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A study of side shape analysis of free-form concrete panel using silicone mold and paraffin

Jongyoung Youn[1], Junwon Bu[2], Seeun Cho[3], Minje Jo[4], Kyeongtae Jeong[5], Donghoon Lee*[6]
[1,2,3,4,5,6]Department of Architectural Engineering, Hanbat National University, Daejeon 34158, Korea; donghoon@hanbat.ac.kr (D.L.).

Abstract: This study analyzes the limitations of silicone molds used for free-form panel production and aims to address these issues by utilizing paraffin wax. Silicone molds are known for their reusability and ease of forming free-form shapes. However, the lack of a fixing method between the side and bottom molds makes them vulnerable to lateral pressure. Through FCP production experiments, 3D scans were conducted and shape errors were analyzed. The results showed that while the overall errors were uniform, errors exceeding 3 mm were observed at both ends of the curved sections. These errors are attributed to the installation of CNC equipment and the assembly process of the molds. Therefore, future research should focus on refining the corners and joints of the molds as well as validating complex curved shapes. This study is expected to serve as foundational data for research related to free-form molds.

Keywords: *Free-form concrete panel, Free-form mold, Paraffin wax. Shape error, Silicone.*

1. Introduction

Free-form buildings are structures composed of panels with various curved surfaces and curvatures. To produce these free-form panels, custom molds are necessary [1]. Depending on the location where the free-form panels are used, different curved surfaces are required, and they must be assembled with precision at regular intervals [2]. Currently, advanced technologies such as BIM, Revit, and CNC milling are employed to manufacture free-form molds, which incur high costs [3-5]. Despite the substantial expenses associated with these new architectural concepts, many free-form buildings are being constructed [6,7]. Therefore, research is being conducted to use recyclable materials for molds or to develop molds that can be variably deformed to reduce production costs [8,9].

Silicone has excellent properties such as heat resistance, chemical stability, electrical insulating, abrasion resistance, and weatherability [10]. Due to these characteristics, silicone molds are easy to use for forming free-form shapes and are reusable [11]. Free-form panels are primarily made of aluminum and metal materials, but the costs associated with processing them are high. In contrast, concrete has good fluidity and is practical for achieving geometric free-form shapes, with excellent compressive and flexural strength, making it widely used in the manufacture of free-form panels [12]. Many studies have been conducted on free-form concrete panels (FCP) due to these characteristics [13]. Silicone molds are classified into lower and side molds depending on the implementation of FCP. The lower silicone mold is implemented by a silicone plate installed on top of CNC (Computer Numerical Control) equipment. The CNC equipment consists of multiple rods that operate vertically. The rods push the silicone plate according to the inputted design shape of the FCP lower part, thereby manufacturing the lower curved surface of the FCP. A silicone cap is installed between the rods and the silicone plate to resist the concrete load and achieve precise curvature. However, the side silicone molds are fixed only by the same frictional force as the lower silicone plate. This fixation method is vulnerable to lateral pressure

* Correspondence: donghoon@hanbat.ac.kr

generated during concrete pouring, which can reduce precision as shown in Figure 1. In such cases, the quality of the produced panels may deteriorate, or defective panels may be manufactured. Therefore, this study aims to improve the structure of the side silicone molds to prevent deformation and resist the lateral pressure of the concrete.

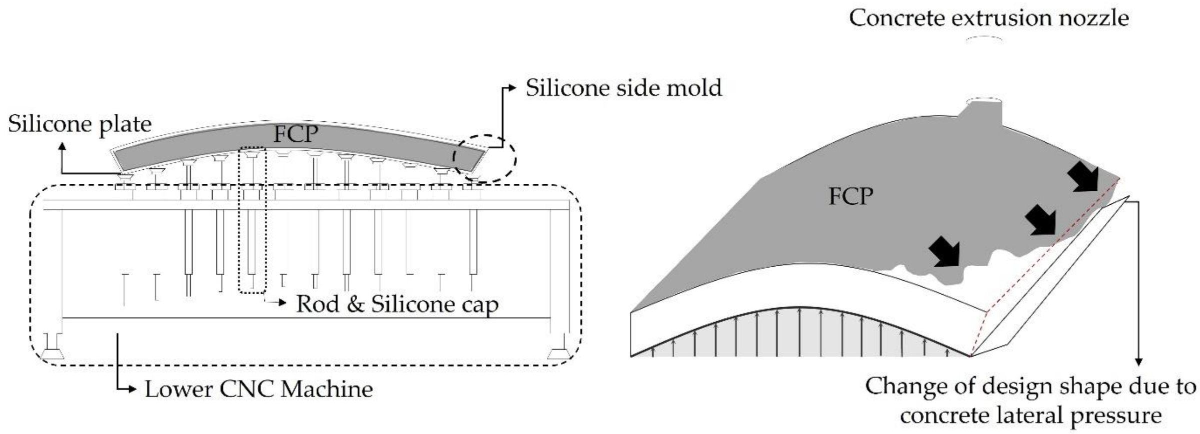

Figure 1.
Components and limitations of silicone free-form molds.

The objective of this study is to develop a side mold that can resist lateral pressure generated during the production of free-form concrete panels (FCP) while being compatible with silicone free-form molds. The research procedure consists of four stages, as shown in Figure 2. First, a review of prior studies on side silicone molds and mold fixation methods will be conducted. Through this analysis, the requirements for silicone side molds will be derived. Based on this, a new side mold using silicone and paraffin will be designed. To verify the performance of the paraffin silicone side mold, experiments for producing free-form concrete panels will be conducted. The shapes of the manufactured free-form concrete panels will be scanned to analyze shape deviations. The analyzed data will be interpreted to validate the performance of the paraffin silicone side mold.

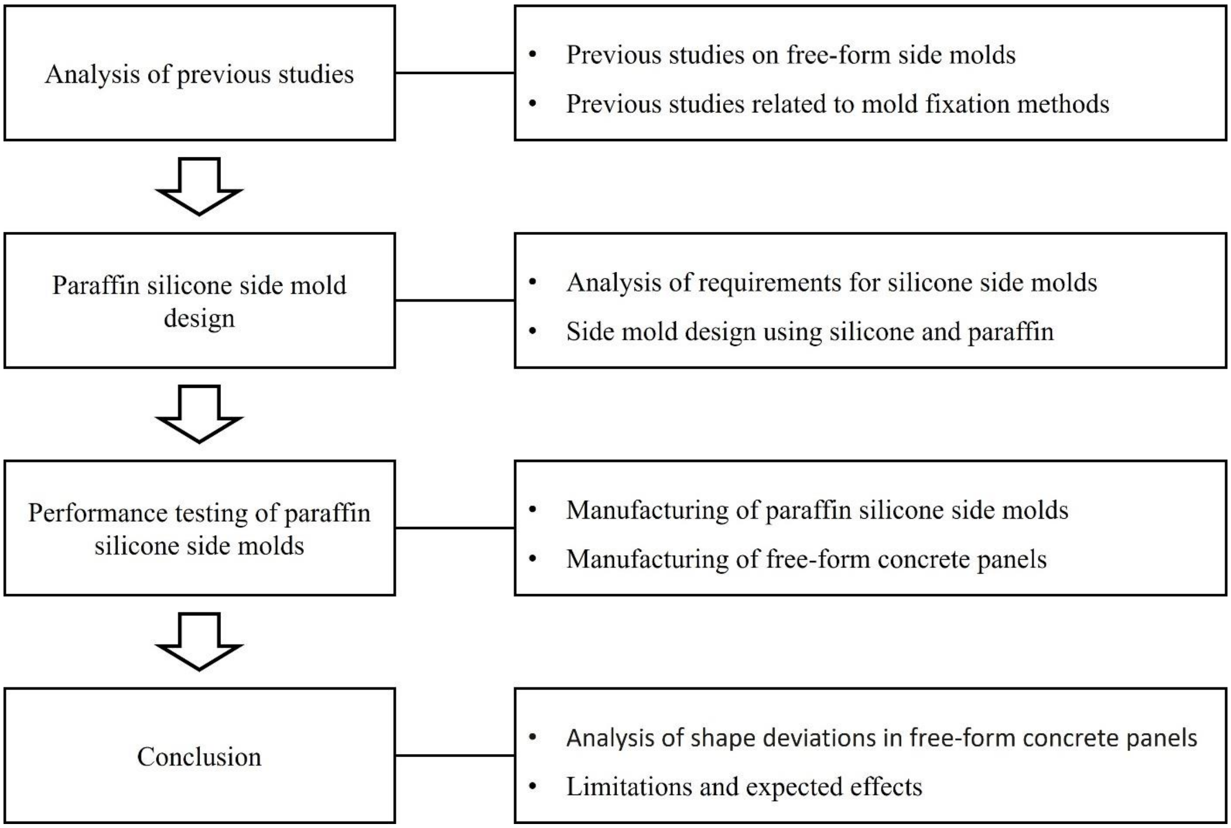

Figure 2.
Flowchart of the research.

2. Literature Review

2.1. Previous Studies on Free-Form Side Molds

Numerous studies have been conducted on the production of free-form concrete panels (FCP) using silicone molds. Jeong (2021) developed a manufacturing device for free-form concrete and proposed the concept of a silicone lower mold. Yun (2022) developed a silicone cap that attaches to the end of the rods in the lower mold. Utilizing this, a lower operation technique for producing intricate FCP was proposed [14,15]. However, while studies related to free-form lower molds have been conducted, there have been comparatively fewer studies on side molds as follow-up research. Most studies have used side molds made of different materials in conjunction with lower silicone molds.

Youn (2022) developed a side mold applicable to the side shape control equipment used in free-form mold manufacturing devices. The side shape control equipment consists of multiple rods with magnets attached to their ends. The variable side mold features a structure where steel plates are joined in a crosswise manner, allowing for free-form deformations and length adjustments by connecting the plates. The material of the steel plates allows them to attach to the magnets at the ends of the rods. When the lower silicone mold implements the designed shape, the rods on the side advance to move the variable side mold. However, since there is no separate fixation method for the variable side mold and the lower silicone mold, they are susceptible to lateral pressure, which can lead to shape deviations. Therefore, experiments for producing FCP were conducted to verify the performance of the variable side mold [9]. Lee (2023) developed a steel mold that can be embedded on the lower silicone equipment, enabling the production of FCP without demolding. However, due to the need to process the steel mesh according to the desired shape, precision is required. Thus, the molds were classified into A-type, which is processed from steel plates, and B-type, which is processed from steel mesh, and the performance of the molds was

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confirmed through FCP production [16].

2.2. Previous Studies Related to Mold Fixation Methods

Research has been conducted to fix free-form molds. Yun (2021) utilized side molds for producing free-form concrete panels and developed side shape control equipment capable of resisting the lateral pressure generated during FCP production. The side shape control equipment consists of multiple rods that can move back and forth to secure the side mold [1]. Youn (2023) fabricated free-form molds using a 3D printer. This was done in an assembly method using curved and standard types to produce unidirectional panels. Assembly pins were used to resist lateral pressure [17]. Based on the analysis of these previous studies, this research intends to develop a silicone side mold that can resist lateral pressure.

3. Development of Silicone Side Molds Utilizing Paraffin

3.1. Analysis of Requirements For Silicone Side Molds Utilizing Paraffin

In this study, requirements have been selected to secure the silicone side mold presented. To be utilized as a free-form mold, the material of the mold must be reusable and easy to shape into non-standard forms. To meet these criteria, this research intends to utilize paraffin. Paraffin is one of the phase change materials (PCM) that can freely change between solid and liquid states at a certain temperature, with a melting point ranging from 30℃ to 90℃. It is insoluble in water but soluble in ether, benzene, and esters. Additionally, solid paraffin can be heated to a liquid state, allowing for reuse [18]. These characteristics provide good compatibility with silicone side molds, and it is intended to use this as a fixation method.

3.2. Design of Silicone Side Molds Utilizing Paraffin

The silicone side mold utilizing paraffin presented in this study is shown in Figure 3. A space is created inside the existing silicone side mold to position the paraffin wax. After pouring the liquid paraffin wax into the interior of the silicone side mold, it is cured to increase the weight. Fixed pins are used to connect the silicone molds that make up each side, reinforcing the weak points at the joints.

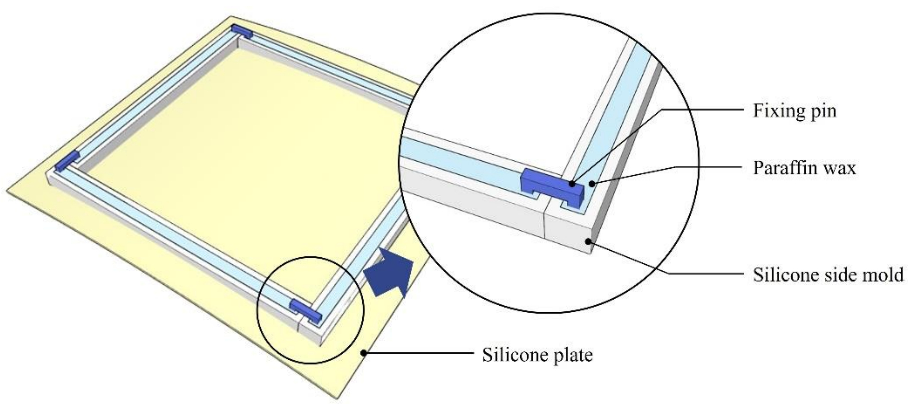

Figure 3.
Components of paraffin silicone side molds.

The mold design was produced using CAD and then printed using a 3D printer. The manufactured mold has a space in the central part for pouring silicone. The specifications of the mold vary according to the size of the FCP to be produced, and in this study, it was designed to be 540*40*30 mm. The space for the internal paraffin wax is designed to be 520*20*20 mm. The fixing pins used for the connection between the molds were printed using a 3D printer, which strengthens the connection between the sides of the components. The produced free-form mold is in the shape of a unidirectional panel, and FCP production experiments were conducted to verify the performance of this mold.

4. Performance Testing of Silicone Side Molds Utilizing Paraffin

4.1. Experimental Production of Free-Form Concrete Panels

To verify the performance of the side molds developed in this study, FCPs will be produced using CNC equipment. The CNC equipment is composed of a total of 36 rods with dimensions of 600*600 mm. The FCP to be produced is designed to be 500*500*30 mm. To implement this, the rod values of the CNC equipment according to the shape of the bottom surface of the FCP were calculated as shown in Table 1.

Table 1.
Load displacement value.

Axis	X1	X2	X3	X4	X5	X6
Y1	15.55	24.81	29.42	29.42	24.81	15.55
Y2	15.55	24.81	29.42	29.42	24.81	15.55
Y3	15.55	24.81	29.42	29.42	24.81	15.55
Y4	15.55	24.81	29.42	29.42	24.81	15.55
Y5	15.55	24.81	29.42	29.42	24.81	15.55
Y6	15.55	24.81	29.42	29.42	24.81	15.55

Note: *(Unit: mm).

The mixing ratio used to produce the FCP is shown in Table 2. In the case of FCP, concrete must flow to fill the interior of the mold following the free-form shape. For this purpose, a suitable fluidity of the concrete is required, and this study utilized PVA and a superplasticizer.

Table 2.
FCP mixing ratio.

W/C(%)	Cement	Sand	Water	PVA	Superplasticizer
40	7,312.5	7,312.5	2,925	109.69	21.93

Note: *(Unit: g).

The FCP production process is shown in Figure 4. First, the CNC equipment is implemented to match the designed shape. After installing the silicone plate on the implemented rod, the manufactured paraffin silicone side mold is placed. Liquid paraffin wax is poured into the interior space of the placed mold to fix the installed side mold. After the paraffin has cured, concrete is poured into the mold to produce the FCP.

Figure 4.
FCP production process.

4.2. Analysis of Shape Errors in Free-Form Concrete Panels

This study scans the shape of the produced FCP to verify the occurrence of errors due to lateral

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pressure. For this purpose, the Go! SCAN SPARK 3D scanner from Proto 3000 was used. The scanned shape data can be overlapped with the CAD design files to analyze the errors. The program used for this analysis is Vxelements, and the overall error values are shown in Table 3.

Table 3.
Shape error value.

Size	Minimum	Maximum	±	Standard deviation
mm	-5.000	4.597	9.597	2.010

The error range of the produced FCP was determined to be 9.597 mm, as shown in Figure 5. A positive value indicates that the produced panel is protruding beyond the design file, while a negative value indicates that it is recessed compared to the design file. The side error values of the panel were analyzed by categorizing them into straight and curved sections. The analysis results showed that the central part of the FCP had a smaller error value, while the error values increased towards the ends. This indicates that the fixing pins installed at the corners of the mold did not fully secure each component.

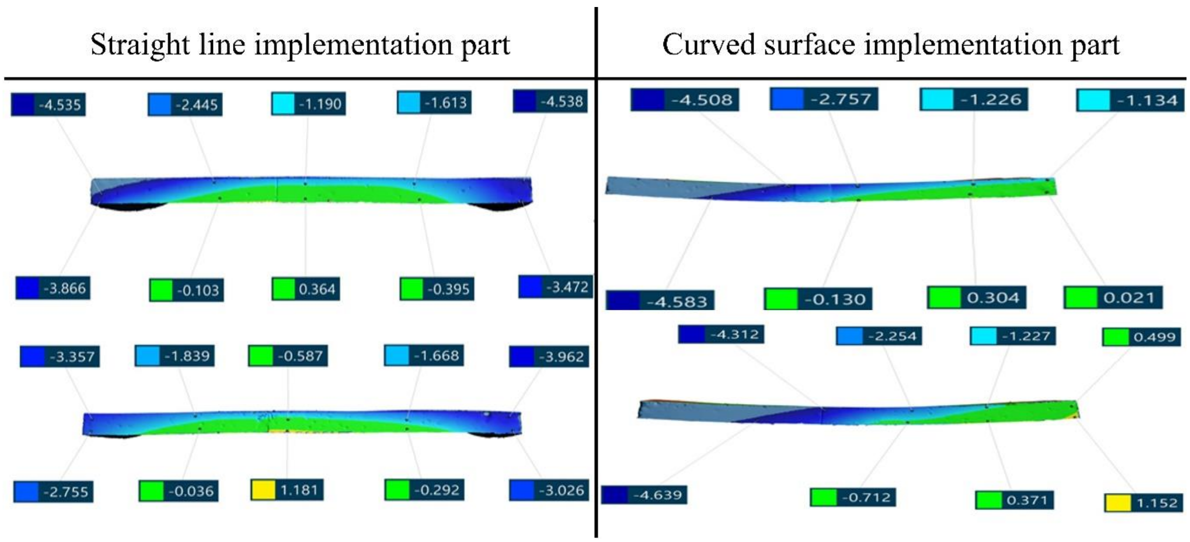

Figure 5.
FCP Shape scan data.

5. Conclusions

This study analyzes the limitations of silicone molds used for free-form panels. Silicone is utilized as a material suitable for free-form molds due to its reusability and ease of implementing free-form shapes. Silicone molds are classified into bottom and side molds and are precisely shaped using CNC equipment. However, there is no fixing method between the side molds and the bottom molds, making the structure vulnerable to lateral pressure. This structure can lead to a degradation in the quality of the FCP due to lateral pressure during concrete pouring compared to precisely implemented molds. Therefore, this study aims to create a space within the silicone side molds to pour paraffin wax. The poured paraffin wax is in a liquid state, but as a phase change material, it solidifies inside the silicone side molds according to the free-form shape. By injecting paraffin, it is possible to compensate for deformation caused by concrete lateral pressure, thereby increasing the load and reinforcing the fixation with the bottom mold.

To verify the performance of the paraffin silicone side molds, FCP production experiments were conducted. The produced panels were 3D scanned, and the shape was overlapped with the design to analyze the shape error of the FCP. The analysis of the FCP shape scan results showed that the overall error occurred uniformly. However, errors exceeding 3 mm were observed at both ends of the curved sections. The cause of these errors is analyzed to be due to the processes involved in installing the CNC equipment and the molds. Additionally, since the molds developed in this study are modular, errors are believed to have occurred at the joints.

Future research should focus on refining the corners of the molds and the joint areas, as well as validating complex curved shapes. This study aimed to address the limitations of previous research by utilizing paraffin wax, and the shape of the FCP satisfied the shape error criterion of within 3 mm. This research is expected to serve as foundational data in terms of materials and new fixation methods related to studies on free-form molds.

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