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Production Technology of Free-form Concrete Segments using Phase Change Material

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***Abstract*—Free-form buildings are beautiful, but production and installation of Free-form Concrete Segments (FCSs) are costly. Especially a form or a mold used to produce FCSs is unrecyclable, so that much more money and time are needed to make it than FCSs. Therefore it is necessary to develop a mold that can be semi-permanently recycled and mass produce FCSs. The objective of this paper is to suggest the production technology of free-form concrete segments using phase change material. Phase change material (PCM) is a substance that presents the change of phase according to temperature variation, which includes most substances as well as water and metal. The mold used to produce FCS is made of solid-state PCM and it should be liquefied to be recycled by adding thermal energy. If a metamorphic mold is developed by utilizing PCM's properties, it can be recycled semi-permanently and mass-produced quickly and easily. The results of this study will be used as basic data for optimizing the production and installation of FCSs. (Abstract)**

***Keywords*—Freeform concrete segment, Mold, Phase change material, Melting point, Heat of fusion**

I. Introduction

Free-form buildings are beautiful, but production and installation of free-form concrete segments (FCSs) are costly. Especially a form or a mold used to produce FCSs is unrecyclable, so that much more money and time are needed to make it than FCSs. Conventional free-form molds are made mostly of iron, wood, styrofoam, textile, etc. [1,2] These are unrecyclable one-off molds, which is a key reason for brining rise in costs. Moreover existing free-form molds generate much waste.

Free-form molds have various irregular curves, so it takes much more time and manpower to produce them compared to an ordinary form. Diverse technologies have been applied to produce FCSs so far [3,4], but an easy and economic production technology has not been developed yet [5]. Therefore it is necessary to develop the technology capable of not only semi-permanently recycling, but also quickly and easily mass-producing FCSs.

The objective of this paper is to suggest the production technology of free-form concrete segments using phase change material. PCM is a substance that present the change of phase according to temperature variation, which includes most substances as well as water and metal. Solid-state PCM mold is used to produce FCSs, but it should be liquefied to be recycled by adding thermal energy. If a metamorphic mold is developed by utilizing PCM's properties, it can be recycled semi-permanently and produce FCSs more economically than existing technologies.

II. Consideration of Preceding Researches

Active research efforts have been made to implement free-form buildings, centering on design and production technologies of FCSs. Especially along with the development of computing power, 3D design technology like BIM and CNC processing technology of design information have advanced to a substantial level. However in most cases, forms for free-form structures and molds for producing free-form finish panels are still unrecyclable, putting tremendous burden on productivity and production cost. In developed countries, a lot of free-form buildings are being newly built based on tremendous financial support and a variety of construction technologies are being applied, but technologies for economically producing FCSs are still lacking [3,6,7].

Representative overseas researches are specifically described in Table 2.1. Looking at relevant researches, P. Mandl et al. and Lindsey and Gehry's studies produced EPS-formwork by using CNC processing technology [3,4] while Toyo Ito & Associates' study processed timber with CNC equipment to produce an one-off form and implement FCSs [8]. This CNC-processed form can accurately implement and cast concrete shapes, but its unrecyclable feature needs to be improved. Franken Architeckten & ABB Architeckten's study implemented FCSs by using a digital form which incorporated CNC and acryl glass so as to express the surface tension of water drop [9]. However, the researches above merely introduced FCS production methods and their excellence. Therefore it is required to develop a metamorphic mold that can be recycled and mass produce FCSs for improving economic efficiency.

III. Concept of Metamorphic Mold

The concept of FCS (free-form concrete segment) production technology is shown in Figure 1. A metamorphic PCM mold is created based on partitioned design data. Concrete is placed and injected into the coagulated PCM mold to produce FCSs. The produced FCSs are installed at the site and the PCM mold is liquefied by heating above a certain temperature to be reused as the mold for other FCSs.

Since all FCSs are in different sizes and shapes, various molds with the unlimited freedom of shaping are needed. PCM

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is phase change material which is maintained in a solid state at room temperature around 20℃, but turns to liquid above a certain temperature. Compared to water which is the representative phase change material, PCM is strong enough to be used as a mold. The semi-permanent metamorphic mold suggested by this study mainly uses PCM to improve efficiency ratio and implement free shapes.

PCM-based mold can be reused infinitely due to its properties that presents the change of phase through fusion and coagulation. If the metamorphic mold incorporating PCM's properties is made, it will not only maximize efficiency ratio but also mass produce FCSs quickly and easily.

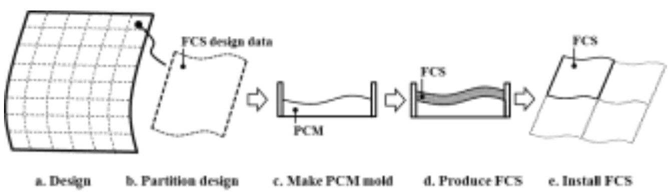

Figure 1. Flow of Production of FCS using PCM mold

IV. Analysis of PCM's Properties and Selection

To select PCM which can be used as main material for making a metamorphic mold, the melting point and the heat of fusion need to be considered. Table 1 shows the investigation results of the melting point and the head of fusion of PCM. To use PCM as main material, the melting point needs to be above room temperature and the heat of fusion needs to be low. For this reason, the substance with the melting point below 50℃ is unfit for the production of a metamorphic mold. The substance with the heat of fusion above 75℃ consumes much energy due to high heating capacity, so it is also excluded. Consequently, stearic acid and paraffin are suitable for producing a metamorphic mold, and especially paraffin with the lower heat of fusion (174kJ/kg) is believed to be the most suitable material.

TABLE I. MELTING POINT AND HEAT OF FUSION OF PCM

Material	Melting point(℃)	Heat of fusion(kJ/kg)
Acetamide	82.3	214
Naphthalene	78.2	148
Stearic acid	71	203
Paraffin	20~64	174
3-heptadecenone	48	218
Cyanamide	44.0	208.41
d-lactic acid	26	184
Glycerol	18.2	200.62
Acetic acid	16.6	192.09
Ethylenediamine	11.1	375.77
Polyglycol E400	8.3	276.35

Paraffin includes various types of compounds as shown in Table 2 with different levels of the melting point and the heat of fusion. To select the most suitable compound as material for a metamorphic mold requires the investigation of room temperature changes, which is the environmental factor in the production of a mold. Table 3 presents data of South Korea's temperature changes surveyed for 20 years from 1993 to 2012. The survey was conducted of Busan and Seoul which are the representative cities of Korea, and it found that the lowest temperature of Seoul was 17℃ below zero while the highest temperature was 38.4℃.

TABLE II. MELTING POINT AND HEAT OF FUSION OF PARAFFIN

Compound	Melting point(℃)	Heat of fusion(kJ/kg)
Paraffin C16-C18	20-22	152.0
Polyglycol E600	22	127.2
Paraffin wax	64	173.6
Paraffin C16-C28	42-44	189.0
Paraffin C20-C33	48-50	189.0
Paraffin C13-C24	22-24	189.0
1-Dodecanol	26	200.0
1-Tetradecanol	38	205.0
Paraffin C18	27.5	243.5
Vinyl stearate	27-29	122.0

TABLE III. TEMPERATURE OF SEOUL AND PUSAN IN 20 YEARS

Classification		Jan	Feb	Mar	Apr	May	Jun
Seoul	Max.	13.5	18.7	22.2	29.8	31.9	35.0
	Avg.	-2.1	0.8	5.8	12.5	18.1	22.4
	Min.	-15.4	-17.1	-7.6	-0.9	5.8	10.8
Pusan	Max.	17.5	20.3	22.9	28.1	29.9	29.9
	Avg.	3.3	5.2	8.6	13.3	24.8	20.2
	Min.	-12.8	-9.9	-5.0	-0.1	7.8	12.4
Classification		**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Seoul	Max.	38.4	37.0	32.8	28.3	21.8	16.2
	Avg.	25.1	25.8	21.5	15.0	7.5	0.3
	Min.	16.2	16.3	8.4	-2.0	-9.0	-15.1
Pusan	Max.	35.8	34.9	35.2	29.1	25.6	19.4
	Avg.	23.5	25.1	22.0	17.5	11.8	6.0
	Min.	15.8	16.8	13.1	1.8	-3.6	-10.6

The range of temperature changes of South Korea as shown in Figure 1 (a) is between 17℃ and 38℃. The melting point must be 45℃ at least by considering the increase in temperature of material by sunlight in summer. Paraffin wax and paraffin C20-C33 maintain their solid state at room temperature regardless of season. Also paraffin wax with the melting point of 64℃ is believed to be the most suitable material when considering that heating load is higher than cooling load. However if the temperature drops below zero in winter, the temperature variation for paraffin wax's melting point increases, so it is inefficient in terms of energy consumption despite cooling load. As a result, selectively

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applying two types of paraffin according to the season is the best way to lower energy consumption.

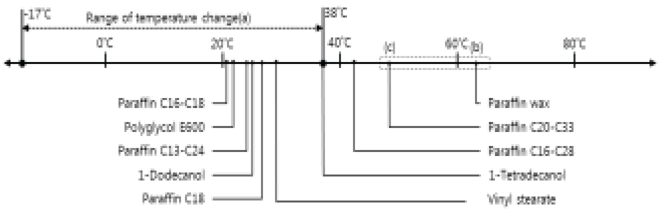

Figure 2. Selection of Paraffin Considering Temperature Change

V. Production Process of PCM Mold

PCM-based metamorphic mold is produced by heating PCM above a certain temperature to be liquefied and applying pressure to liquid PCM from the top or the bottom to create a free-form shape, then cooling it. The production process of a metamorphic mold is divided into four steps as shown in Figure 4.

1) Heat PCM above a certain temperature to liquefy it and inject it into a mold.

2) Implement the requested free-form shape by moving a height adjusting device located at the top or the bottom of PCM. Here, place a molding plate between PCM and the height adjusting device, which serves to support PCM to form a curved surface. This molding plate is returned to its original shape after making and separating PCM from it.

3) Separate PCM from the height adjusting device and place concrete in the PCM mold to produce FCSs.

4) Separate FCSs from the PCM mold and heat the mold above a certain temperature to make it turn to liquid. Since the liquefied PCM is recyclable as a mold of other FCSs, it can maximize efficiency ratio and is economically effective.

The metamorphic mold can reduce time for mold production using PCM's properties of phase change. This study focused on the PCM mold for producing one-sided free-form segments, but if the height adjusting device works simultaneously at both top and bottom sides, it is possible to produce double-sided free-form segments.

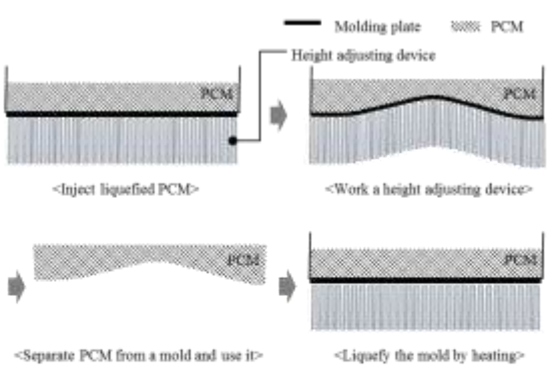

Figure 3. Procedure of PCM Mold Production

VI. FCM Casting Technologies

FCSs can be founded by using the completed PCM mold as a form. Casting technologies for FCS production are divided into grouting, press, and plaster. Casting technology can be selected depending on the shape of FCS' cross section. The three casting technologies are as follows:

Firstly, *Grouting* method is to produce FCSs by injecting concrete between the top and the bottom of the mold made. As shown in Figure 5, the shape of FCSs is implemented by placing a frame with an inlet and an outlet of concrete on the sides of a mold at the top and the bottom. In case of a double-sided free-form segment and an one-sided free-form segment, their shapes are formed by using both top and bottom molds and the top mold or the bottom mold, respectively. For this method, frame's waterproofing and concrete filling are important.

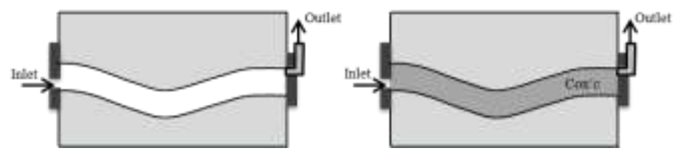

Figure 4. FCS Casting using Grouting Method

Secondly, *Press* method is to produce FCSs by placing concrete in the bottom mold to compress it. As shown in Figure 6, if the FCS has a free-form shape in both sides, the top mold is needed to build segments. But the FCS has an free-form shape in one side, it can be implemented without the top mold depending on the fluidity of concrete. In other words, whether to use the top mold or not is determined depending on the one-sided shape of FCS and the fluidity of concrete. For this method, sealing between molds is important because concrete may be leaked between the top and bottom molds when compression is made by the top mold.

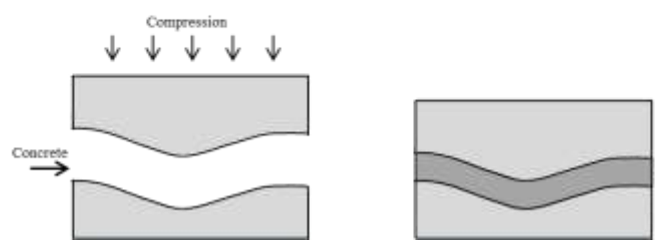

Figure 5. FCS Casting using Press Method

Thirdly, *Plaster* method is to produce FCSs by using a troweling machine after placing concrete in the bottom mold. As shown in Figure 7, concrete is placed in the bottom mold and the surface of segments is finished using a framed troweling machine or a robot-armed toweling machine. Unlike grouting and press, this methods can use automatic finishing.

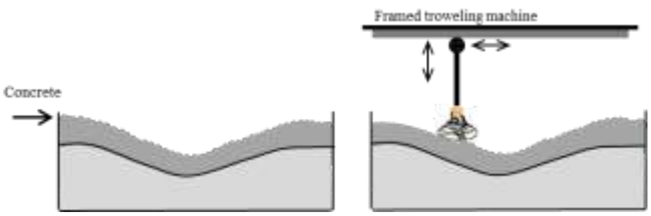

Figure 6. FCS Casting using Plaster Method

VII. Conclusion

Main obstacles to producing free-form panels are the facts that a form or a mold is mostly an unrecyclable one-off and that it requires considerable time and manpower for manufacturing. To solve these problems, this study suggests the production technology of FCS mold. If this FCS mold is used, much less time and manpower will be needed compared to those for producing existing free-form segments; the efficient placement and production of a mold will be possible; productivity will be enhanced as a construction plan between installations is established; and costs and construction period may be reduced.

To solve these issues, this paper suggests the production technology of free-form concrete segments using phase change material. The findings are as follows:

1) PCM-based metamorphic mold can be used semi-permanently, bringing down the cost of production. PCM's properties of phase change will also shorten the time for mold production.

2) The melting point and the heat of fusion are analyzed by comparing with South Korea's temperature. Paraffin wax and paraffin C20-C33 are believed to be most suitable PCM since they maintain their solid state at room temperature regardless of season. Also paraffin wax with the melting point of 64℃ is believed to be more energy efficient; and the selective application depending on temperature will reduce energy consumption.

3) Casting technologies for FCS production are divided into grouting, press, and plaster. The method can be selectively applied depending on the shape of FCS' cross section.

The results of this study will be used as basic data for developing specific technologies for the economic production of FCSs.

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