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Conceptual Study of Innovative Production Technology of Free-form Concrete Panels

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Abstract: ***Free-form building construction needs a tremendous amount of capital as well as the application of a wide range of technologies. There have been studies on production technologies of free-form concrete panels using molds produced with PCM (Phase Change Material), EPS (Expandable Polystyrene), timber, acryl glass and fiber that is processed using CNC (Computerized Numeric Control) machines. However, it is not possible to reuse molds using these technologies and it may place a great burden in terms of cost and quality because it is difficult to achieve an accurate shape. Accordingly, an innovative production technology that can economically produce FCPs (Free-form Concrete Panel) as well as realize a more precise shape is needed. Therefore, the study herein is a conceptual study of innovative production technology of free-form concrete panels. The study analyzes existing technologies problems, advantages, and disadvantages, and proposes an improved production technology. The study results will offer a novel FCP production technique and be used to ensure FCP production technologies that may be commercialized.***

Keywords: **free-form, concrete panel, production process, CNC machine, mold.**

I. INTRODUCTION

Along with the flow of time and technological development, free-form buildings are constructed in various shapes [1], and a wide range of materials and technologies are applied for their construction [2].

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However, it is still impossible to reuse molds for free-form structures and those for free-form finished panel production, laying a heavy burden in terms of productivity and cost [3].

To solve this problem, there were several studies on free-form concrete panel production technologies using molds manufactured with materials such as EPS (Expandable Polystyrene), timber, acryl glass, fiber and PCM (Phase Change Material) that are processed with CNC (Computer Numeric Control) machines [5, 6, 9, 10, 12, 14, 16]. However, those studies suggest production technologies that are at the initial stage, or that are not sufficient developed to be commercialized for it requires a great deal of time and money [4].

In other words, a tremendous amount of capital is required to build a free-form building, and although various technologies can be applied, these are not developed enough to economically produce high-quality free-form concrete panels (FCP). Thus, an innovative low-cost technology that allows mass-production of FCPs and more accurate shapes is needed. Therefore, the study herein is a conceptual study of innovative production technologies of free-form concrete panels. To fulfill the purpose of this study, it complies with the following procedure.

First, previous studies are reviewed to analyze the characteristics of existing FCP production technologies. Then, existing FCP production technologies problems as well as their advantages and disadvantages are drawn out. Second, any solutions and improvements to those problems are analyzed. Based on the analysis, requirements of the proposed production technology are brought about. Third, an innovative FCP production technology that improves upon existing technologies and reflects their requirements is proposed. This makes it possible to economically produce high-quality FCPs.

In the academic perspective, the proposed technology will provide an innovative FCP production technique, and in the practical view, it will be used to ensure that the FCP production technology may be commercialized for mass-production.

II. PRELIMINARY STUDY

A. 1. EPS (Expanded Poly Styrene) Formwork

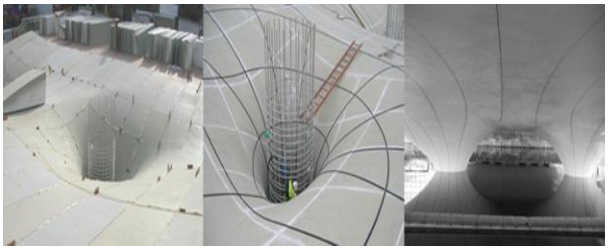

Fig. 1: EPS Formwork [5, 6]

As shown in Fig. 1, P. Mandl et al. (2008) and Lindsey & Gehry (2001) used CNC processing to produce EPS formworks [5, 6]. This method processes the EPS form into a mold using a CNC milling machine and then pours concrete [7]. Although it is easy to cut out a free-form shape, it has a few disadvantages such as an expensive CNC milling machine and time-consuming cutting process [8].

2. Wooden and Acryl Glass Formwork

Fig. 2: Wooden Formwork, Rolex Learning Center, SANAA [11]

Fridh, K. (2017) conducted a study on processing timber using a CNC machine to produce single-use molds and making free-form concrete panels using molds [9]. Additionally, Franken Architeckten (1999) applied acryl glass to make a digital form using a CNC machine and produced free-form concrete [10]. However, these studies revealed that it is difficult to reuse molds and impossible to realize mass-production of panels owing to a tremendous amount of money and time that it requires.

3. Textile Formwork

Fig. 3: Textile Formwork [12, 13]

As shown in Fig. 3, Verhaegh (2010) used fiber as a mold to build free-form concrete panel [12]. However, because of the material characteristics, the mold shape cannot be properly maintained and it is difficult to ensure an even panel thickness and angle [13]. Due to these reasons, high-quality FCP cannot be produced. Thus, additional studies on reusing fiber and improving its shape are needed.

4. 3D Printing

Fig. 4: 3D Printing technology, Lough-borough University [14, 15]

Concrete printing technology co-studied by Lough-Borough University in England and Foster & Partners architectural design and engineering firm is to print out panels in different sizes and curved surfaces using a large concrete printer as shown in Fig. 4 [14]. Despite the fact that this new technology is capable of constructing free-form buildings, it requires large, costly equipment for FCP production and it takes a lot of time in producing a

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single panel since a plotting method is applied for production [15]. In addition, additional manpower is needed for finishing, which makes it impossible to achieve mass production.

5. PCM Formwork

Fig. 5: PCM Formwork [16, 17]

As shown in Fig. 5, Lee et al. (2014) conducted a study on development of variable forms using PCM (Phase Change Material). PCM is a phase-changing material that is at solid state under room temperature and changes to liquid at a specific temperature [16]. However, the developed PCM mold changes its shape when cooled down and crystallized when hardened, making it difficult to produce an accurate mold [17].

As described above, existing technologies have been using various methods and materials to produce free-form concrete panels. However, we are still short of technologies that may economically produce high-quality free-form concrete panels. In this regard, the study intends to improve on solutions to existing technologies problems and propose an innovative technology that enables economical mass-production of high-quality FCPs.

III. LIMITATIONS OF EXISTING TECHNOLOGIES AND SOLUTIONS

This section suggests solutions to existing technologies problems and any improvements that can be made. Based on the drawn solutions, the study proposes an innovative production technology to build high-quality FCPs taking cost into consideration. Some problems related to existing FCP production technologies and their solutions are stated in Table 1.

Table 1: Limitations of Existing Studies and Solutions [18, 19]

Classification		Limitations of Existing Technologies	Solution
Related to Production Management	Cost	Impossible to reuse molds	· Infinitely reusing RTM (Rod Type Mold)
		Highly dependent on manpower	· Minimizing manpower for production owing to automation of the whole FCP production process
	Quality	Inaccurate shapes	· Extracting production data based on BIM
			· Realizing accurate free-form shapes using CNC machines
	Construction Period	Extended production period relying on manpower	· Revolutionarily shorter production time due to production automation for 24 hours
			· Maximizing productivity
Related to Performance	Durability	Insufficient strength and durability	· Using GFRC, HPC, cement composite, etc.
			· Producing members with outstanding physical performance, such as strength and durability

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	Insulation	Inadequate insulation and lightness	· Producing FCPs with internal EPS, if needed
			· Possible to secure insulation and lightness
	Shielding	Inadequate shielding	· Precise production of the joint surface considering air-tightness of the joint
	Environment-friendly	Waste generated	· No production waste generated (zero) owing to infinite reuse of molds
	Satisfaction of Aesthetic Aspect	Limited smoothness of FCPs	· Limited shapes and errors resolved with the technology of using CNC machines
		Limited production of corner panels	· Producing shapes of corner panels and performing cutting with robot arms
		Limited production of double-sided free-form shapes	· Possible to realize double-sided free-forms using a separate CNC machine (lower part: CNC M/C; upper part: robot arm and etc.)

As described in Table 1, existing free-form exterior panels require a separate insulating layer, which results in problems such as higher costs, lower construction productivity and degraded performance because of damages to the insulating layer [15]. An insulating layer can be arranged inside free-form panels applied with cement composite, GFRC and HPC as proposed in the study. Thus, it is more advantageous than existing methods that have an outstanding insulating performance, convenient construction and cost reduction effects [18].

In addition, the cross-section of free-form panels keeps changing depending on the cutting surface in the case of free-form buildings, so integrity, uniformity and shielding performance of free-form panels are inconsistent. Therefore, it is necessary to produce panels with accurate shapes using a CNC machine.

Several technologies including 3D printing, CNC milling and 3D shaping machines have limits in producing different shapes and sizes, and it is likely to generate errors using such technologies [19]. The technology proposed in the study uses equipment, including a CNC machine and robot arm. Various shaping technologies converged to accurately produce single-curved and double-curved panels.

Accordingly, the proposed technology is divided into a lower shaping and upper free-form finishing technologies as illustrated in Fig. 6 to solve existing technologies problems. Their performance requirements are shown in Table 2.

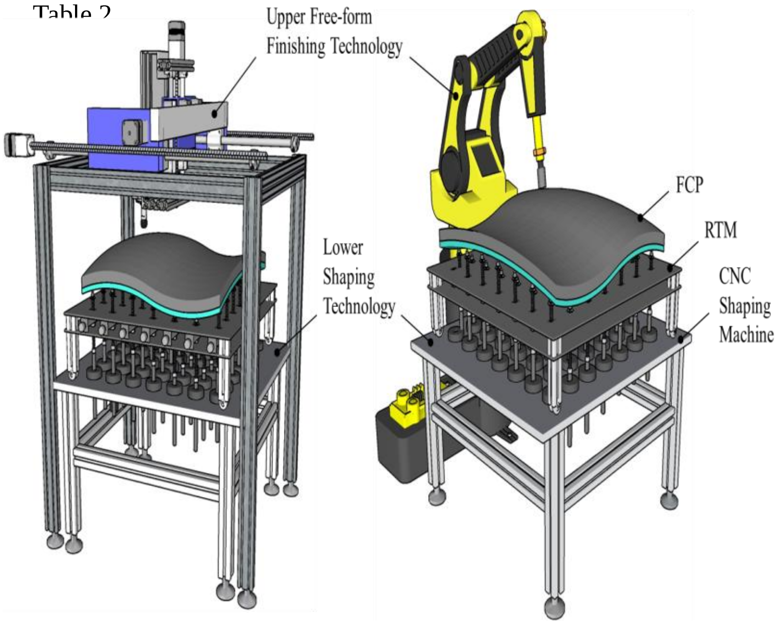

Fig. 6: Lower Shaping & Upper Free-form Finishing Technology

In case of the lower shaping technology as shown in Fig. 6, it acts both as a mold and interior finish so its economic-feasibility, productivity and aesthetic performance should be secured. To achieve these results, a fine finished surface in terms of quality, quick production

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speed in terms of construction period and economic-feasibility of mold materials in terms of cost are required.

In the case of the upper free-form finishing technology as illustrated in Fig. 6, its aesthetic performance and fine finished surface should be secured because it shapes the exterior part of a building. In other words, curved surfaces errors should be reduced for accurate production. Performance requirements to fulfill these include uniform application of materials and surface treatment. In addition, precise cutting and grinding should be possible to achieve high-quality free-form curve shapes.

Table 2: Performance Requirements of the Proposed Technology

Technology Type	Details	Performance Requirements	
Lower Shaping Technology	• RTM (Rod Type Mold) • CNC Shaping machine	FCP Lower Part Shaping	• Quality: Fine finished surface • Construction period: Production speed • Cost: Economic-feasibility of mold materials
Upper Free-form Finishing Technology	• Machine for FCP Producti on • Robot arm for FCP Producti on	Plastering	• Applying materials such as GFRC for FCP production
		Troweling	• Surface treatment for FCP surface finishing
		Cutting and Grinding	• When cutting the corners of FCPs, several pieces may be detached; so FCPs should be produced in bigger sizes considering the cutting error • Bigger FCPs should be accurately grinded to fit a specific size

The technology suggested in the study is transformed from the existing labor-intensive technology into a capital-intensive technology owing to automation of the whole production process. With this technology it is easier to economically produce high-quality FCPs. The following section describes the concept of this technology and explains the production process in detail.

A. Innovative FCP Production Technology

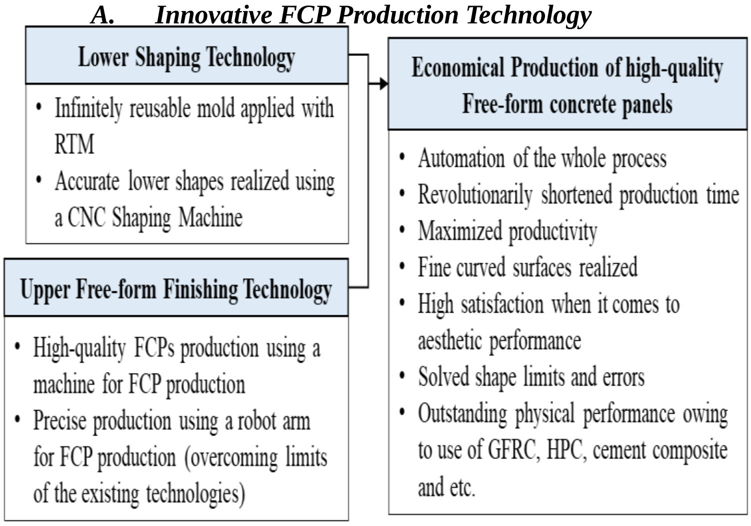
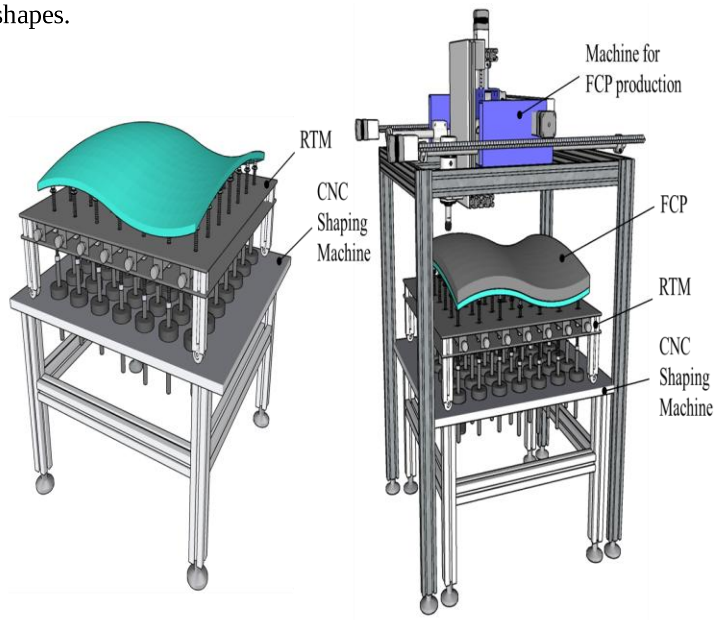


Fig. 7: The Concept of Innovative FCP Production Technology

The concept of an innovative FCP production technology proposed in the study is divided into a lower shaping and upper free-form finishing technologies as shown in Fig. 7, the lower shaping technology being applied to build FCP shapes.



(a) RTM & CNC Shaping Machine (b) Machine for FCP Production

Fig. 8: RTM & CNC Shaping Machine and Machine for FCP Production

Here, lower shapes are produced with RTM (Rod Type

Mold) and CNC (Computerized Numeric Control) shaping machines as illustrated in Fig. 8(a) [20]. RTM (Rod Type Mold) arranges multiple rods at narrow intervals that move up and down, and it is connected to the lower CNC Shaping Machine to apply pressure. Then, it manufactures a fixed shape. It is a variable form used for FCP production at the upper part [15]. Additionally, a machine for FCP Production as illustrated in Fig. 8(b) is used depending on the manufactured shape for plastering (including, application and spraying of FCP materials), troweling (surface treatment) and cutting & grinding (cutting and processing it based on the size requirement) to produce FCPs. Compared to existing technologies, the proposed technology can achieve a more accurate and refined finished surface.

As shown in Fig. 7, the production FCP production technology proposed in the study minimizes manpower through automation of the whole process. Molds can be reused infinitely using the developed RTM. Additionally, the FCP production machines developed are based on CNC machines that can be used to solve shape limits and errors, and to achieve refined free-form curved surfaces, as illustrated in Fig. 8. Ultimately, it has become possible to easily, quickly and economically produce high-quality FCPs.

The FCP production process using the proposed technology is divided into 5 stages as shown in Fig. 9. Parametric modeling is applied to design free-form buildings. Then, numerical data are extracted for FCP production, the lower shape is realized using RTM; and finally, FCPs are produced using the upper free-form finishing technology.

As explained above, the study analyzed problems of the existing technologies to secure FCP production technology that may be commercialized for mass production and suggested relevant solutions. Additionally, the FCP production process reflecting the study analysis and solutions was proposed. The study will be used to ensure that FCP production technology may reach a commercialization level that may lead to FCP mass production.

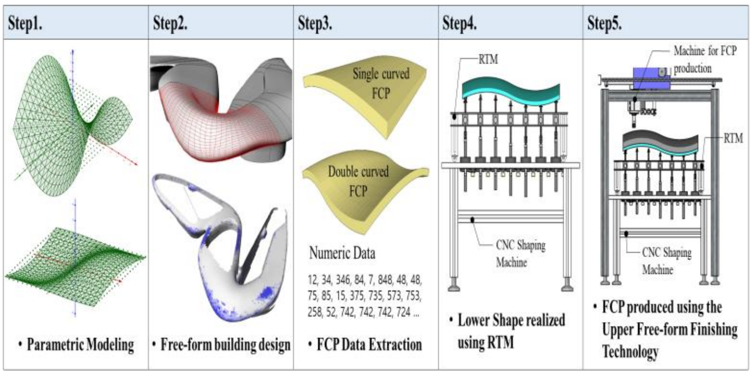


Fig. 9: FCP Production Process

IV. CONCLUSION

The study herein was conducted for the purpose of a conceptual study of an innovative production technology of free-form concrete panels. For the study, existing technologies problems, advantages and disadvantages were analyzed and related solutions were proposed. Additionally, the improved FCP production technology and production process reflecting the study analysis and solutions were suggested. The study results in detail are as stated below.

Firstly, it was confirmed that the existing FCP production technologies that use EPS, timber (wooden), acryl glass and fiber molds manufactured with a CNC machine cause problems, including the impossibility of reusing molds, inadequate shape precision, increased production time and higher costs resulting from a process highly-dependent on manpower.

Secondly, as solutions to the existing problems, the study proposed RTM molds that can be infinitely reused and a FCP production machine that achieves fine finished surfaces. Performance requirements to be realized include refined finished surfaces, production speed and economic-feasibility of mold materials.

Thirdly, the study established a new concept of an innovative FCP production technology (lower shaping and upper free-form finishing technology) that has overcome the limits of existing technologies. With the innovative technology, the following has been realized: automation of the whole process, revolutionarily-shortened production time, maximized productivity, and solutions to shape limit and error. It also made possible to economically produce high-quality FCPs.

Fourthly, the study led to establishment of an improved FCP production process. With the production process, it became possible to secure production technology that may be commercialized for mass production.

Accordingly, the study identified problems of the existing FCP production technology and proposed an improved, innovative FCP production technology. In the academic perspective, it offers an advanced FCP production technique that in the practical aspect, it will be developed into the world's best FCP production technology that may secure economic-feasibility, no waste generation and shortened production time.

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