**ICCEPM 2024** https://dx.doi.org/10.6106/ICCEPM.2024.0186
The 10th International Conference on Construction Engineering and Project Management
*Jul. 29-Aug.1, 2024, Sapporo*

# Research on Development of Magnetic Silicon Mold to Improve Free-form Concrete Panel Precision by Lateral Pressure

Jongyoung YOUN[1*], Kyeongtae JEONG[1], Minje JO[1], Jihye KIM[2], Donghoon LEE[1]

[1] *Department of Architectural Engineering, Hanbat National University, Republic of Korea,*
[2] *SamooCM Archits & Engineers, Assistant, Republic of Korea,*
E-mail address: 97colin@naver.com, wjdrudxo9911@naver.com, chominje63@naver.com, 6312904@naver.com, donghoon@hanbat.ac.kr

**Abstract:** Free-form buildings are composed of different curved surfaces and panels with varying curvatures used for the exterior. Because free-form curved surfaces differ from those of conventional buildings, they serve as landmarks worldwide and generate economic and social profits. However, molds used to realize the curved surfaces of free-form buildings are typically single-use, resulting in construction waste and posing limitations such as environmental pollution and increased construction costs. To address this issue, current research is focused on developing reusable forms that precisely implement free-form curved surfaces. Among these approaches, the Free-form Concrete Panel (FCP) employs reusable silicone material as a mold. The silicone mold consists of a lower part and a side part, with both parts fixed together by friction due to the same material. However, during the concrete pouring process into the silicone mold, lateral pressure can cause shifting, reducing the precision of the FCP and resulting in defective panels. To address this challenge, this study introduces the use of iron powder in the lower part and magnets on the sides to secure the form using magnetic force.

**Key words:** Freeform Concrete Panel, Magnetic Silicone Mold, Magnetic Force, Lateral Pressure, Precision, Neodymium magnet

## 1. INTRODUCTION

Free-form buildings are characterized by geometric structures with naturally curved exteriors, distinguishing them from conventional buildings [1]. These architectural wonders serve as global landmarks, leveraging their curved aesthetics to generate economic and social benefits [2]. Notably, Dongdaemun Design Plaza (DDP) in Seoul stands as a representative example of a free-form building in Korea. DDP incorporates flat, curved, and double-curved types to achieve various curves and twists on its external panel surface [3]. Given the diversity in curvature values based on specific locations within free-form buildings, the shapes of the panels used vary accordingly. Consequently, custom-made free-form molds are employed for panel manufacturing, tailored to the unique requirements of each location. However, a drawback of using custom-made free-form molds is their single-use nature, leading to significant construction waste [4]. To address this challenge, ongoing research focuses on developing innovative materials for free-form molds. Current materials include wood, steel, and expanded polystyrene [5]. Despite the ease of processing these materials, they are designed for one-time use. Reusable alternatives, such as Phase Change Material (PCM), ice, and fabric, have been explored; however, their application remains limited due to lower panel shape precision, making them primarily suitable for basic research purposes [6-8].

Among these materials, silicone stands out as a recyclable and easily deformable option, making it a preferred choice for free-form molds [9]. Silicone boasts excellent characteristics such as heat resistance, chemical stability, electrical insulation, abrasion resistance, and weatherability [10]. The silicone mold comprises a silicone plate at the bottom and a silicone side mold on the side, as illustrated in Figure 1. Silicone can be freely deformed by external force. A rod, operated by Computerized

Numerical Control (CNC is installed at the bottom of the silicone plate, moving up and down to push the silicone plate and realize the lower shape of the Free-form Concrete Panel (FCP). To enhance the curvature of the silicone plate, a silicone cap is attached to the end of the rod.

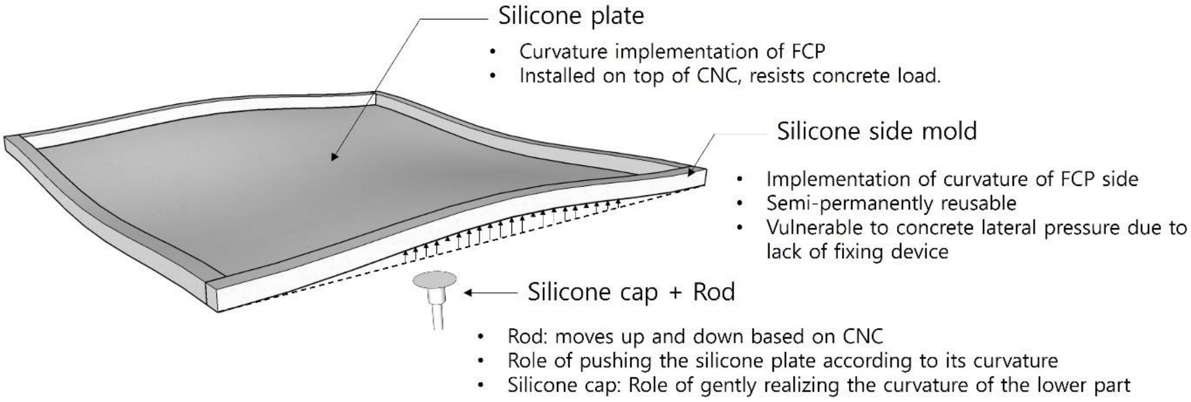


Figure 1. Silicone mold concept

However, the silicone mold lacks a fixation method between the silicone plate and the silicone side mold. This absence of a secure fixation may result in deformation caused by lateral pressure during the extrusion of concrete inside the mold. Such deformation introduces errors in the Free-form Concrete Panel (FCP), reducing precision and overall quality. Therefore, the primary objective of this study is to develop a new fixation method capable of resisting the lateral pressure exerted by concrete, ultimately enhancing the precision of silicone molds.

The research process is illustrated in Figure 2. Initially, a literature review is conducted to analyze previous research on the manufacturing methods of free-form molds. Through this review, fixation methods and requirements for free-form molds are derived. The section on magnetic silicone mold fabrication consolidates the requirements and design considerations for implementing a new fixation method for both the lower and side surfaces. In the conclusion, the study presents the manufacturing of a magnetic silicone mold that achieves magnetic fixation. The limitations of this approach and the expected effects on mold precision are discussed

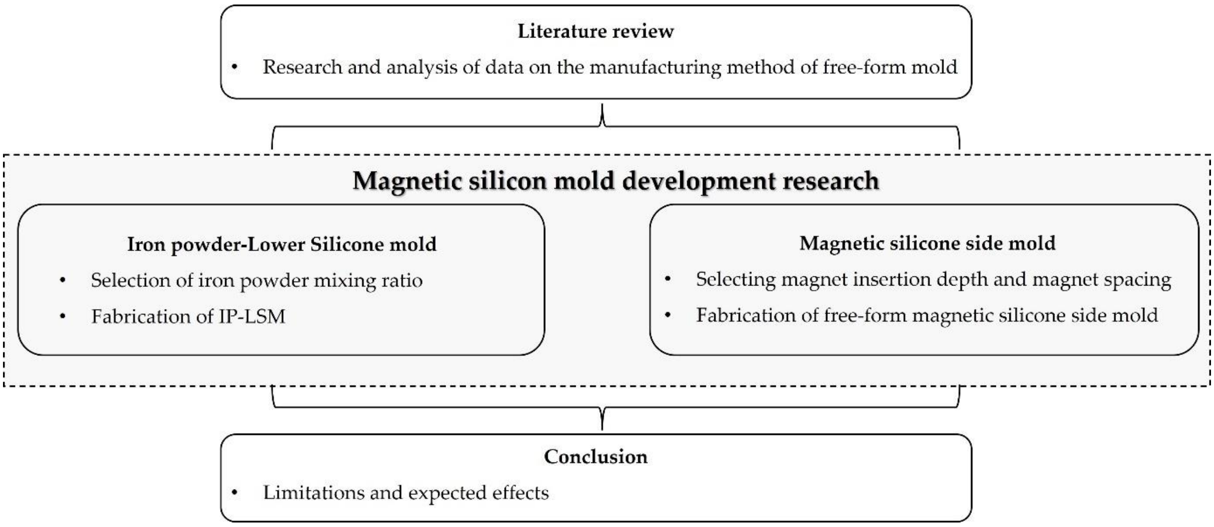


Figure 2. Research process[1]

## 2. LITERATURE REVIEW

### 2.1. Analysis of previous research on free-form mold manufacturing method

The purpose of this study is to develop a new fixation method for securing the bottom and sides of a free-form mold. To achieve this, an analysis of previous research on existing free-form mold manufacturing methods was conducted. The conventional prefabricated manufacturing method utilized CNC milling technology in conjunction with wood and steel molds. While this approach is conducive to precision mold improvement, facilitating the production of high-quality panels, it comes with drawbacks such as extended production times, high costs, and the limitation of being a one-time use [11, 12]. Another method involves using wax molds, which is both reusable and environmentally friendly, producing no waste. After the wax mold hardens, it can be transported to the site for assembly to create concrete panels. Research has explored how to melt and reshape the wax mold for reuse [13]. However, challenges remain, including issues related to solidification time, crystallization, strength, solidification shrinkage, and cracking. Furthermore, the presented concepts lacked detailed explanations of the equipment and technology for shaping with wax molds. Layering using cement materials, a 3D printing technology known as contour crafting, has been employed as well. This method stacks layers of concrete material to print actual-size structures without the need for a mold [14]. Research has also investigated mold-free methods such as the extrusion method and D-shape to implement free-form shapes [15-17]. However, these methods have limitations in terms of material strength and require expensive equipment and high technical skills [18]. In the realm of silicone-based manufacturing, Kim (2021) used a CNC machine and rod to transform the shape of a silicone plate, resulting in a smooth free-form concrete panel. Experimental confirmation of the precision of this manufacturing method revealed an average error rate within 3% at the 95% confidence level based on thickness [19].

Yun (2022) also produced free-form concrete panels using a silicone mold suitable for CNC equipment. While achieving satisfactory performance, a fixing method between the silicone plate and silicone side mold was lacking, resulting in a slight error [20].

## 3. MAGNETIC SILICONE MOLD DEVELOPMENT RESEARCH

In this study, a magnetic fixation method is employed to secure the silicone plate and silicone side mold. As illustrated in Figure 3, an Iron Powder-Lower Silicone Mold (IP-LSM) is fabricated by incorporating 70% iron powder into a silicone plate. Additionally, a Neodymium magnet is embedded in the silicone side mold to establish magnetic fixation between the lower mold and the side mold, effectively resisting the lateral pressure exerted by the concrete.

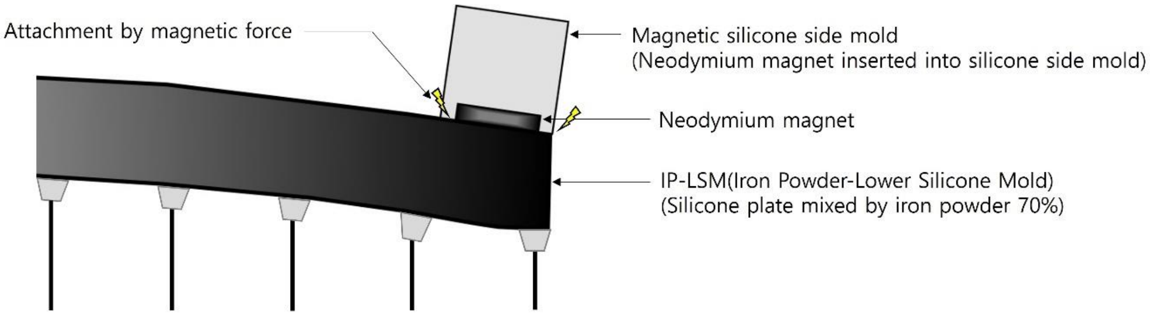
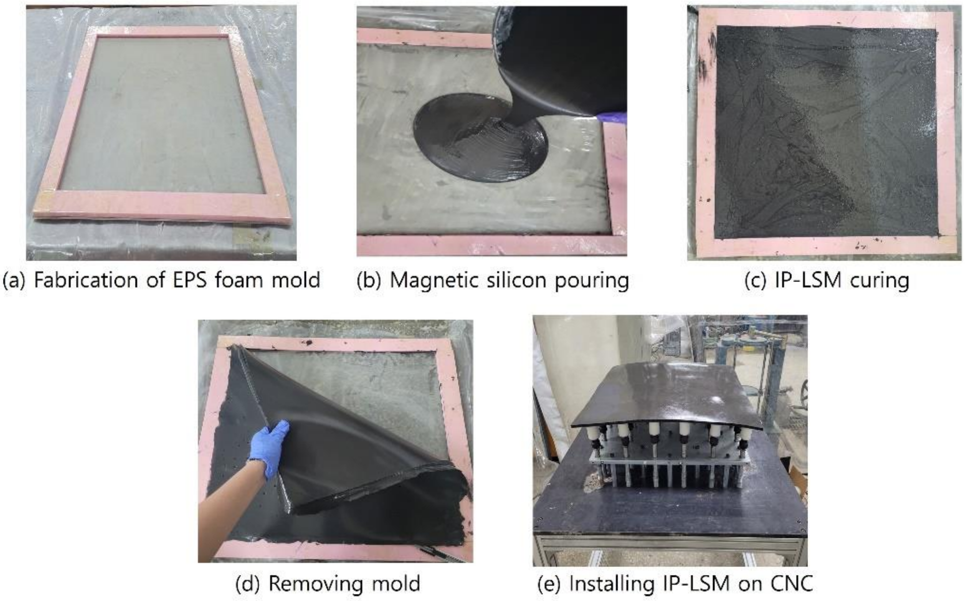


Figure 3. Concept of silicone mold fixation method using magnetic force

### 3.1. Iron powder-lower silicone mold

Kim (2024) conducted a study involving the addition of iron powder to a silicone plate and subsequently assessed its adhesion performance with a magnet [1]. During testing, specimens with less than 30% of added iron powder exhibited weak magnetic force, while those with over 70% of iron powder lost the characteristic properties of silicone. Hence, for the present study, the Iron Powder-Lower Silicone Mold (IP-LSM) with 70% iron powder is utilized. The manufacturing process of the IP-LSM is outlined in Figure 4. To create the mold, an acrylic plate was employed for the bottom, and EPS foam was processed on the sides, as depicted in (a). In the subsequent step (b), 3% hardener and 70%

iron powder were added to the silicone liquid, which was then poured into the mold. The curing time for silicone is 5 hours at 25°C with 50% humidity. However, for complete hardening, it underwent a 24-hour curing process, as illustrated in (c). Subsequently, the mold was demolded, as shown in (d), resulting in an IP-LSM with dimensions of 600*600mm. Finally, the IP-LSM was positioned at the top of the CNC, as depicted in (e).


(a) Fabrication of EPS foam mold (b) Magnetic silicon pouring (c) IP-LSM curing

(d) Removing mold (e) Installing IP-LSM on CNC

Figure 4. IP-LSM manufacturing process

### 3.2. Magnetic silicone side mold

The side mold, which is essential to be placed on top of the IP-LSM, requires magnetic properties. To achieve this, Neodymium magnets are inserted into the lower part of the silicone side mold. However, it is crucial to carefully select the appropriate insertion depth and spacing for the Neodymium magnet. The specifications of the Neodymium magnet are r=15mm, t=1mm, requiring it to closely adhere to the IP-LSM when positioned at the bottom of the silicone side mold. Ensuring a proper fit is essential to avoid deformation of the silicone side mold when the inserted Neodymium magnet is in close proximity to the IP-LSM. To assess the suitable depth, a silicone sheet was introduced between the iron-containing material and the Neodymium magnet to examine the range of magnetic force. In this process, the silicone sheet thickness was increased by 1mm to evaluate magnet attachment. The magnetic force was observed to increase with a closer gap between the Neodymium magnets on the silicone side mold. Therefore, utilizing a magnetic viewer, the magnets were spaced 30 mm apart, a distance that does not compromise their attractive force. The magnetic silicone side mold, produced through this experiment, is illustrated in Figure 5.

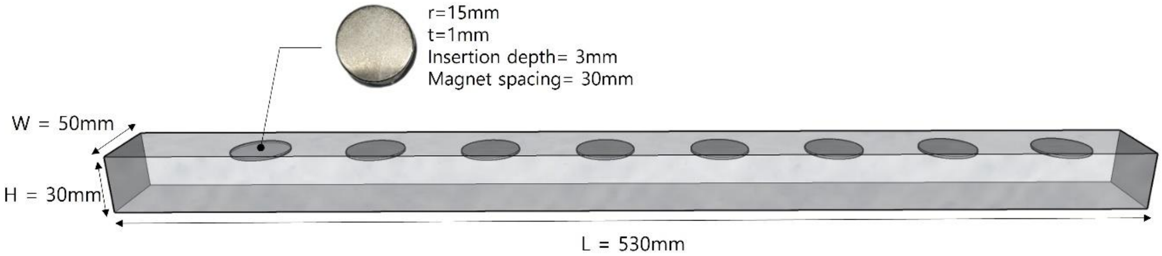
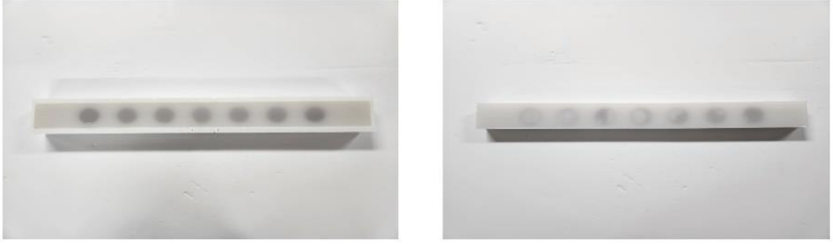


Figure 5. Magnetic silicone side mold design

The manufacturing process of the magnetic silicone side mold is depicted in Figure 6. To avoid deterioration in the quality of the silicone material and precision caused by post-processing with a sharp object for Neodymium magnet insertion, a 3D printer was employed in this study. The 3D-printed mold as shown in (a) was designed with a structure capable of creating a hole at the desired insertion position for the Neodymium magnet. Following the removal of the initial mold, Neodymium magnets were inserted, as illustrated in (b). Subsequently, silicone was poured again (as shown in (c)), left to cure for 5 hours, and then the mold was removed, resulting in the production of a magnetic silicone side mold, as shown in (d).

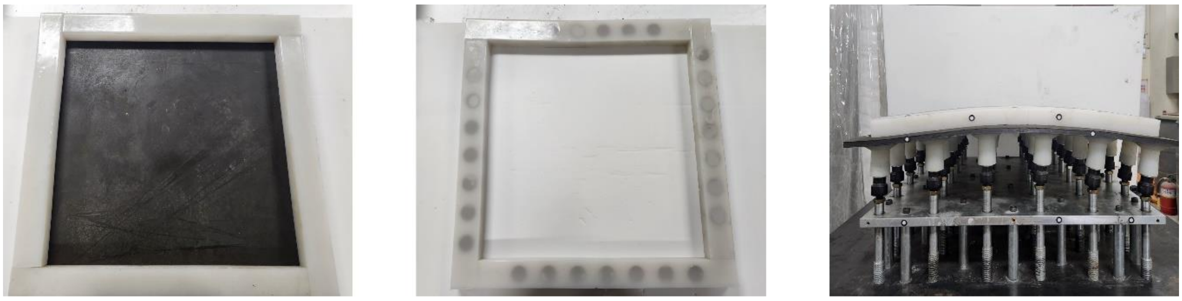
(a) Printing the mold using 3D printer (b) Neodymium magnet arrangement



(c) Silicone pouring (d) Removing mold

Figure 6. Magnet silicone side mold manufacturing process

The Magnetic Silicone mold produced through this process is illustrated in Figure 7. Panel (a) represents the upper surface when the magnetic silicone side mold is installed on top of the IP-LSM, while panel (b) showcases the lower surface of the magnetic silicone side mold. This mold can produce Free-form Concrete Panels (FCPs) with dimensions of 480*480mm and is installed and utilized on a CNC, as depicted in (c).



(a) Upper surface (b) Lower surface (c) Magnetic silicone mold

Figure 7. Magnetic silicone mold

## 4. CONCLUSION

In this study, it was affirmed that silicone molds are extensively utilized in the realm of free-form concrete construction. Previously, single-use free-form molds posed limitations such as heightened construction waste and increased costs. However, silicone molds offer semi-permanent usability owing to their material characteristics, facilitating versatile implementation of various free-form shapes. To materialize the free-form shape, Free-form Concrete Panels (FCPs) were manufactured within an acceptable error range using silicone and CNC technology. Nonetheless, FCPs encountered constraints such as bonding difficulties due to minor errors, stemming from the absence of a fixing method between the silicone plate molding the bottom and the silicone side mold.

To address this issue, Magnetic fixation was introduced as a novel method for silicone molds. Iron powder was integrated into the silicone plate shaping the bottom to confer magnetic properties, following the precedent set by Kim (2024) [1]. Subsequently, an experiment was conducted to determine the optimal depth and spacing for inserting Neodymium magnets into the silicone side mold. As a result, a Magnetic silicone side mold was produced, with Neodymium magnets inserted at a depth of 3mm and a gap of 30mm.

The magnetic silicone mold, crafted through this method, was affixed atop the CNC to assess its curvature. It was confirmed that both the IP-LSM and Magnetic silicone side mold were securely fixed. In subsequent research, the adhesion of the IP-LSM and Magnetic silicone side mold across various curvatures will be examined. This will elucidate the precise shape realization and the extent of magnetic force in FCPs necessitating diverse curvatures.

Finally, the performance will be verified through an FCP manufacturing experiment employing a magnetic silicone mold. This research heralds a new fixation method for silicone molds, promising novel construction technology in the domain of free-form construction.

## ACKNOWLEGEMENTS

This work was supported by the National Research Foundation of Korea(NRF) grant funded by the Korea government(MSIT) (No. 2020R1C1C1012600).

## REFERENCES

[1] J. Kim, “A Study on Improving the Shape Error of the Lower Mold of Free-form Concrete Panels Using Magnet Force”, Master’s thesis, Hanbat National University, Daejeon, Republic of Korea, 2024.

[2] J. Kim, J. Kim, “Effects of trip factors relating to dongdaemun design plaza & park (DDP) on visitor` satisfaction and revisit intention”, Korean Society of Basic Design & Art, vol. 16, no. 2, pp.99-112, 2015.

[3] C. Kim, C. Kim, “A study on expressive characteristics of informal form in the contemporary architecture”, Journal of The Architectural Institute of Korea, vol 19, no 4, pp. 101-108, 2003.

[4] J. Yun, “Development of Connection Technology and Operational Technology for the Lower Mold of Free-Form Concrete Panels”, Master’s thesis, Hanbat National University, Daejeon, Republic of Korea, 2022.

[5] H. Ahn, D. Lee, W. Ji, W. Lee, H. Cho, “Development of method for manufacturing freeform EPS forms using sloped-LOM Type 3D Printer”, Journal of the Korea Institute of Building Construction, vol. 20, no. 2, pp. 171-181, 2020.

[6] D. Lee, S. Lee, S. Kim, “Composite Phase-Change Material Mold for Cost-Effective Production of Free-Form Concrete Panels”, J. Constr. Eng. Manag, vol. 143, no. 6, 04017012, 2017.

[7] V. Stinikov, “Ice Formwork for High-Performance Concrete: A Model of Lean Production for Prefabricated Concrete Industry”, Structures, vol. 18, pp. 109–116, 2019.

[8] N. Cauberg, B. Parmentier, D, Janssen, M. Mollaert, “Fabric formwork for flexible, architectural concrete", Proceedings of the international symposium on fibre-reinforced polymer reinforcement for concrete structures, FRPRCS-9. Sydney, Australia, pp. 2009.

[9] K. Jeong, M. Lee, J. Oh, D. Lee, “Development of Side Silicone Mold for Reducing Shape Error of Free-Form Concrete Panel", Buildings vol. 13, no. 2, 480, 2023.

[10] S. Shit, P. Shah, "A review on silicone rubber", National academy science letters, vol. 36, no. 4, pp. 355-365, 2013.

[11] H. Schipper, “Double-curved precast concrete elements: Research into technical viability of the flexible mould method”, TU Delft, Delft University of Technology, 2015.

[12] J. Seo, D. Hong, "3D Cutting Machine of EPS Foam for Manufacturing Free-Formed Concrete Mold“, Journal of the Korean Society for Precision Engineering, vol. 34, no. 1, pp. 35-39, 2017.

[13] S. Oesterle, A. Vansteenkiste, A. Mirjan, "24 Zero Waste Free-Form Formwork", Proceedings of the Second International Conference on Flexible Formwork, pp. 258-267, 2010.

[14] B. Khoshnevis, “Automated Construction by Contour Crafting – Related Robotic and Information Technologies”, Journal of Automation in Construction, vol. 13, no. 1, pp. 5-19, 2004.

[15] V. Mechtcherine, F. Bos, A. Perrot, W. Leal da Silva, V. Nerella, S. Fataei, R. Wolfs, M. Sonebi, N. Roissel, “Extrusion-based additive manufacturing with cement-based materials – Production steps, processes, and their underlying physics: A review”, Cement and Concrete Research, vol. 132, 106037, 2020.

[16] C. Gosselin, R. Duballet, P. Roux, N. Gaudillière, J. Dirrenberger, P. Morel, “Large-scale 3D printing of ultra-high performance concrete–a new processing route for architects and builders”, Materials & Design, vol. 100, pp.102-109, 2016.

[17] T. Ngo, A. Kashani, G. Imbalzano, K. Nguyen, D. Hui, “Additive manufacturing (3D printing): A review of materials, methods, applications and challenges”, Composites Part :B Engineering, vol. 143, pp. 172-196, 2018.

[18] W. Hawkins, M. Herrmann, T. Ibell, B. Kromoser, A. Michaelski, J. Orr, R. Pedreschi, A. Pronk, H. Schipper, P. Shepherd, D. Veenendaal, R. Wansdronk, M. West, “Flexible formwork technologies– a state of the art review”, Structural Concrete, vol. 17, no. 6, pp. 911-935. 2016.

[19] S. Kim, S. Son, D. Lee, “Development of sustainable production technology of free-form concrete panels using a multi-point press CNC machine", Sustainability, vol. 13, no. 4, 1990, 2021.

[20] J. Yun. J. Youn, J. Kim, D. Lee, “Development of Connection Technology between Multi-Point Press and Flexible Mold for Manufacturing Free-Form Concrete Panel", Buildings, vol. 12, no. 6, 767, 2022.