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Evaluation of CO$_2$ emission reduction effect using in-situ production of precast concrete components

Jeeyoung Lim and Sunkuk Kim

Department of Architectural Engineering, Kyung Hee University, Yongin-si, Republic of Korea

ABSTRACT

Precast concrete (PC) construction method is typically preferred due to its reduced construction time, quality assurance, and cost effectiveness. Experimental studies have proven that in-situ production of PC components ensures equivalent or enhanced quality with substantial cost reductions compared to those of in-plant production, under the same production conditions. The construction method may also be environment friendly due to its relatively low CO$_2$ emissions. However, it is necessary to examine the degree of this method’s effectiveness via experimental studies. The purpose of this study is to evaluate the CO$_2$ emission reduction effect of in-situ production of PC components. Using a case project, the CO$_2$ emission is estimated and compared for the operations between in-situ and in-plant production. The CO$_2$ emission of in-situ produced PC components reduced by 14.3% or more when compared to the in-plant production. This shows that in-situ production of PC components can greatly reduce CO$_2$ emissions, while maintaining its cost effectiveness and quality assurance. Furthermore, this study contributes in changing the negative perception of in-situ production of PC components and in the development of algorithms that scientifically analyze the CO$_2$ emission reduction effect of in-situ production of PC components.

1. Introduction

Precast concrete (PC) construction method has been preferred for building erection operations (Kim et al. 2013). This preference is attributed to its low cost (Polat 2008; Yee and Eng 2001; Ning, Lam, and Lam 2010), high quality assurance (Eastman and Sacks 2008; Lim et al. 2011), and reduced construction time (Kang 2008; Badir, Kadir, and Hashim 2002; Li and Love 2000). Several studies have been conducted and reported for the PC construction method. Furthermore, a few experimental studies have verified that in-situ production of PC components ensures equivalent or enhanced quality and a substantial reduction in cost in comparison to in-plant production under same production conditions (Hong et al. 2014; Na and Kim 2017; Oh 2017).

On-site production refers to the production of PC components on site or near the site, while in-situ production refers only to the production on site. In addition, the use of a tower crane involves production within the crane-working radius, whereas the use of a mobile crane as investigated in this study is associated with the production within the crane range without horizontal movement of the components on the crane’s moving path.

Droughts, heat waves, and sea level increases around the world occur due to climate changes. Moreover, one of the major causes of climate change is CO$_2$ (Jung and Chung 2004). Presently, problems associated with CO$_2$ emissions have gained massive attention, resulting in several international regulations being developed on greenhouse gas emissions (Giesekam, Taylor, and Owen 2014; Sartori and Hestnes 2007; Yu and Kim 2011). For this reason, researches to reduce CO$_2$ emission via the use of sustainable technologies are being continuously performed in the construction area (Ecoinvent 2019; Giama 2016; Jeong, Hong, and Kim 2018; Lee 2014; Mergos 2018). Yepes, Martí, and García-Segura (2015) proposed a methodology to optimize CO$_2$ emissions for road designs using PC components, and they developed a hybrid glowworm swarm optimization algorithm. Kim and Chae (2016) claimed that CO$_2$ emission was significantly increased during the steam-curing process of PC production, and they proposed a method for evaluating CO$_2$ emissions during the production, transportation, and installation of PC components using life cycle assessment techniques. In addition, Dong et al (2015) argued that the PC method was used for reducing CO$_2$ emission, supporting this argument by comparing the PC and cast-in-place construction methods through experimental research using life cycle assessment. The above discussed studies confirmed that the application of the PC method for the construction site is advantageous with regard of CO$_2$ emission; however, there are no studies on CO$_2$ emission that focus on in-situ production.

CONTACT Sunkuk Kim kimsukuk@khu.ac.kr Department of Architectural Engineering, Kyung Hee University, Yongin-si, Gyeonggi-do 17104, Republic of Korea
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In-situ production of PC components may be considered environment friendly due to their reduction in CO\textsubscript{2} emission. However, before considering any generalized assumptions, it is necessary to examine the degree of this effect through experimental studies. Therefore, the purpose of this study is to evaluate the CO\textsubscript{2} emission reduction effect of in-situ production of PC components. From this viewpoint, part of the PC column was produced on site for a storage-building project, where most PC components were supplied from the plant to minimize the risk that may occur during the experimental study, and to check the CO\textsubscript{2} emission reduction effect in detail based on the partial production. In summary, this work was conducted in four stages as described below.

1) Describing the concept of in-situ production and comparing its process with in-plant production.
2) Selecting a case project and estimating the quantity of in-situ produced PC components.
3) Estimating the amount of CO\textsubscript{2} emission during the erection process for in-situ and in-plant production.
4) Analyzing the CO\textsubscript{2} emission reduction effect resulting from the in-situ production of PC components.

2. In-situ production of PC components

Figure 1 shows the in-situ PC production process in the following order: (1) setting the manufactured rebar, (2) casting concrete, and (3) curing, which is the same as in in-plant production (Lim et al. 2016). Setting the rebar and casting the concrete were accomplished using methods similar to those used during in-plant production. First, form oil was applied inside the molds, which reduced the adhesion of PC components to the molds, and a crane was used to arrange the assembled rebar on the steel molds as shown in Figure 1(a). The subsequent casting concrete stage is shown in Figure 1(b), while Figure 1(c) shows the steam-curing stage that is carried out in winter, using a boiler. The cured PC components were partially reconditioned and finished surface. Finally, quality tests were conducted, and the components were stored for additional curing.

Unlike in-plant production of PC components, more difficulties in are encountered in-situ production, which include the need for a storage space for the components, a production area that provides room for sidewalks, vehicle roadways, and a safe space (Hong et al. 2014). Thus, the efficiency of the equipment used for the production of PC components within a limited space is important (Hong et al. 2014). Furthermore, it is essential to generate mold arrangements considering the working radius of the mobile crane, so that no additional transport for lifting and erecting would be required. This arrangement would eventually reduce the time and cost involved in the production process. Moreover, a production plan should be established considering several conditions on site with the goal of supplying PC components in time based on the erection schedule.

In-plant produced components are manufactured using the same process as in-situ production, and they are then transported and stored on site. The erection process of both production systems consists of the same processes as follows: preparation for lifting, component connection, lifting, positioning and disassembling the connections. Thus, the difference between in-plant production and in-situ production is whether PC components are transported or not. In the case of in-plant production, a wide range of equipment, facilities, and manpower may have been required for plant operation, whereas only small-scale resources like equipment would be needed in in-situ production for curing machinery and manpower. Therefore, differences in CO\textsubscript{2} emissions of the plants may be observed, based on the production environment, and the transport of the PC components. However, estimating these differences in CO\textsubscript{2} emission following the production environment of the plant is extremely complicated and may require an in-depth analysis. Therefore, the production environment has been excluded from this study but will be taken into consideration in future studies.

3. Experimental study of in-situ production

3.1. Summary of the case project

A case project was selected to examine the CO\textsubscript{2} emission reduction effect of in-situ production of PC components. The PC components were then selected for in-situ production. Table 1 summarizes the project characteristic of

![Figure 1](image-url)
a huge storage building. The case project involved a four-story building, consisting of PC structures, composed of RC cores and a steel roof. Its floor height was 10 m, with a column span ranged from 12 m to 24 m. It was a heavily-loaded building (2.4 t/m²).

The PC components produced for this study were columns, girders and slabs. Components that could be produced on site were restricted to columns and girders that require smaller production area. In other words, since columns and girders are thin and long, they did not require a large space for production. However, slabs required a wider space, making it difficult to produce them in the limited space. Thus, Figure 2 shows the quantity of columns and girders used for calculating the CO₂ emission reduction effect.

There were 982 columns and 1,207 girders (2,189 components in total) that could be produced on site for the case project. Table 2 shows the quantity of each column produced on site and the estimated total number of columns. The quantity of resources for column production was the same for in-situ and in-plant production. The total quantity of concrete, rebar and steel was not equal to the quantity for each column produced on site, because the size of the in-situ produced PC column and the rebar quantity were relatively smaller than the other columns. For example, the columns for in-situ production used in this study were the same size as equivalent to rebar details, but contained more columns than any other.

### 3.2. Planning of in-situ production

Although the column components for the in-situ production were chosen, the decision to use in-situ production was made after the erection began. Therefore, the quantity of PC components ordered for in-plant production had to be adjusted, and the erection schedule for PC components needed to be re-examined. The columns on the first floor were already erected at the time of the in-situ production planning. Figure 3(a) shows 123 columns on the second floor, while Figure 3(b) shows the selected 117 columns on the third floor (240 columns in total). The selected columns were used to analyze the CO₂ emission reduction effect, and their sizes were similar to the rebar details, considering the convenience of construction.

The decision for the in-situ production was postponed due to lack of cooperation and communication problems among project stakeholders, resulting in the re-evaluation of the established plan and site conditions. Consequently, the number of PC columns that needed to be produced was changed from 240 to 72 (18 and 54 columns, respectively, for the second and third floors), which was based on the lead time required for in-situ production. The detailed drawings of the 240 and 72 columns were checked, and each quantity was estimated. As shown in Table 3, the various estimates for the production of 240 columns were as follows: the quantity of concrete work estimated

---

**Table 1. Description of case project.**

<table>
<thead>
<tr>
<th>Description</th>
<th>Contents</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Cheonan-si, Chungcheongnam-do</td>
</tr>
<tr>
<td>Site area</td>
<td>53,055 m²</td>
</tr>
<tr>
<td>Building area</td>
<td>42,406 m² (246 m long × 178 m width)</td>
</tr>
<tr>
<td>Total floor area</td>
<td>167,614 m²</td>
</tr>
<tr>
<td>No. of floors</td>
<td>4 storeys (floor height 10 m)</td>
</tr>
<tr>
<td>Structure</td>
<td>Columns, Girders, Slabs: Precast concrete structure, Cores: Reinforced concrete structure, Roof: Steel structure</td>
</tr>
<tr>
<td>Remarks</td>
<td>Column span: Normal 12 m long, Longest 24 m long, Load condition: 2.4 t/m²</td>
</tr>
</tbody>
</table>

**Figure 2.** Typical floor plan of the case project (2nd Floor).
was 1,546.6 m³, reinforcement work was 478.1 t, and formwork was 3.8 t. Furthermore, the estimates for the production of 72 columns included: concrete work as 464.0 m³, reinforcement work was 143.4 t, and formwork was 1.1 t. Since the actual input quantity of the materials was the same, the quantity of in-situ and in-plant production was the same. In addition, the material quantity for the production of each column was approximately proportional to the number of columns. This is because the 240 and 72 columns were all of the same size with similar rebar details.

Figure 4 shows the steel mold used for in-situ production, which was the same as that used for in-plant production. The mold had the same specifications as the one manufactured and supplied to the plant. Steel forms are not for single-use and can be used over 50 times, thus, the CO₂ emission for each column production reflected this. Steel molds are highly durable and costly, and the reusable mold can be resold. Therefore, in this study, the molds were used 36 times before it was sold. Considering this, the quantity of steel forms for each column was estimated as follows.

As shown in Table 4, it cost 24,942 USD to purchase two molds used for in-situ production of 72 columns, which were resold at 14,000 USD after production. Hence, the actual cost of the molds used for in-situ production of 72 columns was 10,942 USD. This cost was further estimated to be 24,942 USD for the production of 164 columns. The estimation was based on two molds, so one mold can be reused 82 times. When the total weight of two steel molds (1.297 t) was divided by the reuse count (82 times), the quantity of steel mold for the production of a column was estimated to be 0.016 t. When converted into CO₂ emission, 4,540 kg-CO₂ is generated for two steel molds, and 1,993 kg-CO₂ is allocated for the production of 72 columns. However, the amount of CO₂ generated by steel molds is equally generated even in in-plant production, so it is excluded from the evaluation of CO₂ emission reduction effect.

Curing of the PC components produced in the site was performed in a curing cage in the same manner as in the PC plant. However, this study considered the cost issue relative to the small quantity of in-situ production. Thus, the well-framed curing cage were used in the plant. Moreover, curing was performed at the level of covering the form with the curing cage after the concrete was poured, but within the range of maintaining the quality of the PC components. If in-situ production is performed in the future, as shown in Figure 5 (Won et al. 2013), the curing cage will be manufactured and applied considering the energy efficient algorithms of the steam-curing for in-situ production of PC components. According to the algorithm by Won et al. (2013), information on the project side was first reviewed and a curing plan was

![Figure 3](https://example.com/fig3.png)

**Figure 3.** Selected 240 PC columns for the in-situ production.

<table>
<thead>
<tr>
<th>Work Item</th>
<th>Unit</th>
<th>Each column</th>
<th>Total columns</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete work</td>
<td>Concrete</td>
<td>m³</td>
<td>6.444</td>
</tr>
<tr>
<td>HD13</td>
<td>t</td>
<td>0.302</td>
<td>510</td>
</tr>
<tr>
<td>HD16</td>
<td>t</td>
<td>0.104</td>
<td>176</td>
</tr>
<tr>
<td>HD19</td>
<td>t</td>
<td>0.050</td>
<td>85</td>
</tr>
<tr>
<td>SHD22</td>
<td>t</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SHD32</td>
<td>t</td>
<td>0.175</td>
<td>295</td>
</tr>
<tr>
<td>SHD35</td>
<td>t</td>
<td>1.301</td>
<td>2,197</td>
</tr>
<tr>
<td>UHD25</td>
<td>t</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Embedded parts</td>
<td>t</td>
<td>0.060</td>
<td>102</td>
</tr>
<tr>
<td>Sub-total</td>
<td>t</td>
<td>1.992</td>
<td>3,364</td>
</tr>
</tbody>
</table>


<table>
<thead>
<tr>
<th>Work Item</th>
<th>Unit</th>
<th>Each column</th>
<th>Total columns</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete work</td>
<td>Concrete</td>
<td>m³</td>
<td>1,546.6</td>
</tr>
<tr>
<td>HD13</td>
<td>t</td>
<td>72.4</td>
<td>21.7</td>
</tr>
<tr>
<td>HD16</td>
<td>t</td>
<td>25.0</td>
<td>7.5</td>
</tr>
<tr>
<td>HD19</td>
<td>t</td>
<td>12.0</td>
<td>3.6</td>
</tr>
<tr>
<td>SHD22</td>
<td>t</td>
<td>42.0</td>
<td>12.6</td>
</tr>
<tr>
<td>SHD32</td>
<td>t</td>
<td>312.2</td>
<td>93.7</td>
</tr>
<tr>
<td>UHD25</td>
<td>t</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Embedded parts</td>
<td>t</td>
<td>14.5</td>
<td>4.3</td>
</tr>
<tr>
<td>Sub-total</td>
<td>t</td>
<td>478.1</td>
<td>143.4</td>
</tr>
</tbody>
</table>

Form work | Steel form | t | 3.8 | 1.1 |

![Table 2](https://example.com/table2.png)

**Table 2.** Quantity of each column and total columns.

![Table 3](https://example.com/table3.png)

**Table 3.** Quantities for 240 and 72 columns.
established. The site conditions and genetic curing data were also reviewed, curing conditions were set, as well as the curing time and temperature ranges reviewed.

In Routine 1, concrete and form quantity, as well as the curing cover shapes were determined sequentially and the total heat capacity was calculated. In Routine 2, the

**Table 4. CO₂ use and cost of molds.**

<table>
<thead>
<tr>
<th>Classification</th>
<th>Quantity</th>
<th>Cost (USD)</th>
<th>Cost ratio</th>
<th>CO₂ emission (kg-CO₂)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mold cost (①)</td>
<td>2</td>
<td>24,942</td>
<td>100%</td>
<td>4,540</td>
</tr>
<tr>
<td>Mold resale (②)</td>
<td>2</td>
<td>14,000</td>
<td>56%</td>
<td>2,547</td>
</tr>
<tr>
<td>Balance (①-②)</td>
<td>10,942</td>
<td>10,942</td>
<td>100%</td>
<td>44%</td>
</tr>
</tbody>
</table>

**Figure 4.** Applied steel mold for in-situ production.

**Figure 5.** Energy calculation model (Won et al. 2013).
range of the isothermal curing temperature and time was determined while satisfaction of total curing maturity and curing time examined. Routine 3 shows the process of calculating the total heat consumption of steam curing, and the results of Routine 1 and 2 were used. Routine 4 is the process of determining the most appropriate case after generating multiple isothermal curing temperatures and times that satisfy the total curing maturity and curing time. In other words, it was the process of checking the most appropriate energy usage according to PC curing conditions.

4. Analysis of CO₂ emission reduction effect

For analyzing the CO₂ emission reduction effect of in-situ production, the CO₂ emission sources such as PC material, oil, electricity and transportation were classified and calculated. After defining CO₂ basic units or the estimation equations of the sources in advance, as shown in Figure 6, CO₂ emission generated by in-plant production was estimated using the quantities of the sources. Following the calculation of the CO₂ emission of the in-situ production, the obtained results were compared with that of in-plant production.

1) CO₂ emission by material use

Based on the estimated quantity, CO₂ emissions were calculated using each basic unit of CO₂ emission per material quantity. Concrete and steel were observed to be 140 kg-CO₂/m³ and 3,500 kg-CO₂/t, respectively (Kim et al. 2004). Several studies have estimated the CO₂ emission during the building construction stage using the same method in their investigations (Hong et al. 2009, 2010; Lee et al. 2012; Lim, Lee, and Kim 2015; Lee, Lim, and Kim 2016).

Using the quantities estimated based on the design drawings as shown in Tables 2 and 3, CO₂ emissions for the 982, 240, and 72 columns during in-situ production of PC components were estimated as shown in Table 5. CO₂ emissions for each case were 12,940,250 kg-CO₂ for 982 columns, 1,903,675 kg-CO₂ for 240 columns, and 571,103 kg-CO₂ for 72 columns. Since the same amount of material was used for the production of the column components with similar sizes and rebar details, the quantity of in-situ and in-plant production was the same.

The estimated amount of CO₂ emission from the materials was not the same as that of the total amount of CO₂ emissions during the building construction process. This was due to the cost of oil and electricity used to operate the equipment during construction. These energy sources also emit CO₂ (Kim et al. 2004). Thus, we additionally considered the CO₂ emission caused by the oil and electricity use in order to best estimate CO₂ emissions in the process of constructing the building. That is, CO₂ emission of oil and electricity used during both, the erection and production process, should be considered.

2) CO₂ emission by oil use

Kim et al. (2004), analyzed the construction project of 28 apartment buildings with LCA (Life Cycle Assessment) techniques and proposed a regression equation for CO₂ emission at the construction stage. The total floor area was the variable that made it easier to estimate CO₂ emission based on the oil use.

Equation (2) shows the estimate of CO₂ emission for each construction work type based on oil use at the construction stage. This can be estimated based on Equation (1), which was used to calculate energy consumption (Kim et al. 2004). The total floor area of this case study was 167,615 m², so Qₐₙₜₑ = 987 t-CO₂.

\[
E_{CO} = 0.0017 \times A_f + 37.5
\]

\[
Q_{CO_e} = E_{CO} \times 3.06
\]

where \(E_{CO}\) is the energy (oil) consumption during the construction stage (TOE), \(A_f\) is the total floor area (m²), and \(Q_{CO_e}\) is the CO₂ emission based on oil use in the construction stage (T-CO₂).

<table>
<thead>
<tr>
<th>Table 5. CO₂ emission by material use (units: kg-CO₂).</th>
</tr>
</thead>
<tbody>
<tr>
<td>Classification</td>
</tr>
<tr>
<td>Concrete</td>
</tr>
<tr>
<td>Steel</td>
</tr>
<tr>
<td>Total</td>
</tr>
</tbody>
</table>

Figure 6. Analysis process of CO₂ emission.
The CO₂ emissions of 982, 240, and 72 columns during in-situ production of PC components were estimated. CO₂ emissions in each case were 987 kg-CO₂ for 982 columns, 217 kg-CO₂ for 240 columns, and 147 kg-CO₂ for 72 columns. Due to the same production conditions, the oil used for in-situ and in-plant production was the same.

3) CO₂ emission by electricity use

The total floor area was the variable that made it easier to estimate CO₂ emission based on electricity use. An equation to estimate CO₂ emission based on power consumption during the construction stage is provided in Equation (4) and can be calculated using Equation (3), which is used to estimate energy consumption. Then, \( Q_{\text{CO}_2,e} \) was estimated to be 543 t-CO₂.

\[
E_{\text{ce}} = 0.0247 \times A_f^{0.79} \quad (3)
\]

\[
Q_{\text{CO}_2,e} = E_{\text{ce}} \times 1.64 \quad (4)
\]

where \( E_{\text{ce}} \) is the power consumption in the construction stage (TOE) and \( Q_{\text{CO}_2,e} \) is the CO₂ emission based on power consumption in the construction stage (T-CO₂).

The CO₂ emissions of 982, 240, and 72 columns, respectively, were estimated during the in-situ production of PC components. CO₂ emissions for each case were 543 kg-CO₂ for 982 columns, 100 kg-CO₂ for 240 columns, and 40 kg-CO₂ for 72 columns. Due to the same production conditions, the electricity used for in-situ and in-plant production was the same.

4) CO₂ emission by transportation equipment used

CO₂ emission by the transportation equipment used was only relevant when moving PC components produced from the plant to a construction site. Looking at the details of CO₂ emission, material, oil and electricity used were the same for both in-situ and in-plant production. However, unlike the case of in-situ production, the components needed to be transported for in-plant production. A 25-t trailer was used as the transport equipment, and the basic units of CO₂ emitted were 0.464 kg-CO₂/t-km and 31.080 kg-CO₂/piece of equipment (Kim et al. 2004). The distance from the plant to the site was 97.55 km. If the weight of the PC components and the distance from the plant to the site increased, the CO₂ emissions would increase, accordingly.

5) Comparison of CO₂ emission for in-situ and in-plant production

Table 6 shows the estimated CO₂ emissions for all 982, 240, and 72 columns. The estimated data based on oil, electricity, and transport equipment used, including the data on the material used, were summarized. As shown, CO₂ emission for in-situ production of 982 columns was 14,470 t-CO₂, while that for in-plant production was 16,891 t-CO₂, showing a CO₂ reduction of 2,421 t. In addition, CO₂ emission for in-situ production of 240 columns was 2,221 t-CO₂ whereas that for in-plant production was 2,813 t-CO₂. The CO₂ emission for in-situ production of 72 columns was determined as 758 t-CO₂, while that for in-plant production was 936 t-CO₂, showing CO₂ reductions of 592 t-CO₂ and 178 t-CO₂, respectively.

In addition to the CO₂ generated by the transportation from plant to site in Table 6, CO₂ is additionally emitted in plant production when PCs are transported for curing and yard stock after production. Since the PC elements are heavy, the CO₂ emission amount is not small by using heavy-duty cranes. However, since this moving work in plant varies from plant to plant, it is difficult to estimate the exact amount of CO₂. Therefore, further research is needed to estimate CO₂ emissions for the work from multiple plants with statistical values, so it is excluded from this paper.

Equations (1)–(4) were used to estimate oil and electricity use for 982 columns based on the total floor area. However, the total floor area could not be used for the 240 and 72 columns, and it was converted to the sum of areas to account for production components and mold area.

For the in-situ production of 72 columns as shown in Figure 7, CO₂ emissions decreased by 178 t-CO₂ when compared to that of in-plant production. However, CO₂ emissions were reduced by 592 t-CO₂ for the in-situ production of 240 columns based on the existing plan. Generally, the use of the equipment for transporting the columns influenced the CO₂ emission, as shown in Table 6. In addition, CO₂ emission reduction increased to 2,421 t-CO₂ for in-situ production of 982 columns when compared to the production of 240 columns. In other words, CO₂ emission of in-situ produced PC components was reduced by 14.3% or more compared to that of the in-plant production.

Table 7 shows the estimated amounts of CO₂ emissions of the total columns and girders (982 columns and 1,207 girders). The results showed that 33,699 t-
CO\textsubscript{2} were emitted for in-situ production, and 39,095 t-CO\textsubscript{2} for in-plant production. The difference in CO\textsubscript{2} emission between in-situ and in-plant production was 5,397 t-CO\textsubscript{2}, demonstrating a CO\textsubscript{2} emission increase of 2,976 t-CO\textsubscript{2} when compared to that of 982 columns.

Based on the analysis of Figure 7, Tables 6 and 7, it was seen that CO\textsubscript{2} emission reduction increased with an increase in the material quantity of in-situ production. The results would have been more accurate if the number of in-situ production cases increased.

In the case of in-situ production, the module space was small, as the rebar setting, concrete casting, and steam curing were performed on site. However, a large number of PC components could be simultaneously controlled in the plant at separate spacing for each process, and the area of each workspace was larger. In addition, PC components would be transported for production, and the distance required for material transport will increase as the plant becomes larger. This study did not take into consideration the CO\textsubscript{2} emission based on the production environment of the plant, because it was complicated and difficult to estimate. However, the components were reproduced in the case of in-plant production because of cracks, breakages, and size problems as well as rebar placements that were different from the drawings. Therefore, in-situ production was advantageous in terms of CO\textsubscript{2} emission, cost, and quality as compared to in-plant production.

5. Discussion of CO\textsubscript{2} emission reduction effect

The comparison between the production cost of in-situ and in-plant production for PC columns is shown in Figure 8. Factors such as material, labor, equipment, transport cost, and overhead cost & profit(O&P) were analyzed and added. When producing 72 units, the cost for in-situ production was reduced by 20%. When producing 240 units, the cost was reduced by 39.4% compared to that of in-plant production. In other words, the cost reduction will increase in terms of economy of scale as the quantity of in-situ production increases. However, just like the analyses of CO\textsubscript{2} emission, there was a limit to the increase in the ratio of cost reduction based on increase in the quantity of in-situ production. This ratio was expected to change based on the project characteristics.

Furthermore, the quality of in-situ produced PC components for the following items were verified: crack, breakage, size, and strength in accordance with the PC Production & Erection Guidelines of KCI (Korea Concrete Institute), which was used for quality assurance. It was confirmed that no problems regarding the quality standard were observed. However, the components were reproduced in the case of in-plant production because of cracks, breakages, and size problems as well as rebar placements that were different from the drawings. Therefore, in-situ production was advantageous in terms of CO\textsubscript{2} emission, cost, and quality as compared to in-plant production.

Most of the energy was used during the curing process, and when the steam-curing method for the conventional PC components was applied, unnecessary energy consumption occurred. However, Won et al. (2013) proposed a method that reduces energy consumption by controlling the temperature during the curing period because the curing time can be extended by keeping the concrete wet through post-curing. This was advantageous for long-term strength. Through this experiment, it was shown that the improved curing method could save energy by 22.9% compared to the conventional method. Using this method, CO\textsubscript{2} emissions were estimated by applying 22.9% energy saving oil use for a boiler. As a result, CO\textsubscript{2} emissions for in-situ 982, 240, and 72 columns were calculated as 14,244 t-CO\textsubscript{2}, 2,171 t-CO\textsubscript{2}, and 724 t-

\begin{table}[h]
\centering
\begin{tabular}{|l|c|c|}
\hline
Classification & In-situ & In-plant \\
\hline
Material use & 32,169 & 32,169 \\
Oil use & 987 & 987 \\
Electricity use & 543 & 543 \\
Transport equipment use & - & 5,397 \\
Total & 33,699 & 39,096 \\
\hline
\end{tabular}
\caption{CO\textsubscript{2} emission total components based on materials used (unit: T-CO\textsubscript{2}).}
\end{table}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure7.png}
\caption{Comparison of CO\textsubscript{2} emission for in-situ and in-plant production.}
\end{figure}
As a result of applying the improved curing method as seen in Figure 9, CO$_2$ emissions from the in-situ production of the PC components were reduced by more than 15.7% compared to in-plant production. Presently, there is no carbon tax in Korea, while in European countries such as Sweden, Finland, the Netherlands, Denmark, and Norway, taxes are implemented, and the carbon taxes and transaction cost are expected to increase in the near future.

This study was conducted based on one case project. This was because most engineers have a negative perception on the in-situ production of PC components. As a result, most companies reject proposals on the experimental research of in-situ production as conducted in this study. However, the research team has discussed the cost and CO$_2$ reduction effects of in-situ production with a local company carrying out the construction of large-size logistics buildings. Based on the positive review of the proposed research plan, this study was conducted.

Through this study, we have achieved a 20% increase in the savings in direct cost for in-situ production than in-plant production. In addition, we confirmed that cost savings of up to 39.4% can be achieved by improving the materials procurement, manpower management, curing method, and reuse of steel molds. Seventy-two columns were produced on site, confirming the CO$_2$ emission reduction effect of 15.7% equivalent to 724 t-CO$_2$ than in in plant production. Also, it was confirmed that applying this to all 982 columns of the case project could save up to 14,244 t-CO$_2$. If it is possible to produce girders in site, the CO$_2$ emission reduction effect will be even greater. If the cost and CO$_2$ reduction effects could be demonstrated after further experimental studies on two or three case projects, we are confident that the negative perception of the in-situ production of PC components can be reduced.

6. Conclusion

This paper presented an experimental study on a case project to evaluate the CO$_2$ emission reduction effect of in-situ production. The resources and CO$_2$ emissions used in the test-produced columns were estimated and compared with those from in-plant production. The study results have been described below.

First, the CO$_2$ emissions of in-situ and in-plant production at the case site were compared. The results showed that the emissions of in-situ production had reduced by 178 t-CO$_2$ for 72 columns, 592 t-CO$_2$ for 240 columns, 2,421 t-CO$_2$ for 982 columns, and 5,397 t-CO$_2$ for the total number of components, respectively. In other words, CO$_2$ 

![Figure 8. Cost comparison for in-situ and in-plant production.](image1)

![Figure 9. CO$_2$ emission comparison of in-situ and in-plant production when applying the improved curing method.](image2)
emission of in-situ produced PC components had reduced by more than 14.3% compared to the in-plant production. The CO₂ emissions were estimated using an improved curing method, and it was discovered that CO₂ emissions of in situ had reduced by more than 15.7% compared to the in-plant. In addition, the carbon tax being currently implemented in European countries is expected to increase further in the near future.

Second, by analyzing the CO₂ emission reduction effect, it was discovered that the reduction of CO₂ emission increased with the increase in the quantity of in-situ production. This could be more accurately confirmed when the number of in-situ production cases increases.

Furthermore, this study did not consider the difference in CO₂ generation on the basis of the production environment of the plant. In the case of in-plant production, CO₂ is additionally emitted by using heavy equipment when transferring for curing and yard stock after PCs production. And besides PC production, a lot of electricity is used in plant operation, so corresponding CO₂ is emitted. However, since in-situ production is carried out in existing site conditions, little additional CO₂ is emitted. This means that additional CO₂ emission reductions are expected in in-situ production.

The results of this study showed that in-situ production of PC components greatly reduces CO₂ emissions and provides high quality assurance when compared to those from in-plant production. Furthermore, these results will contribute in changing the negative perception of in-situ production of components. Moreover, they will also contribute to the development of algorithms that scientifically analyze the PC components for CO₂ emission reduction effect. The verification of CO₂ emission reduction effects will be more accurate as the number of in-situ production cases increases.

Data availability statement
The data described in this article are openly available in the Open Science Framework at DOI:10.17605/OSF.IO/TPA6U.

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Notes on contributors
Jeeyoung Lim is a lecturer at California State University Long Beach in USA. She studied Construction Engineering and Management at the department of architectural engineering, Kyunghee University in South Korea. She had joined three Korean construction firms, Deallim Industrial Co., Ltd., Dealdong Corporation Co., Ltd. and Seoktop Construction Co., Ltd., for 12 years. As a visiting scholar, he researched about the construction management & organization at the department of civil engineering, Stanford University from 1994 to 1995. Since September, 1995, he has served at Kyung Hee University as a professor. He has concentrated on the research such as health performance evaluation of buildings, development of sustainable construction technology and management, simulation, optimization and risk management, construction information technology. Especially, for about a decade, he has participated in the development of SMART frame, a sustainable structural system, and production technology of free-form concrete panels.

ORCID
Sunkuk Kim http://orcid.org/0000-0002-7350-4483

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