Embodied CO₂ Reduction Effects of Free-Form Concrete Panel Production Using Rod-Type Molds with 3D Plastering Technique

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Abstract: When using concrete to produce exterior finishing panels of free-form building structures, different panel shapes make it difficult to reuse the forms. This results in increased formwork cost as well as a significant amount of embodied CO₂ (ECO₂) generation. Through years of research, we have developed a free-form panel (FCP) production technique engaging the 3D plastering technique (3DPT) without using conventional plywood forms. When 3DPT becomes available for free-form building projects, a great deal of ECO₂ reduction effects is expected in addition to reduced time and cost in FCP production. The purpose of this study is to prove this by analyzing ECO₂ reduction effects achieved through sustainable FCP production using 3DPT. The study involved project case selection, calculation of resources consumed for conventional plywood forms, and analysis of the reduction effects. As a result, it was demonstrated from the case project that 1196 tons of CO₂ were reduced using 3DPT, accounting for approximately 99% of the amount produced from conventional plywood forms (CPF). The study findings will be used as a basic reference for sustainable production of FCPs ensuring speed and precision in production as well as innovative ECO₂ reduction effects.

Keywords: embodied CO₂; reduction effects; sustainable production; free-form concrete panels; 3D plastering technique

1. Introduction

Recent development of construction technology has created free-form buildings in various structures [1–3]. When using free-form concrete to produce interior or exterior panels of a building, it is difficult to reuse the forms for panel production because panels differ in shape and size [4–6]. With the free-form concrete panel (FCP) production technology using conventional plywood forms (CPF), forms are produced in different shapes each time only to be discarded once used [7–9]. As a result, an enormous amount of resources including materials, labor and time are required to produce these single-use forms [10–12]. In terms of carbon footprint, such massive resource input becomes a major cause of cost increases and greenhouse gas (GHG) generation which is linked to global climate change. In addition, increased plywood demand for producing single-use forms leads to cutting down trees that absorb CO₂ and supply oxygen. Therefore, it is necessary to develop innovative forms that can be reused for sustainable FCP construction in terms of carbon footprint.

Through years of research, a technique of engaging the 3D plastering technique (3DPT) was developed to produce FCPs without using CPFs [13,14]. Lee [13], Son, Lim and Kim [14] used computer numerical control (CNC) machines and rod-type molds (RTM)—variable forms that can be used repeatedly—to produce FCPs. Results demonstrated that it was possible to produce high-quality FCPs while at the same time significantly reducing...
time and costs. When the technique becomes available for free-form building projects, large embodied $\text{CO}_2$ ($\text{ECO}_2$) reduction effects are expected in addition to reduced time and costs in FCP production. However, no study has yet been conducted to verify the $\text{ECO}_2$ reduction effects in FCP production using RTMs with 3DPT.

The purpose of this study is to analyze the $\text{ECO}_2$ reduction effects of free-form concrete panel production using RTMs with 3DPT. Through this study, not only 3DPT’s $\text{ECO}_2$ reduction effects but cost reduction effects will be verified. The study findings will be used as a basic reference for sustainable production of FCPs ensuring speed and precision in production as well as innovative $\text{ECO}_2$ reduction effects.

2. Methodology

The study procedure is described in Figure 1. First, a free-form design building is selected as a case project. Second, CPFs are designed to produce the case project’s FCPs using concrete. Third, resource quantity is calculated for materials, labor, energy and other items that are put to use for CPF production. Fourth, analysis is performed on the energy spent to produce FCPs by using RTMs with 3DPT. Fifth, analysis data are used to calculate $\text{ECO}_2$ generated from producing FCPs in both methods: CPFs and RTMs with 3DPT. Lastly, $\text{ECO}_2$ reduction effects are analyzed and cost reductions are reviewed.

Figure 1. Methodology.

3. Overview of Three-Dimensional Plastering Technique (3DPT)

3.1. Concept of Free-Form Concrete Panels (FCPs) Production Using 3DPT

Figure 2 shows the study’s FCP production concept. Firstly, a free-form construction structure is designed using the BIM concept as in Figure 2a. Here, FCP production data are automatically extracted from the BIM design model and the extracted data are then automatically transmitted to the CNC shaping machine of Figure 2b [15]. The CNC machine’s rods are operated by the transmitted FCP production data and the corresponding RTM rods are operated subordinately so that free-form shapes are created [16]. RTMs act as repeatedly usable forms here. Rubber and silicone rubber are installed on the upper part of the RTM as in Figure 2b to facilitate free-form shapes to be created freely [13]. Next, FRC (fiber reinforced concrete) is plastered on to the RTM as in Figure 2c and FCPs are produced accordingly [17].

Thus, when planning LPRI, it is essential to have both operation plans on operating party and source of income and a sustainable O&M cost plan. With this in consideration, LPRI constructed with a huge government budget will continue to operate and a sustainable O&M cost plan can be set.
Figure 2. Concept of free-form concrete panel (FCP) production using three-dimensional plastering technique (3DPT): (a) FCPs data extraction; (b) Free-form shaping; (c) FCP production using 3DPT [13,15–17].

To further explain the RTM operation process of Figure 2b, $z = 0$ applies to the initial status of the NCR and the rods as in Figure 3a. Next, NCR operates based on the data automatically extracted from the BIM design model as in Figure 3b. NCR moves sequentially on the $z$-axis direction until it reaches the assigned location coordinate. RTM rods move subordinately to NCR at this point. The outcome is a free-form shape which follows the transmitted data as in Figure 3c.

Figure 3. Process of shaping by rod-type molds (RTMs): (a) NCR’s initial status; (b) shape transformation; (c) finished free-form shape.

It can be seen in Figure 3 that a number of back-up rods placed on the RTM follow NCR to create free-form shapes. For reference, 3D design technology and CNC processing techniques are under continuous development to ensure the quality of curved shapes in the FCP production process [18]. When 3DPT as shown in Figures 2 and 3 for FCP production is adopted, it is more economical than the previous way of processing plywood to produce single-use forms and facilitate quick FCP production [18,19]. In terms of carbon footprint, in particular, massive resource reduction can lead to significant CO$_2$ reduction [20].

3.2. Features and Advantages of 3D Plastering Technique

As explained above, FCP production using CPFs creates a number of problems including non-reusable forms, difficulty in creating shapes and long production time. That is, a huge amount of cost and effort is required to construct a free-form building [21–25]. When this is viewed from the project management perspective, consuming large volumes of resources such as materials, labor and time to produce single-use forms is far from efficient [26]. In particular in terms of carbon footprint, these single-use resources become a major cause of GHG generation that contributes to global climate change.

When RTMs with 3DPT are adopted for FCP production, many benefits follow including those listed in Table 1. As described in Table 1, RTMs with 3DPT can reduce manpower
requirements thanks to full automation of the entire FCP process [27] and facilitate free-form shapes to be created precisely with CNC based on BIM design data [28]. Forms also become available for unlimited, repeated use through RTMs. This leads to significant ECO$_2$ reduction effects in terms of carbon footprint. In the end, 3DPT using RTMs facilitates sustainable production of high-quality FCPs.

Table 1. Advantages of RTMs with 3DPT [13,14].

| Facility                | Description                                                                 |
|-------------------------|-----------------------------------------------------------------------------|
| Sustainability          | • By using RTMs with 3DPT and CNC, production time will be reduced and RTMs can be reused unlimitedly and repeatedly from not having to do manual work.  
                          • The unlimited repetitive reuse of RTM implements resource conservation, cost efficiency and eco-friendly architecture. |
| Cost                    | • Manpower requirements are reduced thanks to full automation of the entire FCP process.  
                          • The cost savings from unlimited repetitive reuse of RTM are maximized. |
| Quality                 | • Free-form shapes can be created precisely using data extracted from BIM.  
                          • Sophisticated plastering is facilitated in a short time as the CNC method is adopted. |
| Construction period     | • Productivity can be maximized as 24 h automated production is available. |
| ECO$_2$ reduction effects| • Unlimited, repeated use of RTMs leads to significant ECO$_2$ reduction compared to CPF methodology. |

As such, use of the study’s main subject—RTMs with 3DPT—reduces a relatively large amount of resources including materials and labor compared to the existing FCP production technology using CPFs thanks to unlimited, repeated use of RTMs. An equivalently large amount of ECO$_2$ reduction is expected.

4. Case Study

4.1. Overview of the Case Building

To verify the ECO$_2$ reduction effects of 3DPT in this study, Dongdaemun Design Plaza (DDP) was selected as the case building (See Figure 4) [29]. Table 2 shows the outline of the case project. As can be seen in Table 2, the case project’s total construction time was 1907 days with a site area of 62,957m$^2$, building area of 25,104m$^2$ and total floor area of 83,024m$^2$. In this study, the case project was used to verify ECO$_2$ reduction effects of FCP production using RTMs with 3DPT.
Table 2. Brief description of the case project [29].

| Item          | Description                                                                 |
|---------------|-----------------------------------------------------------------------------|
| Location      | 2–1 Eulgi-ro, Joong-gu, Seoul, Korea                                         |
| Const. time   | 10 September 2008–30 November 2013 (1907 days)                              |
| Site area     | 62,957 m$^2$                                                                |
| Building area | 25,104 m$^2$                                                                |
| Total floor area | 83,024 m$^2$                                                           |
| Volume        | 43.98%                                                                      |
| Building coverage | 39.25%                        |
| No. of floors | 4 floors above ground, 4 basement floors                                    |
| Usage         | Cultural and convention center                                              |
| Structure     | Steel and reinforced concrete                                               |
| Remarks       | Largest free-form building in Korea (3-dimensional curved surface)          |

As can be seen in Table 3, the total quantity of the case project’s exterior panels is 45,133 composed of 13,841 flat plates, 9,554 single-curved panels and 21,738 double-curved panels [14,29–31]. Using the same conditions of the case building, a comparative analysis was undertaken in this study on ECO$_2$ reduction effects between RTMs with 3DPT and CPFs.

Table 3. Exterior panel quantification of the case project [29].

| Item                     | Unit | Contents    |
|--------------------------|------|-------------|
| Flat plates              | EA   | 13,841 (34%)|
| Single curved panels     | EA   | 9,554 (27%) |
| Double curved panels     | EA   | 21,738 (39%)|
| Total                    | EA   | 45,133 (100%)|

4.2. Fabrication of Conventional Plywood Form

This study was targeted on the case building’s exterior panels. Single-curved panels and double-curved panels were used to create free-form shapes from the case building, in this case, with aluminum perforated panels. It was assumed in this study that FCPs of 1500 mm width, 1500 mm length and 1500 mm thickness were produced (see Figure 5).
Figure 5. Types of the case building’s free-form panels: (a) single-curved panel; (b) double-curved panel.

The process of fabricating CPFs to produce FCPs depicted in Figure 5 is shown in Figure 6. The 12 mm thick plywood goes through precision processing to produce internal frames as in Figure 6a. Figure 6b shows the internal frames that are inserted into the dents for assembly. Side frames are produced to support the internal frames as in Figure 6c. Then, as in Figure 6d, external side frames are produced to ensure that FCPs are uniform in thickness. Figure 6e shows that plywood is produced following the FCP shape. Easily deformable 6 mm-thick plywood is used here. Plywood is joined to the upper part of the assembled frame to complete the CPF fabrication. The same material as GFRC is spread over the CPF to produce a FCP.

Figure 6. CPF production process: (a–c) internal plywood frame production; (d) edge guard form production; (e) free-forming plywood installation; and, (f) FCP production with manual plastering.

As shown in Figure 6, additional manpower and materials are used for FCP production technology using CPF compared to RTM with 3DPT. In addition, CPFs are used once and then discarded due to FCP’s different curvatures. Much time and cost is required and a large amount of ECO₂ is generated in this process.

4.3. Analysis of Resource Quantity

In this section, calculations were made for resource quantity invested to produce the CPFs shown in Figure 6. Materials and labor invested to produce one set of FCPs were first analyzed, costs were calculated, and the resulting values are listed in Table 4. Price information data, provided annually by the Korea Price Research Center [32] were used for material costs.
| Item                          | Unit | Q’ty  | UniPrice (USD) | Amount (USD) | Remarks               |
|-------------------------------|------|-------|----------------|--------------|-----------------------|
| 1. Material Cost             |      |       |                |              |                       |
| Plywood, 12mm thick          | M<sup>2</sup> | 4.953 | 6.80           | 33.68        |                       |
| Plywood, 6mm thick           | M<sup>2</sup> | 2.484 | 1.79           | 4.44         |                       |
| Subtotal                      |      |       |                | 38.12        |                       |
| 2. Labor Cost                |      |       |                |              |                       |
| Carpenter                    | MDY  | 0.5   | 177.37         | 88.69        |                       |
| Common Labor                 | MDY  | 0.5   | 120.68         | 60.34        |                       |
| Subtotal                      |      |       |                | 149.03       |                       |
| 3. Tools and Consumables     | %    | 7     | 10.43          | 7% of labor cost |                       |
| TOTAL                         |      |       | 197.58         |              |                       |

Note: Exchange rate is KRW 1146.30/USD as of 12 July 2021 (Bank of Korea).

Data from the standard market unit price of construction works by type in the first half of 2021, provided annually by the Ministry of Land, were used for labor costs [33]. The exchange rate applied in the calculation was KRW 1146.30/USD as of 12 July 2021 from the Bank of Korea. As can be seen from Table 4, 4.953 m<sup>2</sup> of 12 mm thick plywood and 2.484 m<sup>2</sup> of 6 mm thick plywood were consumed for each CPF set. Unit price was USD 6.80 per m<sup>2</sup> for 12 mm thick plywood and USD 1.79 per m<sup>2</sup> for 6 mm thick plywood. The cost of materials invested to produce 1 set of CPFs was calculated to be USD 38.12. To explain further in detail the calculation of materials invested to produce 1 set of CPFs shown in Table 4, 12 mm thick plywood was used in the process of internal frame production depicted in Figure 6a–d. In order to produce internal frames that follow FCP’s free-form shape, plywood processing was required. Figure 7 takes 12 mm thick plywood as an example to show the cutting process.

Figure 7. Example of 12 mm thick plywood cutting: (a) before cutting; (b) after cutting.

Figure 7 shows that part of the plywood is lost (1 in Figure 7a,b) during the plywood cutting process to fit the CPF size. Since these losses were not suitable for recycling, they were immediately discarded after use. Therefore, the amount of material was calculated to include lost parts (1 in Figure 7a,b) and usable parts (2 in Figure 7a,b) as shown in Figure 6b. Based on the construction work break-down created by the Korea Institute of Civil Engineering and Building Technology (KICT) in 2021 [34], a 5% plywood markup was applied and the calculated amount of material was 4.953 m<sup>2</sup>. When the same calculation was undertaken for 6 mm-thick plywood, it was 2.484 m<sup>2</sup>

In addition, the number of man-days (MDY) required for one set of CPF is 0.5 MDY for carpenters and 0.5 MDY for common labor, as shown in Table 4. Unit costs were USD 177.37 for carpenters and USD 120.68 for common labor. Labor costs invested to produce
one set of CPFs were calculated to be USD 149.03 as a result. To explain this further, labor 
was basically a two-man crew consisting of a carpenter and common laborer under the 
assumption that two sets of CPFs can be produced over 8 work hours a day. The value 
of MDY was determined to be 0.5 for producing 1 set. The standard market unit price 
of construction works by type in the first half of 2021 was used as a reference for unit 
prices [33] and calculations were made based on 8 work hours a day.

In the case of tools and consumables (T&C) shown in Table 4, professional opinion 
was sought and used as a reference. Gloves, nails, bands, etc. used by labor for plywood 
cutting were assumed to account for 7% of labor costs. The resulting calculation of T&C 
for producing one set of CPFs was USD 10.43. In conclusion, the total cost of investment 
required to produce one set of CPFs was calculated to be USD 197.58.

Calculations were made for the resources invested to produce 1 set of CPFs as above 
and the total resource investment was determined depending on the number of exterior 
panels of the case project due to FCP’s different curvatures. In contrast, significant resource 
and cost reduction effects are expected from 3DPT as it is possible to reuse RTMs used 
as forms.

4.4. Analysis of Embodied CO$_2$ Reduction Effects

In this section, earlier analysis data of the quantified materials were used to analyze 
CO$_2$ generated from the case building. For CPFs, based on the IPCC guideline, the 
amount of invested materials were multiplied by each material’s carbon emission factor 
to determine the carbon emission volume as described in formula (1) [35–37]. Also for 
RTMs with 3DPT, again based on the IPCC guideline, the amount of energy used from 
equipment operation was multiplied by each net heating value and emission factor to 
determine carbon emission volume [35–37].

Material $CO_2 = \sum Q_M \times C_E$ (1)

where, Material $CO_2$: CO$_2$ emission volume resulting from materials used, $Q_M$: amount 
of materials used, $C_E$: carbon emission factor.

Machine $CO_2 = \sum Q_E \times F_H \times C_E$ (2)

where, Machine $CO_2$: CO$_2$ emission volume resulting from equipment operation, $Q_E$: amount 
of fuel used, $F_H$: net heating value, $C_E$: carbon emission factor.

As displayed in Table 5, $CO_2$ emission volume of the materials required to produce 1 
set of CPFs was calculated using formula (1). The calculation was undertaken by taking 
a quantified resource from Table 4 and multiplying it by $CO_2$ emission volume per unit 
quantity. In the case of materials, the national LCI DB and their volumes were taken into 
account [38], for 12 mm-thick plywood result was 48.676 kg-$CO_2$ obtained by multiplying 
9.828 kg-$CO_2$/m$^2$ with the quantified plywood of 4.953 m$^2$. 6.102 kg-$CO_2$ was the result for 
6 mm-thick plywood obtained by multiplying 2.484 kg-$CO_2$/m$^2$ with 2.484 m$^2$. As a result, 
the calculated volume of $CO_2$ emission generated from materials required to produce one 
set of CPFs is 54.779 kg-$CO_2$.

Also, as displayed in Table 5, the volume of $CO_2$ emission generated from labor was 
calculated as follows. If one adult is engaged in light activities for 8 h on average per day, 
the amount of generated air is 18.71 L/min [39]. When this was multiplied by the rate 
of $CO_2$ in the emitted amount of air, the calculated value was 0.297 kg-$CO_2$. That is to 
say that the amount of $CO_2$ emitted for 8 h by one person of labor was 0.148 kg-$CO_2$. 
Therefore, the calculated amount of $CO_2$ emitted by labor was 0.297 kg-$CO_2$. T&C refers 
to tools such as hammers and saws, etc. and consumables (gloves, sand paper, etc.) used 
in the form production process. Taking into account data provided by KICT, the T&C 
proportion was assumed to constitute 7% of the labor $CO_2$.

Table 6 displays the amount of $CO_2$ emission when using RTMs with 3DPT. In the 
technology using RTMs with 3DPT, unlimited and repeated use of the form for FCP
production is available. Since the technology uses electricity, it is perfectly eco-friendly compared to CPFs.

Table 5. CPF cost break-down (1 set).

| Item                              | Unit | Q’ty | Kg-CO₂/Unit | Carbon Emission Volume (kg-CO₂) | Remarks |
|----------------------------------|------|------|-------------|---------------------------------|---------|
| 1. Material                      |      |      |             |                                 |         |
| Plywood 12mm thick M2            | M2   | 4.953| 9.828       | 48.676                          |         |
| Plywood 6mm thick M2             | M2   | 2.484| 2.457       | 6.102                           |         |
| Subtotal                         |      |      |             | 54.779                          |         |
| 2. Labor                         |      |      |             |                                 |         |
| Carpenter MDY                    | MDY  | 0.5  | 0.297       | 0.148                           |         |
| Common Laborer MDY               | MDY  | 0.5  | 0.297       | 0.148                           |         |
| Subtotal                         | %    | 7    | 0.021       | 7% of labor ECO₂                 |         |
| Total                            |      |      |             | 55.096                          |         |

Table 6. CO₂ emission volume of RTMs with 3DPT (1 set).

| Item                              | Unit    | Q’ty | Kg-CO₂/Unit | Carbon Emission Volume (kg-CO₂) | Remarks |
|----------------------------------|---------|------|-------------|---------------------------------|---------|
| 1. Energy usage                  |         |      |             |                                 |         |
| Electricity usage                | 1 kWh   | 0.16 | 0.424       | 0.067                           |         |
| Total                            |         |      | 0.067       |                                 |         |

Carbon emission factors were based on the IPCC guideline and the amount of electricity used to produce one set of FCPs was taken from the average electricity usage per hour of a 3D printing machine of the same size. The average electricity usage per hour of a 3D printing machine of the same size is 270 W [40]. According to Son et al. [14], it takes 2188 s for 1 unit of a CNC shaping machine to produce 1 set of FCPs using RTMs with 3DPT. When this was applied to calculate the amount of electricity used to produce 1 set of FCPs using RTMs with 3DPT, the result was approximately 162 W as can be seen in Table 6. To explain this in more detail, the average hourly power consumption of a 3D printing machine similar in size to the 3D plating equipment in this study is about 270 W. Converting this into power consumption per second, it is about 0.074 W/s. The time required to produce 1 set of FCP using RTM with 3DPT is 2188 s. Therefore, the amount of power consumed to produce 1 set of FCP using RTM with 3DPT is calculated to be about 162 W by multiplying 0.074 W/s by 2188 s. Using this value to calculate ECO₂ of RTMs with 3DPT, the result was 0.067 kg-CO₂.

As can be seen from Table 7, ECO₂ emission was 55.096 kg-CO₂ when CPFs were used to produce 1 set of FCPs, and ECO₂ emission was 0.067 kg-CO₂ when using RTMs with 3DPT. This demonstrates that 55.029 kg-CO₂ of ECO₂ was reduced with RTMs with 3DPT compared to CPFs, signifying a 99.878% reduction effect. Such a result was obtained because RTMs with 3DPT are mechanical devices which function as reusable forms and require no resources such as materials and labor compared to the CPF approach. Particularly in terms of carbon footprint, forms should be produced in different shapes each time to be discarded once they are used, becoming a major source of GHG generation that contributes to global climate change. The technology of reusable RTMs with
3DPT is, therefore, expected to make sustainable FCP production available in terms of carbon footprint.

**Table 7. CO₂ emission reduction effects.**

| Item                        | CO₂ Emissions (kg-CO₂) | Difference (C = B − A) | Ratio of CO₂ Emissions Reduction (%) (C/A) |
|-----------------------------|------------------------|------------------------|------------------------------------------|
| CPF (A)                     | RTM with 3DPT (B)      |                        |                                          |
| Material                    | 54.779                 | −54.779                | −                                       |
| Labor                       | 0.297                  | −0.297                 | −                                       |
| Tools and Consumables       | 0.021                  | −0.021                 | −                                       |
| Electricity usage           | 0.067                  | 0.067                  | −                                       |
| Total                       | 55.096                 | −55.029                | −99.878                                 |

As explained earlier in Table 3, the study’s case building was composed of 21,738 double-curved panels. Table 8 shows the total amount of ECO₂ input in the case building calculated by using ECO₂ for producing one set of FCPs which is analyzed in Table 7. When the case building’s FCPs were produced using CPFs as in Table 8, total ECO₂ emission was 1,197,697 kg-CO₂ consisting of 1,190,785 kg-CO₂ of materials, 6456 kg-CO₂ of manpower and 456 kg-CO₂ of T&C.

**Table 8. ECO₂ reduction effects for the case building (CPF vs. RTM with 3DPT).**

| Item                        | Total CO₂ Emissions (kg-CO₂) | Difference (C = B − A) | Ratio of CO₂ Emissions Reduction (%) (C/A) |
|-----------------------------|-----------------------------|------------------------|------------------------------------------|
| CPF (A)                     | RTM with 3DPT (B)           |                        |                                          |
| Material                    | 1,190,785                   | −1,190,785              | −                                       |
| Labor                       | 6456                        | −6456                  | −                                       |
| Tools and Consumables       | 456                         | −456                   | −                                       |
| Electricity usage           | −1456                       | 1456                   | −                                       |
| Total                       | 1,196,241                   | −99.878                | −                                       |

When the case building’s FCPs were produced using RTMs with 3DPT, total ECO₂ emission was equal to the electricity usage of 1456 kg-CO₂. Table 8 shows that 1,196,241 kg-CO₂ of ECO₂, a huge amount of ECO₂, was reduced compared to the CPF approach if RTMs with 3DPT are adopted to the case building. According to examinations so far, the study has verified ECO₂ reduction effects achieved by using RTMs with 3DPT for FCP production. Cost reduction effects of 3DPT were also verified through the study in addition to ECO₂ reduction effects. The study findings will be used as a basic reference for sustainable production of FCPs ensuring speed and precision in production as well as innovative ECO₂ reduction effects.

5. Conclusions

According to the UNEP (United Nations Environment Program), buildings use about 40% of global energy, 25% of global water, 40% of global resources, and they emit approximately one-third of greenhouse gas emissions [41]. Therefore, studies in the construction field should focus on sustainable production or construction for reduced greenhouse gas emission in addition to seeking time and cost reduction.

3DPT is a FCP production technology without using CPFs. The study examined a case building with exterior panels designed in free-form shapes and conducted a comparative analysis on ECO₂ reduction effects in terms of carbon footprint between two different panel production methodologies using RTMs with 3DPT and CPFs. After choosing the case building, quantified resources were analyzed and the resulting amounts of ECO₂ were compared for each methodology. The study findings are described in the following paragraphs.
When 3DPT is adopted for FCP production, it has been confirmed that innovative ECO\textsubscript{2} reduction effects are demonstrated in terms of carbon footprint. From the case project, approximately 99.87% of ECO\textsubscript{2} quantified as 55,029 kg-CO\textsubscript{2} was reduced by using RTMs with 3DPT compared to the CPF approach in producing one set of FCPs. Since RTMs with 3DPT are reusable, ECO\textsubscript{2} reduction effects are likely to be maximized as more FCPs are produced. When all 21,738 double-curved exterior panels are assumed to be produced for the case project, it is demonstrated that a large amount of ECO\textsubscript{2} quantified as 1,196,241 kg-CO\textsubscript{2} is reduced.

As examined so far, it was verified that 3DPT creates innovative ECO\textsubscript{2} reduction effects compared to the conventional approach. The study findings will be used as a basic reference to achieve sustainable FCP production ensuring speed and precision in production as well as innovative ECO\textsubscript{2} reduction effects.

In addition, a current free-form building project requires enormous cost and time. If the technology of this study is commercialized, the demand for free-form building construction will increase even in the construction of small and medium-sized houses due to innovative cost reduction and time reduction.

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**Abbreviations**

- CNC: computerized numeric control
- CPF: conventional plywood form
- ECO\textsubscript{2}: embodied CO\textsubscript{2}
- FCP: free-form concrete panel
- FRC: fiber reinforced concrete
- GHG: greenhouse gas
- KICT: Korea institute of civil engineering and building technology
- MDY: man-day
- Q'ty: quantity
- RTM: rod type mold
- T&C: tools and consumables
- UNEP: united nations environment program
- 3DPT: 3D plastering technique

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