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Energy and CO_2 Reduction of Aluminum Powder Molds for Producing Free-Form Concrete Panels

Donghoon Lee [1] and Sunkuk Kim [2,*]

1 Department of Architectural Engineering, Hanbat National University, Daejeon 34158, South Chungcheong, Korea; donghoon@hanbat.ac.kr
2 Department of Architectural Engineering, Kyung Hee University, Yongin-si 17104, Gyeonggi-do, Korea
* Correspondence: kimskuk@khu.ac.kr; Tel.: +82-31-201-3685

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Abstract: Free-form design may enhance the architectural value of buildings in terms of aesthetic and symbolic effects. However, it is difficult to reuse the mold of free-form concrete segments, so they are manufactured for single use. Manufacturing these molds is a time-consuming process that requires a lot of manpower. To solve these problems, there have been numerous studies on the use of phase change materials (PCMs) to make the molds. PCM molds represent a new technique of producing free-form panels using a computerized numeric control (CNC) machine that employs low-cost material to produce free-form concrete panels. However, PCM molds require a substantial amount of time and energy during fabrication because repeated heating and cooling cycles are required during panel production, and this process increases the CO_2 emissions. Thus, the purposes of this study were to develop composite molds using aluminum powder to improve PCM mold performance and to conduct experiments to quantify the reduction of energy use and CO_2 emissions. As a result of cooling experiments, it was found that the aluminum powder mold had an energy reduction effect of 14.3% against the PCM mold that had been produced only with paraffin wax, and CO_2 reduction effect of more than 50% against the conventional mold.

Keywords: free-form building; free-form concrete panel; aluminum powder; composite PCM mold; CO_2 emission reduction

1. Introduction

Free-form design is being increasingly adopted in monumental buildings to improve aesthetic and symbolic effects. However, the molds used for the production of free-form panels are 3–10 times more expensive than conventional molds [1]. This is because free-form concrete segments are not produced in fixed shapes, which make it difficult to produce a mold using conventional materials like metal, wood, and synthetic resins; it is also impossible to reuse the produced mold [2]. Presently, molds for the production of free-form concrete segments (FCS) are only used one time. Due to this, the construction of free-form buildings requires longer construction times, is significantly more expensive, and also produces more CO_2 emissions compared to conventional construction. However, there have been no studies on the development of practical production technologies for free-form concrete segments to realize the environmentally-friendly construction of free-form buildings [3].

Since free-forms are composed of various irregular curved surfaces, they require more construction time and resources than ordinary molds. There has been a wide range of technologies applied to the production of free-form concrete segments [4–6], but the production of free-form concrete segments is not fit for sale [2,6].

Recently developed phase change material (PCM) molds can be semi-permanently reused, and it is easy and quick to produce free-form concrete segments (FCSs) with this new technique [7]. Here, PCM refers to a material that changes its phase from liquid to solid and vice-versa, depending on the temperature. PCM molds are used in the solid-state for FCS production, and it changes the mold back to a liquid state for reuse. However, heating and cooling must be repeated every time concrete segments are produced, so there is great concern about the environmental impact, including energy consumption and CO_2 emissions arising from energy consumption. It is absolutely necessary to evaluate energy consumption as well as CO_2 emissions when developing new molding materials [8]. Thus, the purposes of this study were to develop aluminum powder molds to improve PCM mold performance and to verify the reduction in energy consumption and CO_2 emissions achieved using these molds. This study is limited to frequently used conventional PCM molds, plywood (wooden) molds, and the newly developed aluminum powder molds. We also analyzed the effect of these techniques on energy consumption and CO_2 emissions. This study was conducted in five steps, as described below:

(1) Consideration of previous studies
(2) Development of aluminum powder molds
(3) Analysis of the characteristics of aluminum powder molds
(4) Analysis of energy consumption
(5) Analysis of CO_2 emissions

2. Consideration of Previous Studies

Steel, wood, expandable polystyrene (EPS), and plastic were used to produce free-form segments in many of the free-form buildings that have recently been completed [6,9–12]. Latorre [13] developed a "pneumatic system" to produce free-form domes, yet each material had to be individually produced, and it was difficult to produce shapes other than domes. Verhaegh [6] developed a "fabric formwork" using fabric forms, however many of the molds were used for shape constraints, and a great deal of manufacturing time was needed. This method failed to improve construction duration and cost when compared to conventional methods. Mandl et al. [14] and Lindsey and Gehry [15] conducted studies on the formwork made with EPS using computerized numeric control (CNC) technology and Toyo Ito and Associates [16] developed a wooden system form. Franken and ABB [17] used digital forms with CNC and acrylic glass to produce free-form concrete. However, these molds cannot be reused, generate a lot of waste, and require an extremely long manufacturing time. Researchers at the University of Southern California hoped to come up with a building process using a robot automation system, but additional studies are required due to limitations in the production of large segments. To address the problems with free-form molds, CRAFT (Center for Rapid Automated Fabrication Technologies) [18] are conducting a study on the 3D printing of buildings. However, the concrete deposited using a 3D printer nozzle needs time for curing, and it is not yet ready for commercialization because the size of the 3D printer is limited.

The need for developing economical, variable mold, and free-form concrete production technologies is on the rise and has focused on the reuse of molds and the reduction of production time [3]. Recognizing this need, Oesterle et al. [19] developed a reusable wax mold. PCM changes from solid to liquid and vice-versa depending on the type of external stimulation (temperature, electric current, etc.). Therefore, PCM molds can be used to make shapes and can be reused to reduce waste generation. Paraffin, one of the PCMs used in this study, is an alkane hydrocarbon with a chemical formula expressed as C_nH_{2n+2} ($n \geq 19$). It does not dissolve in water, but it does dissolve in ether, benzene, or ester. Paraffin is a mixture of hydrocarbon molecules comprised of 20 or 40 carbon molecules. It is a soft, white solid without color that is derived from petroleum, coal, or oil shale. The melting point of paraffin ranges from 47 °C to 64 °C, and the density is 0.9 g/cm^3 [20–22].

However, Oesterle et al. failed to analyze and discover solutions to address the increased energy consumption, increased CO_2 emission arising from the energy consumption, long freezing times, crystallization effects, strength issues, solidification shrinkage, and cracking. The study focused only on the realization of wax mold shapes and did not comprehensively explain the device or technology. In particular, the study had some limits in that it lacked specific verification of the shrinkage in wax molds, freezing time, and energy consumption.

Lee et al. [4] developed PCM molds using a CNC machine and suggested a production process of FCP (Free-form Concrete Panel). The production process was composed of a total of nine stages, as illustrated in Figure 1. In the stage wherein PCM molds were produced, liquid PCM was first filled into a CNC machine to produce a shape. After shaping, the hot liquid PCM was cooled to solidify the PCM. The solid PCM was then separated from the CNC machine and was attached to the frame on the side to produce a PCM mold. Production of the FCP involved pouring concrete into the PCM mold, followed by curing to produce FCPs [7]. However, the study failed to suggest solutions to various problems, including the extensive cooling energy of the PCM mold and the effects of crystallization and cooling time.

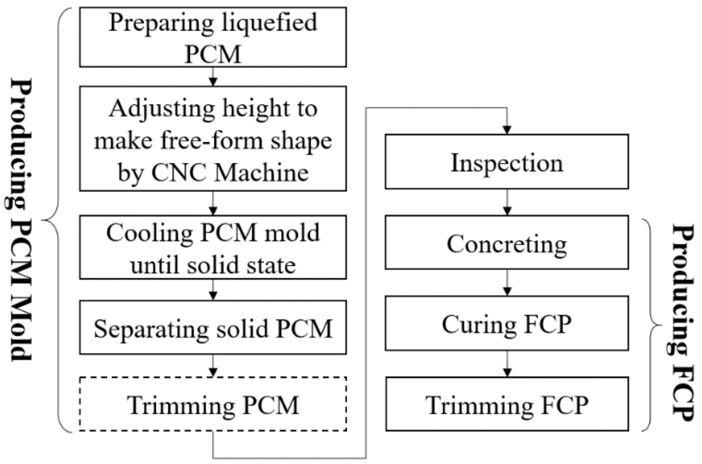

Figure 1. FCP (Free-form Concrete Panel) production process with phase change material (PCM) mold (Lee et al., 2015).

3. Aluminum Powder Mold

As examined in Section 2, there have been great efforts to develop free-form concrete panel molds. In addition, there have been some studies on the development of PCM molds that can be used to make free shapes. However, there are no case studies on the production of concrete panels for free-form buildings using novel PCM molds. This is because newly developed molds may be less practical or have some problems. A wide range of shapes can be produced with PCM molds, yet two problems still exist. First, PCM cooling takes a long time and requires a lot of energy. Second, the low strength of the PCM may result in crushing or sinking of the mold when concrete is poured into it. A light aluminum with outstanding thermal conduction was chosen as a material to improve the performance of the PCM molds in this study. The aluminum powder mold (c) shown in Figure 2 is a free-form mold mixed with aluminum powder (a) and paraffin wax (b); this mixture is produced using a CNC machine.

Aluminum, the main ingredient of the mold, is the most common chemical element found in the earth after oxygen and silicon. The heat of fusion of aluminum is 94.6 cal/g, and it has a melting point of 660 °C. As listed in Table 1, aluminum has a specific gravity of 2.71, and it is fairly light, only 1/3 of the weight of copper or iron. In addition, its thermal conductivity is 204 W/m·h·K, which is more than three times higher than that of iron (67 W/m·h·K) [23,24]. In this study, we developed free-form molds by mixing the aluminum powder with paraffin wax. The aluminum powder mold could be used to produce any shape in the heated, liquid state using a CNC machine. Then, it was cooled and used as a robust mold in the solid-state. The thermal conductivity of the aluminum powder mold was high, which solved previous problems related to the high consumption of cooling energy and long cooling times in other PCM molds. When the aluminum/paraffin wax PCM mold was cooled, the surface was first cooled and then frozen, letting down the energy efficiency. However, the thermal conductivity of the aluminum powder mold could solve the problem.

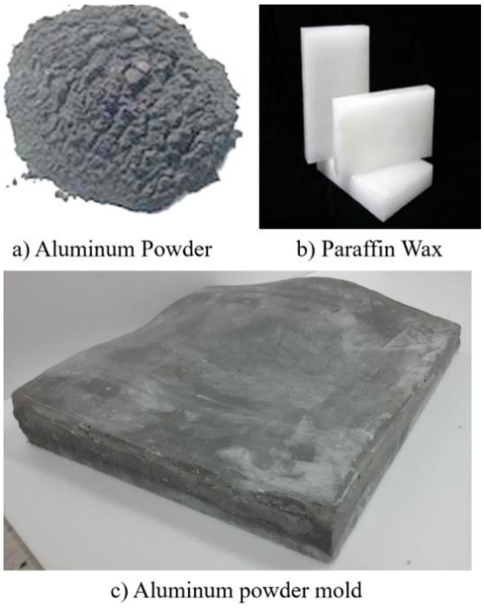

Figure 2. Ingredients of the aluminum powder mold.

Table 1. Specific heat and thermal conductivity of main metal and paraffin wax [25].

Ingredient	Specific Heat (cal/g·°C)	Thermal Conductivity (W/m·h·°C)	Specific Gravity
Al	0.215	204	2.71
Fe	0.107	67	7.86
Cu	0.0924	386	8.93
Paraffin wax	0.7	0.25	0.9
Water	1	0.016	1

Powder molds have been used for casting metal molds for a long time. They are reusable and are able to produce a wide range of shapes. However, the shape can be easily crushed or deformed. When paraffin wax is added to these powder molds, there is no change to the powder, which is densely packed after freezing. The molds are movable, and they are highly resistant to compression. As shown in Table 2 these types of molds can be reused semi-permanently, yet melting energy and cooling energy must be added during each reuse. Aluminum powder with high thermal conductivity is a suitable material for solving this problem.

Table 2. Characteristics of the mold materials.

Materials	Characteristics
Paraffin wax	- Owing to the crystallization effect, energy consumption, and cooling time increased upon cooling. - Deformation occurs due to compression caused by pouring concrete. - Any shape can be produced, and it can be moved after freezing.
Powder (sand, minerals, etc.)	- There is almost no energy consumption since it requires no melting or cooling. - The mold material can be reused semi-permanently. - Shapes are easily crushed or deformed. - The mold is not movable.
Powder + Paraffin wax	- The mold material can be reused semi-permanently. - Any shape can be produced, and it can be moved after freezing. - There is no deformation due to compression after addition of concrete. - Energy is needed for melting and cooling.

4. Analysis of Energy Consumption and CO_2 Emission

4.1. Analysis of Energy Consumption

Since aluminum powder molds and PCM molds are plate-type molds, they release heat mostly through the upper and lower parts. We used the experimental apparatus shown in Figure 3 to study the heat release of molds for the analysis of energy consumption. A movable heating device was used for heating and cooling of the materials, and a cooler along with other auxiliary devices, were used to maintain a constant cooling temperature. Furthermore, the surface upper and lower parts were exposed so that the heat was released from those parts, and the sides were insulated. The volume of the mixture used in the experiments was 600 mL, and the mixture was sufficiently heated to 90 °C or above and then air-cooled to 20 °C. Aluminum powder (3 μm) was mixed with commercial-grade paraffin wax. After melting the paraffin wax and mixing it with the aluminum powder, we found that it became saturated at a volume ratio of approximately 30:17. At this ratio, the ingredients were mixed so that the paraffin wax filled in the small spaces between the aluminum particles.

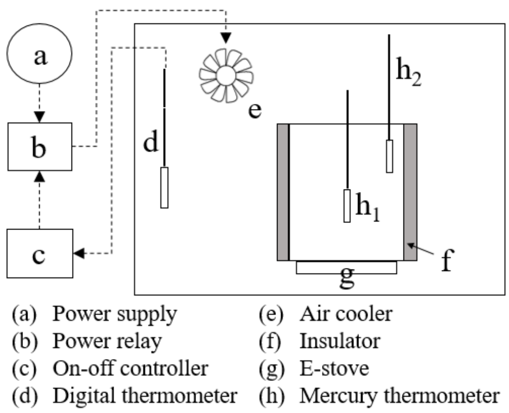

Figure 3. Schematic diagram of the experimental apparatus.

There was a significant difference in temperature profile during the cooling of paraffin wax molds and aluminum powder molds, as shown in Figure 4. It was instructive to compare the cooling times from a heated state of 60 °C to the temperature where the paraffin wax congealed (40 °C). This cooling step took 50 min for the Al powder-based material and took 255 min for the paraffin wax, a more than five-fold difference. This result implied that a CNC machine that produces shapes of melted molds could make five times more molds in the same amount of time.

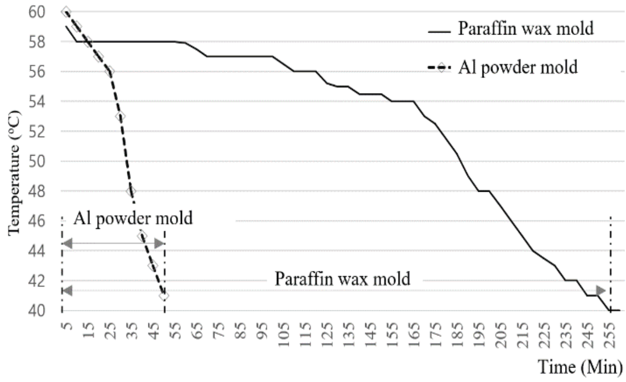

Figure 4. Temperature variation of the molds.

The temperature variation in the liquid state was determined by the removal of sensible heat. When the upper/lower cooling surfaces were exposed to air that was below the phase change temperature, the liquid started to solidify. At this point, natural convection began to be restricted. There was no difference in the output of sensible heat through the thin solid surface layers between the two mixtures in the early stages of cooling. However, as shown in Table 3 and Figure 5, as the solid layers thicken, the transfer of sensible heat inside the PCM molds dropped significantly as the liquid near the cooling surface solidified. The PCM mold must be completely frozen to be used as a mold, so long cooling times are required to freeze all of the paraffin in a solid-state.

Table 3. Temperature variation and heat output of the PCM mold.

Thickness of Solid Layer (mm)	10	15	20	25	30	35	40
Temperature of the Surface (°C)	39	38	37.5	36	35	32.5	31
Temperature of the Inner Part (°C)	55	54.5	54	53	50.5	45	42
Cooling Temperature (°C)	20	20	20	20	20	20	20
Heat Output per Min. (kcal)	9.92	6.52	4.82	3.74	2.88	2.02	1.56

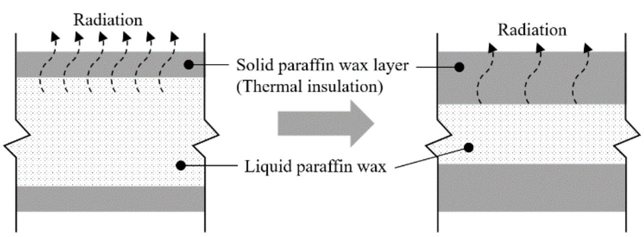

Figure 5. Reduced heat output owing to the solid layer.

This phenomenon did not occur in the case of the aluminum powder molds because the inner thermal energy was quickly transferred. Figure 6 shows the temperature variation inside the surface of the molds. The freezing temperature of both materials was about 40 °C. The difference between the time required for the inner surface to freeze was about 10 min for the aluminum powder mold and more than 110 min for the paraffin wax mold. As shown in Figure 6a,b, the temperature difference between the surface and inner part of the PCM mold after 160 min of cooling was 15 °C or above. After 260 min, the temperature difference in the PCM mold was 10 °C or above. In contrast, the aluminum powder mold showed a temperature difference between the surface and inner part of around 10 °C in the earlier stage, as shown in Figure 6c, but the temperature difference drastically declined after 40 min of cooling, as shown in Figure 6d. This was because the inner heat was immediately transferred to the air since the heat transfer efficiency of the material itself was high.

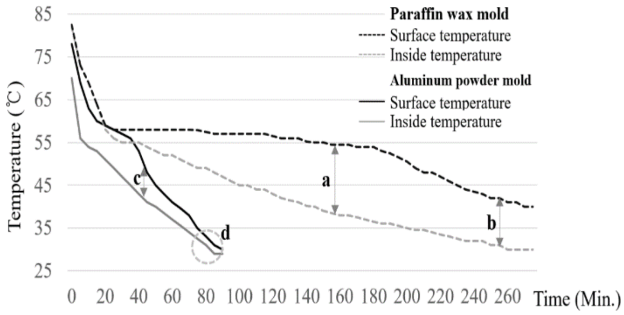

Figure 6. Temperature variation on the inside and on the surface of the molds.

In order to freeze and cool 1 L of hot paraffin wax from 80 °C to 40 °C, 56.7 kcal must be removed from the system, as shown in Table 4. This estimation was reached by adding the 25.2 kcal required to cool the wax and lower the temperature and the 31.5 kcal required for the phase change (freezing). A total of 49.125 kcal was needed to cool 1 L of the aluminum powder mold. The specific heat of this material was 0.215 kcal/kg, which was significantly lower than that of the paraffin wax (0.7 kcal/kg), and there was no phase change between 80 °C and 40 °C, which implied that there was no need to account for latent heat. Although the specific gravity of aluminum powder mold was bigger, it had a 14.3% lower required cooling energy.

Table 4. Heat consumption of molds (based on 1 L).

Type	Weight (kg)	Cooling Heat (kcal)	Remarks
Paraffin wax mold	0.9	56.7	
- Paraffin wax	0.9	25.2 31.5 (latent heat of fusion)	0.9 kg · 0.7 kcal/kg · 40 °C 0.9 kg · 35 kcal/kg
Aluminum powder mold	1.316	49.125	
- Aluminum	0.621	5.34	0.621 kg · 0.215 kcal/kg · 40 °C
- Paraffin wax	0.695	19.46 24.325 (latent heat of fusion)	0.695 kg · 0.7 kcal/kg · 40 °C 0.695 kg · 35 kcal/kg

The PCM molds required around 150 L of paraffin wax to produce 1 m^2 of concrete panels; 8505 kcal of heat was required to melt this amount of paraffin at 80 °C. As shown in Table 5 one kWh of electric power could generate 2150 kcal of heat, so 3.96 kWh was needed to heat 1 m^2 of the PCM mold. Assuming that the efficiency of the cooler was 67% and its heat loss is 50%, this process required 11.88 kWh of electric power to cool 150 L of the PCM mold at 40 °C. Using the same method, the energies required for heating and cooling the aluminum powder mold (1 m^2) were 3.43 kWh and 13.71 kWh, respectively. We, therefore, concluded that there was an energy reduction effect of around 2.1 kWh as compared with the PCM mold.

Table 5. Power consumption of PCM mold and aluminum powder mold.

	PCM Mold	Aluminum Powder Mold
Heating	3.96 kWh (56.7 kcal × 150 L/2150 kcal/kw)	3.43 kWh (49.13 kcal × 150 L/2150 kcal/kw)
Cooling	11.88 kWh (3.96 kWh/0.67/0.5)	10.28 kWh (3.43 kWh/0.67/0.5)
Total	15.84 kWh	13.71 kWh

4.2. *Analysis of CO_2 Emissions*

The molds that are used in conventional free-form building projects have different curvatures, sizes, and shapes, and it is therefore not possible to reuse them. In addition, they are frequently twisted and damaged during the separation of the mold. The increased use of temporary materials leads to increased CO_2 emissions and costs. To compare the energy consumption of conventional methods where numerous temporary wooden boards were used with the use of PCM and aluminum powder molds, we evaluated CO_2 emissions from the manufacture of the materials to the completion of the molds. As shown in Table 6, we found that there was a great difference in CO_2 emissions between the aluminum powder mold that can be reused semi-permanently and with conventional plywood.

Table 6. Comparison of total CO_2 emissions.

Type	Wooden Mold	PCM Mold	Aluminum Powder Mold
Material use	Plywood (12 mm, 7 ply) 105 m^2	Paraffin wax 135 kg	Aluminum powder 93.15 kg Paraffin wax 104.25 kg
	2226 kg-CO_2 (105 m^2 × 21.2 kg-CO_2/m^2)	398 kg-CO_2 (135 kg × 2.95 kg-CO_2/kg)	484.53 kg-CO_2 (93.15 kg × 1.9 kg-CO_2/kg + 104.25 kg × 2.95 kg-CO_2/kg)
Electricity use	-	1584 kWh (Heating: 396 kWh, Cooling: 1188 kWh)	1371 kWh (Heating: 343 kWh, Cooling: 1028 kWh)
	-	671.6 kg-CO_2 (1584 kWh × 0.424 kg-CO_2/kWh)	581.3 kg-CO_2 (1371 kWh × 0.424 kg-CO_2/kWh)
Total CO_2 emissions	2226 kg-CO_2	1069.6 kg-CO_2	1065.83 kg-CO_2

The energy consumption and CO_2 emissions required to produce each material can be estimated using interindustry analysis. Interindustry analysis uses an interindustry transaction matrix to construct an input coefficient matrix that can be used to estimate the total energy input for manufacturing the materials. This study applied this method to calculate all CO_2 generated associated with panel production. Lee et al. [26] used interindustry analysis to analyze the energy needed for plywood manufacturing, and they found that 3.37 kg-CO_2/kg of plywood was emitted. Considering the unit weight of plywood, 21.2 kg-CO_2 is emitted per m^2. Here, a small amount of electric power was used for assembling the mold, but this was not included for calculation since it was extremely small.

Since PCM molds can be reused semi-permanently, CO_2 emissions were estimated based on 150 liters of paraffin wax (the amount needed to produce 1 m^2 of concrete panels). In addition, heating to 80 °C and cooling to 40 °C were repeated with 150 L of paraffin wax whenever 1 m^2 of concrete panels were produced. The total electric energy input during this process was analyzed. In the case of PCM molds, 1584 kWh of electric power in total was used. In the case of the aluminum powder molds, 1371 kWh of electric power was used. A coefficient of 0.424 kg-CO_2/kWh [27,28] was used to estimate the total CO_2 emissions, which were 1069.6 kg-CO_2 and 1065.83 kg-CO_2, respectively, for PCM molds and aluminum powder molds. Therefore, compared with CO_2 emission of conventional wooden molds (2226 kg-CO_2), PCM and aluminum powder molds could be used to reduce the emission to less than 50%. Taking into consideration the waste generated after removal of a single-use wooden mold, there should be a greater reduction of CO_2 emissions from aluminum powder molds that do not generate any waste.

5. Conclusions

In this study, we developed an aluminum powder mold to improve energy consumption and reduce the time required for heating and cooling PCM molds. Our mold utilized the effect of phase change, so it was a type of PCM mold. Since heating and cooling should be repeated for the production of concrete panels using PCM molds, there was a negative impact on the environment, including increased energy consumption and the corresponding higher CO_2 emissions.

Our aluminum powder molds had a high thermal conductivity, which allowed them to reduce the required cooling energy and reduced the cooling time. The surface of the aluminum powder mold was first cooled and then congealed to prevent heat blockage, which reduced the consumption of cooling energy. A mold made only of paraffin wax required 1584 kWh of electric power in total, but the aluminum mold required 1371 kWh of electric power, reducing power consumption by 14.3%. In addition, CO_2 emissions that result from using the PCM mold and the aluminum powder mold were 1069.6 kg-CO_2 and 1065.83 kg-CO_2, respectively. These represent a reduction of 50% compared to the use of conventional wooden molds (2226 kg-CO_2). Considering the waste generated after the removal of single-use wooden molds, we believe that there was an even greater reduction in CO_2 emissions from aluminum powder molds that do not generate any waste.

Aluminum powder molds could be used to easily produce any shapes, just like conventional PCM molds. The aluminum powder molds could also reduce energy consumption and CO_2 emissions relative to conventional molds. Our aluminum powder-based molds could be used to improve the economic feasibility of the construction of free-form concrete buildings and reduce energy consumption and CO_2 emissions, which would be helpful in realizing various building designs and creating value. Additional studies related to composite molds mixed with a wide range of materials are needed.

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