advantages, such as high workability, high late age strength, high chloride resistance, and low cost and CO2 emissions. However, the addition of slag lowers the carbonation resistance of concrete (Papadakis and Tsimas 2002, Papadakis 2013, Demis et al. 2014). Hence, to confirm the sustainability of slag-blended concrete, the positive and negative aspects of slag should be carefully considered.

Sustainability is an important issue of the concrete industry. Many studies have been performed about the evaluations of sustainability of concrete containing slag. Won et al. (2015) reported that when 60% binder was replaced by slag, the CO2 emission of precast concrete reduced about 33.8%. Kim et al. (2016) found that when waste additive slag was used to replace 30% cement, the global warming potential of concrete reduced about 25%. Saade et al. (2015) showed that as compared with plain concrete, for concrete containing 33% to 66% slag in the binder, the global warming potential reduced by about 20% and 50%, respectively. Kim et al. (2018) reported that the optimum ratio of slag in binder was about 30%. At this replacement ratio, the CO2 emission reduced about 30%. Li et al. (2016) found that, compared with the control cement, the abiotic depletion potential and land use potential of slag-blended cement was much lower. Jiang et al. (2014) reported that, for concrete with a strength of 35MPa, alkali-activated slag concrete has 73% lower greenhouse gas emissions, 43% less energy and 25% less water. Yang et al. (2015) reported that, compared with plain concrete, concrete with high volume supplementary cementing materials can reduce global warming potential by about 75% to 86% and reduce abiotic depletion by about 73-82%.

Although fundamental studies have been done regarding the evaluation of sustainability of slag-blended concrete (Jiang et al. 2014, Saade et al. 2015, Won et al. 2015, Yang et al. 2015, Kim et al. 2016, Li et al. 2016, Kim et al. 2018), studies into the material design of sustainable blended concrete are limited. Lee et al. (2012) determined the mixtures of concrete with target strength and workability using the harmony search algorithm. Golaflshani and Behnood (2019) predicted the strength of silica fume-blended concrete using biogeography-based programming, and determined optimal mixtures using constrained biogeography-based optimizations. Park (2013) determined the optimal concrete mixtures using the genetic algorithm. The slump, strength, carbonation speed, cost, and CO2 emission were considered. Fennis and Walraven (2012) made a mixture design of sustainable concrete using particle packing technology. The cement content was reduced by about 50% and CO2 emission was lowered by about 25%. Young et al. (2019) evaluated the compressive strength of blended concrete using the machine learning method and
found the optimal mixture using the Broyden-Fletcher-Goldfarb-Shanno (BFGS) algorithm. Material cost constituted the aim function of optimization (Young et al. 2019). Chen et al. (2019) designed low CO₂ concrete with different strengths using an adaptive surrogate model. The adaptive sampling method was used to improve the accuracy of the surrogate model.

Although previous studies (Fennis and Walraven 2012, Lee et al. 2012, Park 2013, Chen et al. 2019, Golafshani and Behnoood 2019, Young et al. 2019) have proposed optimal mixture design methods of concrete, these methods show some limitations. First, methods in references (Fennis and Walraven 2012, Lee et al. 2012, Chen et al. 2019, Golafshani and Behnoood 2019, Young et al. 2019) mainly focus on concrete strength and workability. The durability aspect, such as carbonation, is not considered. However, when slag blended concrete has the same strength as plain concrete, the carbonation depth of slag blended concrete is higher than plain concrete (Papadakis and Tsimas 2002, Demis et al. 2014). Hence carbonation durability is a necessary constraint of the mixture design of blended concrete. Second, although Park’s model (2013) considers the carbonation durability, the aim function and constraints are not clear in Park’s model (2013). Furthermore, because the greenhouse effect becomes more severe when CO₂ emission becomes more severe, the carbonation of concrete is accelerated (Yoon et al. 2007, Talukdar and Banthia 2016). It is necessary to consider the effect of climate change on carbonation durability for the mixture design of blended concrete. Third, current concrete mixture design methods (Fennis and Walraven 2012, Lee et al. 2012, Park 2013, Golafshani and Behnoood 2019, Young et al. 2019) assume that strength is major factor of mixture design, and treat durability as a secondary concern. However, for ordinary strength-blended concrete, due to the limit of carbonation resistance, carbonation durability may be the dominant factor of mixture design (Demis et al. 2014).

To overcome the lack of previous research, this research shows an optimization procedure for determining the optimal mixture of air-entrained slag blended concrete considering durability and sustainability. The aim function of optimization is set as total cost which equals the cost of materials plus the cost of CO₂ emissions. The aim function is as follows

\[ \text{COST} = \text{COST}_M + \text{COST}_{CO2} \]  

where COST, COST_M, and COST_CO2 are the total cost, material cost, and CO₂ emissions cost of concrete, respectively.

The material cost is the sum of the individual cost of concrete components. The material cost can be determined as follows

\[ \text{COST}_M = \sum_{i=1}^{7} m_i \text{Pr}_i \]  

where \( m_i \) is the mass of cement, slag, water, fine aggregate, coarse aggregate, water-reducing agent, and air-entraining agent, and \( \text{Pr}_i \) is the unit price of the individual components of concrete.

The CO₂ emission cost equals the mass of CO₂ emission times the unit price of CO₂. The CO₂ emission cost can be established as

\[ \text{COST}_{CO2} = \text{Pr}_{CO2} \times \sum_{i=1}^{7} m_i \text{CO}_{2i} \]  

where \( \text{Pr}_{CO2} \) is unit price of CO₂ (\( \text{Pr}_{CO2} \) is set as NT $885.496/ton (Park et al. 2013, Ahn and Jeon 2019) ), and \( \text{CO}_{2i} \) is the CO₂ emissions of individual components of concrete. Table 1 shows the unit price and unit CO₂ emission of concrete components (Yeh 2007, Nazari and Sanjayan 2016).

2.2 Constraints

The mix design is subjected to numerous constraints, for example, compressive strength, workability, carbonation durability, frost durability, absolute volume, component range, and component ratio (Yeh 2007).

2.2.1 Compressive strength constraint

The compressive strength constraint means that the actual strength at given ages ought to be greater than or comparable to the design strength. For air-entrained concrete, because the content of entrained air increases, the compressive strength decreases. Based on experimental results (Yeh 1998), the 28-day compressive strength of air-entrained slag-blended concrete is determined as

\[ f_c = 18.63 \left( \frac{W}{C+0.8075C} \right)^{1.137} (1 - 0.05V_{air}) \]  

where \( W, C, \) and \( \text{SG} \) are the mass of water, cement, and slag, respectively; \( V_{air} \) is the content of entrained air (the

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**Table 1 Unit cost and unit CO₂ emissions of concrete components (Yeh 2007, Nazari and Sanjayan 2016)**

<table>
<thead>
<tr>
<th>Component</th>
<th>Unit Cost</th>
<th>Unit CO₂ Emission</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>$2.25/\text{kg}$</td>
<td>$0.031/\text{kg}$</td>
</tr>
<tr>
<td>Slag</td>
<td>$1.2/\text{kg}$</td>
<td>$0.0265/\text{kg}$</td>
</tr>
<tr>
<td>Water</td>
<td>$0.01/\text{kg}$</td>
<td>$0.00196/\text{kg}$</td>
</tr>
<tr>
<td>Fine aggregate</td>
<td>$0.28/\text{kg}$</td>
<td>$0.0026/\text{kg}$</td>
</tr>
<tr>
<td>Coarse aggregate</td>
<td>$0.236/\text{kg}$</td>
<td>$0.0075/\text{kg}$</td>
</tr>
<tr>
<td>Water-reducing agent</td>
<td>$15.75/\text{kg}$</td>
<td>$0.25/\text{kg}$</td>
</tr>
<tr>
<td>Air-entraining agent</td>
<td>$23.625/\text{kg}$</td>
<td>$0.53/\text{kg}$</td>
</tr>
</tbody>
</table>

Density (kg/m³): 3150, 2850, 1000, 2600, 2540, 1200, 1050
unit of $V_{air}$ is percentage); $\frac{W}{C+S}0.75S$ is the efficient water to binder ratio of concrete; and the coefficient 0.05 of $V_{air}$ means that as the content of entrained air increases by 1%, the compressive strength decreases by 5% (Mehta and Monteiro 2014).

2.2.2 Workability constraint

Slump is a straightforward and helpful index of concrete workability. The workability constraint means the actual slump of concrete should greater or comparable to the preferred slump. Based on experimental results (Lim et al. 2004, Benazzouk et al. 2006, Thomas 2013), the slump of air-entrained slag blended concrete is determined as

$$\text{Slump} = \left( -2.509 \times \frac{W}{C+S} + 100 + 0.088 \times W \times 1.462 \right) \times \frac{SD}{CA} \times 100 + 0.184 \times \frac{SG}{C+SG} \times 100 + 0.199 \times SP \times 341 \times (1 + 0.03 \times V_{air})$$

where $SD$, $CA$, and $SP$ are the mass of sand, coarse aggregate, and superplasticizer, respectively; $\frac{W}{C+S}$ is the water to binder ratio; $\frac{SD}{CA}$ is the sand ratio; $\frac{SG}{C+SG}$ is the slag replacement ratio; and $1+0.03V_{air}$ considers the increase in slump due to the entrained air (Benazzouk et al. 2006).

The mass of superplasticizer is determined using the water to binder ratio as follows (Lim et al. 2004, Thomas 2013)

$$SP = \begin{cases} 18.43 - 37.11 \times \frac{W}{C+S} & W \leq 0.497 \times \frac{W}{C+S} \\ 0 & W > 0.497 \times \frac{W}{C+S} \end{cases}$$

The mass of air-entraining agent is determined as a function of air content and binder content. The mass of air-entraining agent can be determined as (Thomas 2013, Young et al. 2019)

$$AE = 0.00005 \times V_{air} \times (C + SG).$$

This equation implies that because the binder content and air content increases, the content of air-entraining agent should increase.

2.2.3 Carbonation durability constraint

Adding slag boosts the carbonation depth of concrete. Carbonation durability should be thought of as a necessary constraint for this specific mixture type of slag-blended concrete. The carbonation durability constraint means that the carbon depth of concrete ought to be less than the coverage depth.

Our previous studies (Lee and Wang 2016, Wang and Park 2017) proposed that for the environment with a relative humidity higher than 50%, the carbonation depth of slag blended concrete can be determined as follows

$$x_c = \frac{2D(\text{CO}_2)\mu t}{[\text{CH}] + 3[\text{CSH}]}$$

where $x_c$ is carbonation depth; $D$ is the CO$_2$ diffusivity of concrete; [CO$_2$] is the CO$_2$ concentration; $t$ is exposure time; [CH] and [CSH] are the molar content of calcium hydroxide (CH) and calcium silicate hydrate (CSH) in concrete, respectively.

The mass of CH and CSH can be determined as follows (Lee and Wang 2016, Wang and Park 2017)

$$CH = C \times v_1 \times \alpha - SG \times v_2 \times \alpha_{SG}$$

$$CSH = 2.85 \left( C \times f_{SC} \times \alpha + SG \times f_{SG} \times \alpha_{SG} \right)$$

where $\alpha$ and $\alpha_{SG}$ are the reaction degree of cement and slag, respectively; $v_1$ and $v_2$ are stoichiometric ratio of cement hydration and slag reaction, respectively. $v_1$ is the production of CH from 1 g cement, and $v_2$ is the consumption of CH from 1 g slag. $f_{SC}$ and $f_{SG}$ are the mass fraction of SiO$_2$ in cement and slag, respectively. Eq. (9) considers the production of CH from cement hydration and the consumption of CH from slag reaction. Eq. (10) shows both cement hydration and slag reaction will form CSH.

The reaction degree of cement and slag can be determined using blended hydration model. The blended hydration model considers the effect of water to binder ratio, slag substitution ratio, and curing condition on reaction degrees. The details of blended cement hydration model can be found in references (Lee and Wang 2016, Wang and Park 2017).

The diffusivity of CO$_2$ can be determined as follows (Papadakis and Tsimas 2002, Lee and Wang 2016)

$$D = 6.1 \times 10^{-6} \left[ \frac{\varepsilon}{\rho_w} \right] \left[ \frac{\mu}{\rho_a} \right]^{3} \left( 1 - \frac{RH}{100} \right)^{2.2} \exp \left[ \beta \left( \frac{1}{T_{ref}} - \frac{1}{T} \right) \right]$$

$$\varepsilon = \frac{w}{\rho_w} - \Delta \varepsilon_{CR} - \Delta \varepsilon_{SG} - \Delta \varepsilon_{CR} + (V_{air} - 2)^{0.01}$$

where $\varepsilon$ is porosity of concrete, $\rho_w$ and $\rho_a$ are the density of cement and water, respectively, RH is the relative humidity of exposure, $\beta$ is the activation energy of CO$_2$ diffusion ($\beta = 4300$), $T_{ref}$ is the reference temperature (293 K); and $T$ is environmental temperature. $\Delta \varepsilon_{CE}$, $\Delta \varepsilon_{SG}$, and $\Delta \varepsilon_{CR}$ means the porosity reduction due to cement hydration, slag reaction and carbonation, respectively (Papadakis and Tsimas 2002, Demis et al. 2014, Lee and Wang 2016). $(V_{air} - 2) \times 0.01$ considers the increasing concrete porosity due to entrained air (for non-air entrained concrete, the content of entrapped air is assumed to be 2%). Eqs. (8) and (11) considered the effect of climate change, such as the increasing of CO$_2$ concentration and temperature. With the increase of CO$_2$ concentration and temperature, the carbonation rate also increases.

2.2.4 Frost durability constraint

The freezing and thawing cycles damage concrete. This is evidenced through surface scaling and internal cracking. Entained air is essential to verify the frost reliability of concrete. The frost durability constraint means the harm of concrete ought to be under the specifications stipulated. The ACI code recommends that when the maximum size of a coarse aggregate is 19 mm, the recommended entrained air content is 3.5%, 5%, and 6% for mild, moderate, and severe exposure, respectively (Thomas 2013, Mehta and Monteiro 2014). We approximately assumed that when the
Table 2 Lower and upper limits of concrete components and component ratios

<table>
<thead>
<tr>
<th>Component</th>
<th>Lower limit (kg/m³)</th>
<th>Upper limit (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>50</td>
<td>540</td>
</tr>
<tr>
<td>Slag</td>
<td>0</td>
<td>500</td>
</tr>
<tr>
<td>Water</td>
<td>120</td>
<td>250</td>
</tr>
<tr>
<td>Coarse aggregate</td>
<td>700</td>
<td>1100</td>
</tr>
<tr>
<td>Fine aggregate</td>
<td>550</td>
<td>1000</td>
</tr>
<tr>
<td>Water-to-binder ratio</td>
<td>0.20</td>
<td>0.75</td>
</tr>
<tr>
<td>Water-to-solid ratio</td>
<td>0.08</td>
<td>0.12</td>
</tr>
<tr>
<td>Slag-to-binder ratio</td>
<td>0</td>
<td>0.50</td>
</tr>
<tr>
<td>Aggregate-to-binder ratio</td>
<td>2.1</td>
<td>6.4</td>
</tr>
<tr>
<td>Sand ratio</td>
<td>0.40</td>
<td>0.52</td>
</tr>
</tbody>
</table>

2.2.5 Absolute volume constraint

Absolute volume constraint means that the sum of the components of concrete should equal 1 m³ minus the volume of entrained air. The absolute volume constraint is

$$\sum_{i=1}^{7} \frac{p_i}{\rho_i} = 1 - V_{air} \times 0.01. \quad (13)$$

2.2.6 Component range and component ratio constraint

The concrete component contents should fall inside the lower and upper limits (Table 2). The component ratio constraint means the ratios of concrete component, for example, water-to-binder ratio, slag substitute ratio, sand ratio, aggregate-to-binder ratio, and water-to-solid ratio, should fall inside the lower and upper limits (Table 2) (Yeh 2007, Young et al. 2019).

2.3 Optimization procedure

The optimization of mixtures consists of two parts: object function and constraints. The object function is the total cost (material cost plus CO₂ emission cost). The constraints include strength, workability, carbonation and frost durability, absolute volume, component range, and component ratio. The genetic algorithm (GA) toolbox in MATLAB can be used to solve optimization problems. The genetic algorithm uses the theory of biological evolution to simulate the problem to be solved as the process of biological evolution, and generates the next generation of solutions through selection, crossover and mutation, and gradually eliminates the solutions with low fitness and increases the fitness function value. Thus, after N generations, individuals with high adaptive function values may evolve (Park et al. 2013, Park 2013, García-Segura and Yepes 2016).

The flowchart from the calculation is proven in Fig. 1. The GA fitness function is total price, which equals the material cost plus CO₂ emission cost. The property evaluation model includes a strength model, slump model, and carbonation model thinking about climatic change. The restrictions include mechanical, workability, service life, absolute volume, limit of components, and component ratio. Once the fitness function with constraints is solved, the optimal mixture is possible.

3. Illustrative examples

Within this section, we design mixtures for slag-blended concrete with assorted entrained-air contents thinking about carbonation and climatic change. The utmost size coarse aggregate is assumed to become 19 mm. Based on the design code, once the maximum size coarse aggregate is nineteen mm, the suggested entrained air contents are 3.5%, 5%, and 6% for mild, moderate, and severe exposure, correspondingly. Thinking about carbonation and frost durability, the minimum design strength and minimum cover depth are assumed to become 30 MPa and 25 mm, respectively (Molsy et al. 2012). Considering scaling resistance of frost concrete, upper limit of slag replacement ratio is set as 50% (Thomas 2013). The needed slump is set as 150 mm. The CO₂ concentration is 0.038%, relative humidity is 65%, and the environmental temperatures is 15°C. The service existence is assumed to be half a century (Molsy et al. 2012).

Four design cases are considered: Situation 1, mixture design without thinking about carbonation durability, Situation 2, mixture design thinking about carbonation durability, Situation 3, mixture design thinking about the result of climatic change on carbonation, and Situation 4, mixture style of high-strength concrete. The design strength for situation one to three is 30 MPa, and the design strength for situation 4 is 55 MPa. As many as 12 mixtures (4 cases × 3 air contents=12) were studied.

The result of carbonation, climate change, and design strength on mixture design could be clarified in line with the comparisons of design cases. From Situation one to two, the result of carbonation durability is highlighted. From Situation two to three, the result of climatic change is

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Fig. 1 Flowchart of calculation
Table 3 Optimal mixtures of concrete

<table>
<thead>
<tr>
<th>Section</th>
<th>Mix</th>
<th>Cement (kg/m³)</th>
<th>Slag (kg/m³)</th>
<th>Water (kg/m³)</th>
<th>Sand (kg/m³)</th>
<th>Gravel (kg/m³)</th>
<th>Super-plasticizer (kg/m³)</th>
<th>Air entraining agent (kg/m³)</th>
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</thead>
<tbody>
<tr>
<td>Section 3.1</td>
<td>Mix1</td>
<td>167</td>
<td>167</td>
<td>167</td>
<td>167</td>
<td>704</td>
<td>1055</td>
<td>0.00</td>
</tr>
<tr>
<td>-no durability</td>
<td>Mix2</td>
<td>179</td>
<td>179</td>
<td>165</td>
<td>165</td>
<td>681</td>
<td>1022</td>
<td>1.31</td>
</tr>
<tr>
<td></td>
<td>Mix3</td>
<td>188</td>
<td>188</td>
<td>163</td>
<td>163</td>
<td>666</td>
<td>999</td>
<td>2.31</td>
</tr>
<tr>
<td>Section 3.2</td>
<td>Mix4</td>
<td>234</td>
<td>234</td>
<td>168</td>
<td>168</td>
<td>652</td>
<td>979</td>
<td>5.12</td>
</tr>
<tr>
<td>-with durability</td>
<td>Mix5</td>
<td>264</td>
<td>264</td>
<td>166</td>
<td>166</td>
<td>617</td>
<td>926</td>
<td>6.79</td>
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<td></td>
<td>Mix6</td>
<td>284</td>
<td>284</td>
<td>164</td>
<td>164</td>
<td>594</td>
<td>892</td>
<td>7.68</td>
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<tr>
<td>Section 3.3</td>
<td>Mix7</td>
<td>249</td>
<td>249</td>
<td>168</td>
<td>168</td>
<td>641</td>
<td>962</td>
<td>5.91</td>
</tr>
<tr>
<td>-with climate change</td>
<td>Mix8</td>
<td>280</td>
<td>280</td>
<td>166</td>
<td>166</td>
<td>606</td>
<td>909</td>
<td>7.42</td>
</tr>
<tr>
<td></td>
<td>Mix9</td>
<td>299</td>
<td>299</td>
<td>164</td>
<td>164</td>
<td>583</td>
<td>874</td>
<td>8.23</td>
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<tr>
<td>Section 3.4</td>
<td>Mix10</td>
<td>286</td>
<td>286</td>
<td>169</td>
<td>169</td>
<td>614</td>
<td>921</td>
<td>7.50</td>
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<tr>
<td>-high strength concrete</td>
<td>Mix11</td>
<td>307</td>
<td>307</td>
<td>166</td>
<td>166</td>
<td>586</td>
<td>879</td>
<td>8.38</td>
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<tr>
<td></td>
<td>Mix12</td>
<td>323</td>
<td>323</td>
<td>165</td>
<td>165</td>
<td>565</td>
<td>848</td>
<td>8.97</td>
</tr>
</tbody>
</table>

Table 4 Performance of optimal mixtures

<table>
<thead>
<tr>
<th>Section</th>
<th>Mix</th>
<th>Strength (MPa)</th>
<th>Slump (mm)</th>
<th>Air content (%)</th>
<th>Carbonation depth (mm)</th>
<th>Total Cost ($NT/m³)</th>
<th>W/B</th>
<th>Slag Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Section 3.1</td>
<td>Mix1</td>
<td>30.00</td>
<td>199.51</td>
<td>3.50</td>
<td>37.48</td>
<td>1174.42</td>
<td>0.50</td>
<td>0.50</td>
</tr>
<tr>
<td>-no durability</td>
<td>Mix2</td>
<td>30.00</td>
<td>219.32</td>
<td>5.00</td>
<td>40.98</td>
<td>1232.56</td>
<td>0.46</td>
<td>0.50</td>
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<tr>
<td></td>
<td>Mix3</td>
<td>30.00</td>
<td>233.15</td>
<td>6.00</td>
<td>42.92</td>
<td>1278.69</td>
<td>0.43</td>
<td>0.50</td>
</tr>
<tr>
<td>Section 3.2</td>
<td>Mix4</td>
<td>43.94</td>
<td>240.35</td>
<td>3.50</td>
<td>25.00</td>
<td>1512.83</td>
<td>0.36</td>
<td>0.50</td>
</tr>
<tr>
<td>-with durability</td>
<td>Mix5</td>
<td>46.53</td>
<td>263.30</td>
<td>5.00</td>
<td>25.00</td>
<td>1647.13</td>
<td>0.31</td>
<td>0.50</td>
</tr>
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<td></td>
<td>Mix6</td>
<td>47.55</td>
<td>277.33</td>
<td>6.00</td>
<td>25.00</td>
<td>1730.56</td>
<td>0.29</td>
<td>0.50</td>
</tr>
<tr>
<td>Section 3.3</td>
<td>Mix7</td>
<td>47.10</td>
<td>246.43</td>
<td>3.50</td>
<td>25.00</td>
<td>1582.71</td>
<td>0.34</td>
<td>0.50</td>
</tr>
<tr>
<td>-with climate change</td>
<td>Mix8</td>
<td>49.58</td>
<td>268.38</td>
<td>5.00</td>
<td>25.00</td>
<td>1716.62</td>
<td>0.30</td>
<td>0.50</td>
</tr>
<tr>
<td></td>
<td>Mix9</td>
<td>50.48</td>
<td>281.89</td>
<td>6.00</td>
<td>25.00</td>
<td>1799.74</td>
<td>0.27</td>
<td>0.50</td>
</tr>
<tr>
<td>Section 3.4</td>
<td>Mix10</td>
<td>55.00</td>
<td>258.76</td>
<td>3.50</td>
<td>20.23</td>
<td>1750.81</td>
<td>0.29</td>
<td>0.50</td>
</tr>
<tr>
<td>-high strength concrete</td>
<td>Mix11</td>
<td>55.00</td>
<td>276.10</td>
<td>5.00</td>
<td>21.48</td>
<td>1837.15</td>
<td>0.27</td>
<td>0.50</td>
</tr>
<tr>
<td></td>
<td>Mix12</td>
<td>55.00</td>
<td>288.01</td>
<td>6.00</td>
<td>21.90</td>
<td>1904.25</td>
<td>0.25</td>
<td>0.50</td>
</tr>
</tbody>
</table>

Highlighted. From Situation 3 to Situation 4, the result of design strength is highlighted.

3.1 Mixture design without considering carbonation durability

In this section, air-entrained slag blended concrete was created without thinking about carbonation durability. Based on the GA, the mixtures were calculated as proven in Table 3. The entrained air items in Mix1, Mix2, and Mix3 are 3.5%, 5%, and 6%, correspondingly. The performance of Mix1 to Mix 3 shows up in Table 4. From Mix1 to Mix3, the binder content increases, the all-inclusive costs increase, and the water to binder ratio decreases. The strengths of Mix1 to Mix3 are identical, i.e., 30 MPa. The slump of mixtures is greater compared to needed slump (150 mm). The slag to binder ratios are identical, i.e., .50%, the maximum of slag since the cost of slag is a lot lower compared to cement. Given a particular real strength (30 MPa), because the content of binder increases, the price of concrete increases.

In line with the carbonation model, the carbonation depth of Mix1 to Mix3 was calculated and it is provided in Fig. 2. After 50 years of service, the carbonation depth is more than the coverage depth (25 mm). Quite simply, Mix1 to Mix3 cannot fulfill the carbonation durability requirement. The constraint of carbonation durability should be thought about when making the mixture of air-entrained slag blended concrete. Under the same compressive strength, with the increase of entrained air, concrete carbonation depth increases.

3.2 Mixture design considering carbonation durability

Section 3.1. showed the necessity of considering
carbonation durability as a constraint on the mixture design of air-entrained slag blended concrete. In this section, we set carbonation durability as the constraint on mixture design. According to the GA, the mixtures were calculated and are listed in Table 3. The entrained air contents of Mix 4 to Mix 6 are 3.5%, 5%, and 6%, respectively. The performance of Mixes 4-6 is described in Table 4. According to Table 3 and Table 4, the following results are obtained: First, the water contents in Mixes 4-6 were similar to those of Mix1 to Mix3, respectively. The binder contents of Mixes 4-6 were higher than those of Mix1 to Mix3, respectively. The strengths of Mixes 4-6 were higher than those of Mix1 to Mix3, respectively. Second, the compressive strengths of Mixes 4-6 were higher than the design strength (30 MPa). This means that, for Mixes 4-6, carbonation durability was the decisive factor in mixture design. As proven in Fig. 3, the carbonation depth equaled the coverage depth (25 mm). Third, for Mix1 and Mix4, the entrained air contents were same, however the strength was elevated in Mix4. Consequently, the price was also elevated. Similarly, the price of Mix5 and Mix6 are greater than individuals Mix2 and Mix3, correspondingly.

3.3 Mixture design considering the effect of climate change

In Sections 3.1-3.2, the CO₂ concentration is assumed to become constant. However, as suggested through the Intergovernmental Panel on Climate change (IPCC), the CO₂ concentration and global temperature increase yearly (IPCC 2014). The IPCC suggested various climate change scenarios, for example, Representative Concentration Pathways 8.5 (RCP8.5), RCP6.0, RCP4.5, and RCP2.6. RCP 8.5 describes the scenario most abundant in serious climatic change, and RCP2.6 describes relatively slight climatic change. The quality of climatic change of RCP6.0 is between RCP 8.5 and RCP2.6. Within this section, we think about the aftereffect of the RCP6.0 climatic change scenario on mixture design. The growing CO₂ concentration and temperature in RCP 6.0 are proven in Fig. 4(a), and 4(b), correspondingly. To consider climate change, the time-averaged CO₂ concentration (\(\frac{\int_{t_0}^{t} [CO_2] dt}{t}\)) and time-averaged temperature increase (\(\frac{\int_{t_0}^{t} [\Delta T] dt}{t}\)) are used for calculating carbonation depth (Kwon et al. 2009). Fig. 4(c) to 4(e) show the carbonation depths with and without climate change (the beginning time is the year 2000). Because of climate change, the carbonation depth of RCP 6.0 scenario is greater compared to cover depth. In other words, Mix4 to Mix6 cannot satisfy the requirement of carbonation durability with the RCP6.0 climate change scenario.

The suggested carbonation model views the effect of climatic change on carbonation depth. The GA will find the optimal mixtures under climate change scenario RCP6.0. As proven in Tables 3 and 4, after considering climate change,
the binder content of concrete increases. Consequently, the compressive strength increases. As proven in Fig. 5, the carbonation depth of Mix7 to Mix9 equals the coverage depth. Quite simply, Mix7 to Mix9 satisfies the carbonation durability requirement thinking about climate change.

3.4 Mixture design of high strength concrete

In Sections 3.1-3.3, the design strength is 30 MPa, the real strength is more than the design strength, and also the carbonation durability may be the decisive element in mixture design. Within this section, the design strength is set as 55 MPa. Other constraints are similar to those in Section 3.3. Based on the properties' evaluation models and also the GA, the mixtures were determined (Table 3). The performance is supplied in Table 4, which shows that the compressive strengths of Mix10 to Mix12 were exactly the same, i.e., 55 MPa. Fig. 6 implies that the carbonation depth is underneath the cover depth. Hence, for greater-strength concrete (55 MPa), strength is a decisive element in mixture design, and carbonation is not. Quite simply, high binder content and low porosity provide enough carbonation resistance. Fig. 7 shows the cost of all mixtures (Mix1 to Mix12) with assorted entrained air contents and strengths. Generally, given a particular entrained air content, as concrete strength increases, the cost of concrete also...
Fig. 5 Carbonation depth of Mix7 to Mix 9 (mixtures considering the effect of climate change)

Fig. 6 Carbonation depth of Mix10 to Mix 12 (high strength concrete)

3.5 Discussion

First, the suggested model views not only mechanical qualities and workability, but also the durability of air-entrained slag blended concrete. Traditional mixture design methods disregard the durability of concrete (Mehta and Monteiro 2014, Shi et al. 2015). However, we discovered that, for air-entrained slag blended concrete with ordinary strength (design strength 30 MPa), carbonation durability may be the decisive element in mixture design. The actual strength is greater compared to design strength. When climatic change is recognized, the actual strength and binder content ought to be improved.

Second, the findings reveal that, for high strength concrete (design strength 55 MPa), strength may be the decisive factor for mixture design because of the greater binder content and greater carbonation resistance (Rajasekar et al. 2019). The suggested design method may be used to discover the threshold value of the design strength with distinct strength control and durability control.

Third, the suggested technique is flexible and could be adapted to numerous design codes. The different design codes might have different calculation equations for mechanical, workability, and durability qualities (Yang et al. 2015, Wang and Luan 2018, Young et al. 2019). Quite simply, the GA constraints equations might be different. However, the GA is really a general procedure you can use to obtain the global optimization results with various constraints (Yeo and Potra 2015).

The suggested design method has some limitations. Finding general models for frost damage, for example, surface scaling and internal cracking, continues to be difficult. Within this study, we assumed that, whenever the suggested strength, upper limit of slag replacement ratio, and entrained air of design code are utilized, concrete has good frost resistance (Ozbay et al. 2016). Later on, design
the mix of concrete with frost exposure, precise evaluation types of surface scaling and internal cracking ought to be built. The carbonation durability with frost damage should be thought about thoroughly in future studies.

4. Conclusions

This paper outlines a process to determine the optimal mixture of air-entrained slag blended concrete regarding carbonation and frost durability.

First, the optimization process of mixtures includes two aspects: the aim function and constraints. The aim function is the all-inclusive costs (material cost plus CO$_2$ emission cost). The restrictions include strength, workability, carbonation and frost durability, absolute volume, component range, and component ratio. The carbonation model considers climatic change.

Second, a GA can be used for making an optimal mixture. A complete set of 12 design examples (four cases with three different air contents=12) was investigated. The 4 design cases were Situation 1, mixture design without thinking about carbonation durability; Situation 2, mixture design thinking about carbonation durability; Situation 3, mixture design thinking about the result of climatic change on carbonation; and Situation 4: mixture style of high strength concrete.

Third, case study results demonstrated that for ordinary strength concrete (real strength 30 MPa), as the air content increases from 3.5% to 6%, carbonation depth increases from 37.48 mm to 42.92 mm, which are higher than cover depth. Carbonation durability may be the decisive factor for mixture design of ordinary strength concrete. On the other hand, after considering carbonation durability, for concrete containing 3.5% to 6.5% entrained air, the real strength is from 43.94 to 47.55 MPa, which is much greater compared to the design strength of 30 MPa. Furthermore, when climatic change is recognized, for concrete containing 3.5% to 6.5% entrained air, the real strength is from 47.10 to 50.48 MPa. The real strength and binder content are higher than those without considering climate change.

Fourth, for high strength concrete (design strength 55 MPa), as the air content increases from 3.5% to 6%, carbonation depth increases from 20.23 mm to 21.90 mm. The carbonation depths are lower compared to cover depth, and strength may be the decisive factor for the mixture design of high strength concrete. Given a certain amount of entrained air, the cost of concrete increases as the strength of the concrete increases.

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Reference


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