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A Study on Radiant Heat Application to the Curing Process for Improvement of Free-Form Concrete Panel Productivity

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Abstract: As free-form panel production takes a long time, it extends the construction period and increases construction expenses. This study suggests a method to apply radiant heat to concrete for the purpose of shortening the curing and removal process in free-form panel production. The optimal temperature and time for removal are determined based on the results of constant temperature/humidity curing experiments and quartz tube heater curing experiments. Through an experiment in various time settings, the general time of FCP (Free-form Concrete Panel) production is measured to examine whether the productivity is enhanced. It is expected that findings of this study contribute to shortening the construction period and reducing construction expenses as well as future studies on the FCP manufacturing equipment.

***Keywords**: Free-form concrete panel, Radiant heat, Surface of concrete, Shortening the curing period, Productivity*

1. Introduction

1.1. Background and Purpose of Research

As design and construction technologies advance recently, it is possible now to embody new forms or free-form buildings different from existing ones. However, free-form buildings feature each unique outward configuration, and it is difficult to embody them in reality. To build up such free-form outward sections, free-curvature exterior parts of a complicated geometrical form are divided into workable shapes and sizes (Piegl, L. & Tiller, W., 2002). Free-form configurations are difficult to be produced or constructed because of the variance of curvatures and free curves. Therefore, it is necessary to reduce the panel production period by optimizing varied free-form configurations to the extent possible (Lim, J.S., 2014)

Many recent studies examine methods to realize such free-form construction in an economical and efficient manner, and the number is increasing. In contrast, there has been little research on the productivity of free-form panels. Free-form construction projects often involve problems due to lack of experience such as inaccurate estimation of construction costs, excessive change to the basic design, delayed completion, etc. (Lee, E.Y., 2014). In the case of Opera House in Sydney, the actual construction period was delayed for four years and cost USD 102 million, 15 times as much as estimated (Kim, Y.G., 2022).

To overcome such limitations, studies have been conducted. Donghoon Lee (2015) developed the equipment to automatically manufacture FCP (Free-form Concrete Panel) which were produced manually in general. This equipment consists of the lower-part multi-point press operation and the side configuration control operation. This equipment produces FCP in four steps: mold embodiment, extrusion, curing, and removal. The production period is shortened since the steps of mold embodiment and extrusion proceed automatically. In contrast, there has been little research on how to shorten the period of curing and removal.

This study applies radiant heat to concrete in the steps of curing and removal to shorten the FCP production period. If heat is applied to concrete in the curing step, the compressive strength of concrete develops earlier. As a result, the productivity of FCP will be improved by securing fast hardening and as well as the proper mold removal strength as high as 5MPa. This study applies radiant heat to the curing process for free-form panel production based the results of constant temperature/humidity curing and quartz tube heater curing experiments.

1.2. Scope and Method of Research

As to the scope of this study, the suggested radiant heater is applicable to the multi-point CNC equipment developed in the papers of Jeong (2021) and Yun (2021). This study intends to improve the productivity and economical efficiency of FCP by shortening the curing

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time in FCP production. The curing time that is varied when radiant heat is applied to the surface of concrete is measured. In addition, experiments are conducted to examine defects that may harm the strength and durability of concrete. The top priority is to shorten the time that it takes for the strength to reach the mold removal strength after forming and to shorten the removal time compared to the existing method.

In this study, the temperature and timing of the highest efficiency to shorten the mold stripping time in the possible range of temperature for concrete curing is calculated based on the initial strength. First of all, the temperature and humidity are adjusted by using a thermos hygrostat, and then concrete curing is initiated immediately after forming. The time when the compressive strength reaches the point of 5MPa, which is the reference point for moldboard removal, is measured at each temperature. Based on the temperature and time measured in the above-stated experiment by means of a thermohygrostat, the specific range was reestablished in the next compressive strength experiment where the panel radiant heating method was applied by using a quartz tube heater. The long-term strength was then measured to examine the possibility of concrete durability problems.

2. Theoretical Investigation

2.1. Early Curing Technology of Concrete Panel by Calorific Control

This study applies the multi-point CNC equipment to the FCP production process. The multi-point CNC equipment consists of the lower-part multi-point press operation and the side configuration control operation. It is possible to adjust the panel shape and side angle. As shown in Figure 1 regarding the panel production process in use of this equipment, FCP is manufactured in the four steps of combination, extrusion, curing, and removal. First of all, the bottom and side molds are combined according to the shape of the panel to be produced. Concrete is then infused by using the concrete extrusion equipment for curing. Once concrete curing is completed, the mold is removed and the production process ends.

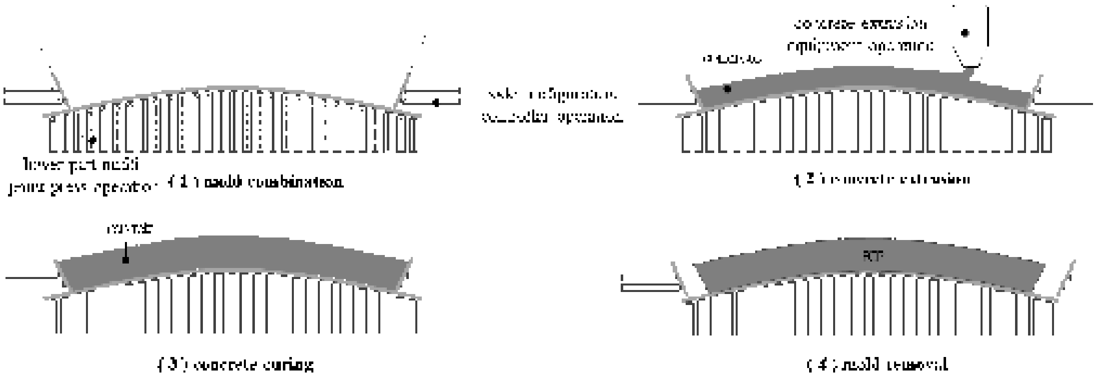

Fig. 1. Panel fabrication process for multi-point CNC equipment

In contrast, there has been little research on how to shorten the period of curing and removal. In the process of selecting the way to adjust temperature for reduction of the curing time and mold stripping time, radiant heat is applied to the concrete surface in consideration of the fact that the free-form concrete panel is thinner and broader than other concrete panels in order to reduce the general mold stripping time.

To design the optimal method that suits the volume and condition of the multi-point CNC equipment, this study prioritizes the productivity and economical efficiency of free-form panel production. Accordingly, a quartz tube heater was used to apply radiant heat since it involved no significant financial burden regarding the volume and requirements of the multi-point CNC equipment and it involved a low risk as a heat source even it was used for a long time.

3. Radiant Heat Curing Experiment

3.1. Constant Temperature/ Humidity Curing

3.1.1 Experiment Planning

The constant temperature/humidity curing experiment was planned as summarized in Table 1. An experiment was conducted where the mortar mixing ratio common to the multi-point CNC equipment for free-form production was applied. Right after forming, curing was performed for 4 hours each time at each temperature setting (20℃, 40℃, 60℃, and 80℃) and then the compressive strength was measured. The compressive strength was then measured three times in consideration of the age, and then the measurements were used to calculate the average. The calculated strength was compared with the standard strength for mold removal to determine the method’s suitability for the removal process.

Curing Temperature (℃)	Curing Hour (hr)					
20	4	8	12	16	20	24
40	4	8	12	16	20	24
60	4	8	12	16	20	24
80	4	8	12	16	20	24

Table 1. Experiment Procedures

Since this experiment aimed to examine the maximum value of time reduction depending on the temperature adjustment, the mortar was mixed at the most common ratio. Therefore, the effect would be better if an admixture was added. The materials used included cement, aggregate, water, and PVA. Table 2 shows the types and mixing ratios of materials used in this experiment.

W/C	Cement(g)	Aggregate(g)	Water(g)	PVA(g)
0.4	6000	6000	2400	90

Table 2. Materials used in the Experiment

After sufficient dry mixing, mortar was mixed by using a concrete mixer. The mixed mortar was formed in a 4*4*16cm mold. Prior to the experiment, the humidity of the thermohygrostat was all set to 60%, and then the temperature was adjusted to 20℃, 40℃, 60℃, and 80℃.

After forming, the mold itself was put into the thermohygrostat for curing with no preliminary curing. In the heated state at 20℃, 40℃, 60℃, and 80℃ as set to the thermohygrostat, the high-temperature curing was performed. The mold was then taken out of the curing machine at intervals of 4 hours, followed by the removal step. Right after removal, the mortar was divided to test piece specimens of 4*4*8cm in size, and these heated test piece specimens were compared in terms of the age and temperature setting by means of a concrete test piece compressive strength measuring device. The compressive strength was measured 3 times for each age value, and the average was used in the experiment.

3.1.2 Performance Experiment Results

With the humidity set to 60% by using a thermohygrostat, the temperature was set to 20℃, 40℃, 60℃, and 80℃ respectively during the experiment. The compressive strength was measured at intervals of 4 hours, and the strength right after removal and the long-term strength also were measured. Table 3 below shows the results.

(Unit: MPa)

	20℃			40℃			60℃			80℃		
Day hr	0	7	28	0	7	28	0	7	28	0	7	28
4	-	27.5	35.6	-	22.0	31.2	3.8	25.4	26.5	6.1	21.1	24.3
8	-	28.9	35.8	8.3	28.1	30.7	16.3	26.0	30.9	16.6	23.8	28
12	2.1	30.0	37.8	16.3	34.1	34.9	20.5	22.9	31.5	16.1	22.3	25.9
16	7.2	28.9	36.4	21.2	31.8	34.9	21.7	26.1	32.0	17.1	20.4	27.1
20	11.5	28.2	31.7	25.2	32.5	38.8	21.3	28.7	31.0	17.6	21.7	25.6
24	15.4	28.7	33.2	26.4	33.5	37.4	20.5	27.4	28.4	18.3	22.7	26.6

Table 3. Compressive strength at each temperature

Experiment results show that except certain samples in the existing condition (20℃, less than 20 hours), most samples were found to meet the strength criteria for mold removal.

(Unit: MPa)

Initial	20℃	40℃	60℃	80℃
4hr	-	-	8.8	6.1
8hr	-	8.3	16.3	16.6
12hr	2.1	16.3	20.5	16.1
16hr	7.2	21.2	21.7	17.1
20hr	11.5	25.2	21.3	17.6
4hr	15.4	26.4	20.5	18.3

Table 4. Compressive Strength Right After Removal in the Constant Temperature/Humidity Curing Experiment

As in Table 4 that shows the strength right after removal in the experiment, when the temperature is 20℃, removal is possible after at least 20 hours. At 40℃, in contrast, the strength meets the criteria for removal 8 hours after forming. This is the same when the temperature is 60℃ and 80℃. At 80℃, however, the strength was inferior to that at 60℃.

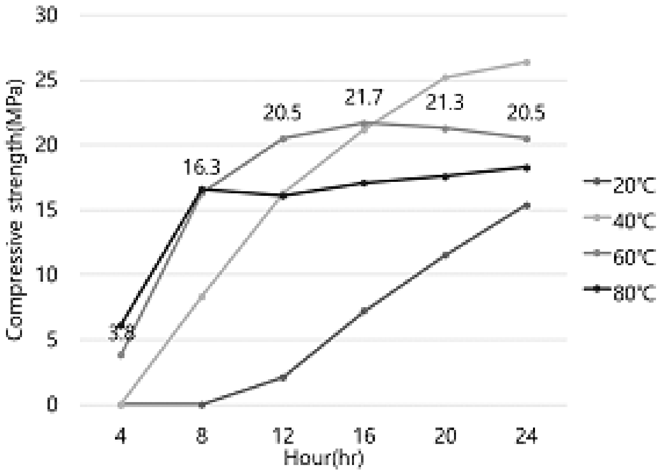

Fig. 2. Graph of compressive strength measurements in the constant temperature/humidity curing experiment

The strength right after forming was compared with the long-term strength at each temperature to determine the condition that involves less risk in a long run. The strength results in this experiment were compared with the compressive strength of concrete stated in concrete standard specifications in terms of the timing of moldboard removal. As shown in Figure 2, the condition where the proper mold removal strength was reached within the shortest time was 80℃ and 4 hours. However, the long-term strength at 80℃ was inferior to those at other temperature settings. Thus, this condition was excluded because of the instability in terms of long-term strength. With the top priority to time reduction, the curing condition of 60℃ and 8-hour heating showed the most appropriate result.

In view of the strength right after removal or the long-term strength, the condition of 40℃ and 8-12 hours heating also had potentials and thus was included in the quartz tube heater curing experiment. In comprehensive view of the strength right after removal and the long-term strength, the conditions of 40℃ and 60℃ were more specified to 40℃, 50℃, and 60℃ with the heated curing time in the range of 5 to 8 hours for the quartz tube heater curing experiment.

3.2. Quartz Tube Heater Curing

3.2.1 Experiment Planning

Based on the data acquired from the constant temperature/humidity curing experiment, the optimal curing temperature and curing time that met the strength criteria for mold removal and could shorten the stripping time were determined. The priority was given, not to the strength level, but to the condition of the shortest curing time among samples that reached the proper strength for removal. After samples of the highest efficiency were selected, it was verified whether the results would be the same if the concrete surface was heated by radiant heat. Samples selected from the quartz tube heater curing experiment were used to determine the condition of temperature and curing time where the constructability and economical efficiency would be the best when radiant heat was applied to the mortar surface after forming. Table 5 shows details of the experiment plan.

Curing Temperature (℃)	Curing Hour (hr)			
40	5	6	7	8
50	5	6	7	8
60	5	6	7	8

Table 5. Experiment Procedures

Based on the results derived from the constant temperature/humidity curing experiment, the selected condition—the mold of 4*4*16cm—was applied to forming. A quartz tube heater was selected as the heat source. The distance between the structure and concrete surface was adjusted according to the temperature setting. The experiment proceeded after it was confirmed that the set temperature maintained for 1 hour. In each temperature condition and at the time set, the removal step was conducted to measure the bending strength.

The concrete was divided to test piece specimens of 4*4*8cm in size and then measured by using a concrete test piece compressive strength measuring device. The compressive strength was measured 3 times for each age value, and the average was used in the experiment. As shown in Table 6, it was determined that the time was appropriate for curing when it reached 5MPa based on the criteria of mold removal. Table 6 below is based on standard specifications for construction work

Member Materials		Compressive Strength of Concrete
Sides of spread footings, beam, pillars, etc.		At least 5MPa
Slab and arches of the beam	Single-layered structure	At least 2/3 of the standard compressive strength, min. 14MPa
	Multi-layered structure	At least the standard compressive strength (When the pillar supporting post structure is used, the construction period may be shortened based on the structure calculation data. Even in this case, however, the minimal strength should be at least 14MPa)

Table 6. Timing of moldboard removal

3.2.2 Performance Experiment Results

In the temperature conditions of 40℃, 50℃, 60℃ selected in the constant temperature/humidity curing experiment as stated above, heating was performed for 5 to 8 hours and then right after concrete forming, radiant heat was applied onto the concrete surface by using a quartz tube heater as shown in Figure 3.

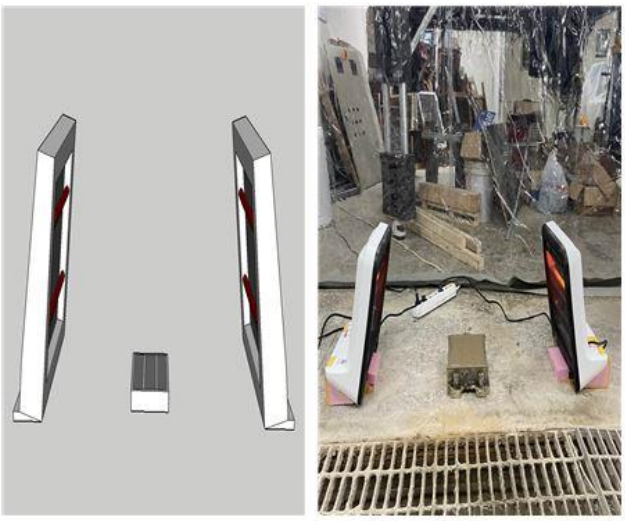

Figure 3. The experiment plan (left) and the actual experiment image (right)

After radiant heat curing for 5 to 8 hours at 40℃, 50℃, and 60℃, the strength was measured as presented in Table 7 and Table 8. In the quartz tube heater curing experiment, both the flexural strength and compressive strength were measured.

(Unit: MPa)

Initial	40℃	50℃	60℃
5hr	0.7	1.2	4.5
6hr	1.1	5.4	8.7
7hr	2.9	6.6	13.2
8hr	7.3	9.5	18.5

Table 7. Compressive Strength Measurements in the Quartz Tube Heater Curing Experiment

(Unit: MPa)

Initial	40℃	50℃	60℃
5hr	0.2	0.3	1.2
6hr	0.3	1.5	2.4
7hr	1.3	1.8	2.5
8hr	2.5	2.5	4.0

Table 8. Bending Strength Measurements in the Quartz Tube Heater Curing Experiment

The results of the quartz tube heater curing experiment are shown in Figure 4 and Figure 5 at the bottom. The result shows that the strength suitable for mold removal was reached after 8 hours at 40℃. At both 50℃ and 60℃, the strength was reached after 6 hours, but the measurement at 60℃ was higher. This indicates that at 60℃, the strength suitable for mold removal would be reached faster.

In addition, the data obtained by using a thermohygrostat were compared with the data obtained after 8 hours by using a quartz tube heater, and the result shows that the strength when a quartz tube heater was used was higher and better in terms of effectiveness.

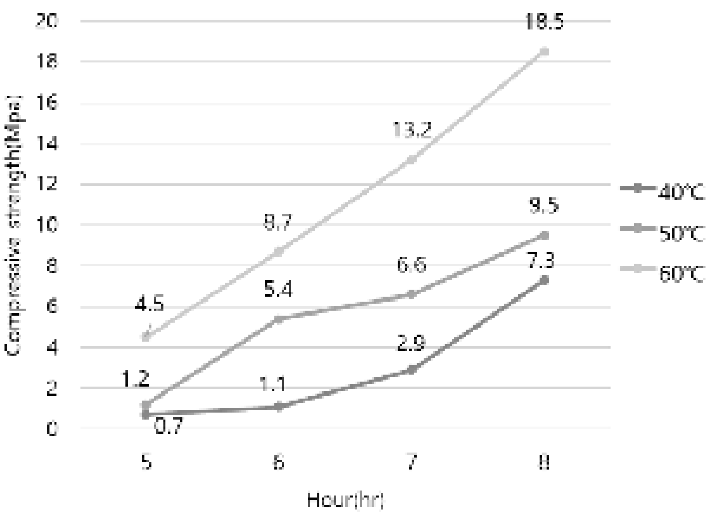

Fig. 4. Graph of Compressive Strength Measurements in the Quartz Tube Heater Curing Experiment

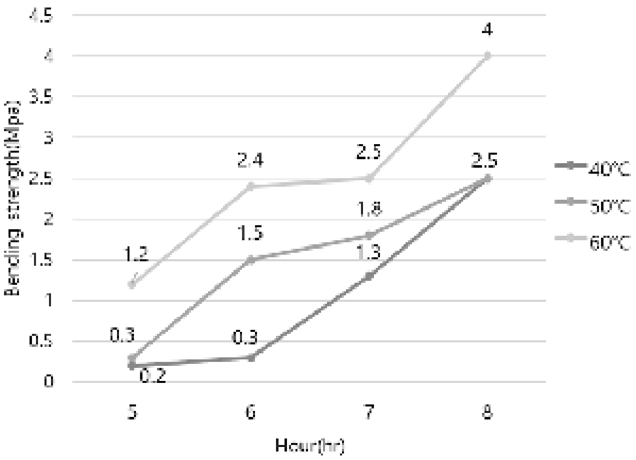

Fig. 5. Graph of Bending Strength Measurements in the Quartz Tube Heater Curing Experiment

The result of the quartz tube heater curing experiment shows that the strength suitable for mold removal was reached after 8 hours at 40℃. At both 50℃ and 60℃, the strength was reached after 6 hours, but the measurement at 60℃ was higher. This indicates that at 60℃, the strength suitable for mold removal would be reached faster.

In addition, the data obtained by using a thermohygrostat were compared with the data obtained after 8 hours by using a quartz tube heater, and the result shows that the strength when a quartz tube heater was used was higher and better in terms of effectiveness.

4. Conclusion

This study suggests a method to secure the productivity of free-form panels based on the results of concrete heating experiments, and this suggested method is applicable to the existing FCP production equipment. Specifically, the constant temperature/humidity curing experiment and the quartz tube heater curing experiment were conducted in this study, and the results may be summarized as below:

1) In the constant temperature/humidity curing experiment, curing was performed after mortar forming at different temperature settings on test piece specimens of a 4*4*16cm mold with a thermohygrostat used. The condition of temperature and time where the compressive strength reached the strength criteria at the point of moldboard removal was determined in consideration of the age. The optimal condition was derived in application of different temperature settings, and the range was narrowed down based on the results to determine the specific condition for curing experiments where a quartz tube heater was used.

After experiments at 20℃, 40℃, 60℃, and 80℃ respectively, it was confirmed that the condition of 8 hours heating at 40 and 60℃ was the most appropriate. To derive more specific values, the duration of radiant heat application was subdivided to 5, 6, 7, and 8 hours at 40℃, 50℃, and 60℃.

2) In the range stated above, radiant heat was applied onto the surface of formed mortar by using a quartz tube heater in the experiment. Based on the results, it was confirmed that the compressive strength when a quartz tube heat was used was somewhat superior to that when a thermohygrostat was used for curing. In addition, after 6 hours at both 50℃ and 60℃, the condition was proper for removal and there was no problem in terms of long-term strength either. Therefore, it was verified that the moldboard stripping time could be shortened by heating after mortar forming at 50℃ or 60℃. The findings of this study verify that the curing time can be shortened with the standard strength secured at the point of moldboard removal after 6 hours, which is expected to contribute to improving the productivity of free-form panels as well as the economical efficiency through cost saving and construction period reduction.

However, there is limitation in applying the suggested method to the existing equipment. In the quartz tube heater curing experiment, only the initial strength was measured within 5 to 8 hours, the time appropriate for removal. Besides, it was unable to adjust the humidity in the case of panel curing unlike the existing constant temperature/humidity curing method. Thus, there should be a solution to cracks that might occur inside or outside the panel. The future study, therefore, needs to design a heater that is appropriate for the scale of the existing FCP production equipment and also can adjust the humidity.

If FCP is manufactured by applying the quartz tube heater to the FCP equipment for free-form concrete panel production based on the findings of this study, it is expected that the productivity of FCP, which requires a long production period, can be improved.

5. Acknowledgements

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