

Experimental Study on Fire Resistance Performance of a Hollow Slab Using a Lightweight Hollow Sphere

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ABSTRACT

This study evaluates the fire resistance performance (1–2h) of a reinforced concrete (RC) structure-void slab using a lightweight hollow sphere, which can reduce the unnecessary dynamic of removing the central concrete. For this experiment, we set up the depth of the concrete cover, live load, and span length as the factors. The result comes out with 50 mm cover depth of the RC structure hollow slab secured. It was shown that 120 minutes of fire resistance performance can be secured regardless of the length of the structure and loading. Among these factors, the resisting capability changes more sensitively with the live load rather than the thickness of cover. The shorter span in length could assure better fire resistance performance.

1. INTRODUCTION

1.1. Purpose of the study

Recently, buildings tend to be high-rises with long spans to satisfy overpopulation and various lifestyles. A building's own dead load and live load, which have to be accommodated for, are increased in large-scale buildings that are high-rises or have a long span. To settle this, the size of the structure should be increased or a material with high strength should be used. In case the size of the structure is increased, the dead load is higher and the quantity of materials used is increased in proportion to the increase, which leads to the increase of construction costs. In addition, using high strength materials leads to the increase of material unit prices, so economic efficiency is worse than the construction cost.

However, the thickness of slabs is currently being increased, compared to other major structures, to prevent structural deflection, reduce noise between layers, and improve the performance of insulation. The increase of the slab thickness is in proportion to the volume of the concrete required and is a direct cause to increase the dead load of the structure. Concrete emits approximately 300 kgf per unit of space (m^2). This is a negative factor against the environmental and green movement which have attracted high interest in Korea and the world.

Therefore, a reinforced concrete (RC) structure hollow slab using a lightweight hollow sphere is the target method of this study: to reduce slab self-weight by removing the central concrete on the slab section because it does not have any effect on structural characteristic in the existing RC structure slab. Since the sectional area is converged in the upper and lower sections of the slab where the most bending stress is converged, the slab has structurally favorable benefits

against the dynamic bending. In addition, it is in the structure method that there are various benefits, reduction of concrete volume, reduction of carbon dioxide emission, etc., compared to the RC structure slab method. The target method is applied as shown in Figure 1. However, to apply the method having those benefits mentioned above to the actual site, fire safety should be secured by evaluating the fire resistance performance. The target method developed to secure minimum fire resistance performance (1–2 hours) should be delivered to apply it to the actual site specified in Korean and International Regulation by the fire resistance test to prove its performance.

1.2. Scope and Method of Study

In this study, to reduce the slab self-weight, the central concrete between the reinforcements that have no role as a structure was removed. In the section where concrete was removed, Expanded Polystyrene (EPS) was used for fabricating and inserting the lightweight sphere, enabling the weight to be reduced and insulation performance to be secured. For the RC structure with a hollow slab fabricated with the method mentioned, the cover depth, span (lengthwise), and fire resistance performance based on the loading were compared and analyzed under a standard fire with loading condition in accordance with ISO 834-1.

2. EXPERIMENT

2.1. Selection of Experiment Variable

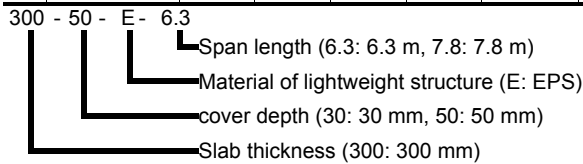
To evaluate the fire performance of the RC structure with a hollow slab and a lightweight hollow sphere, experimental factors and standards were used for the fire resistance test, as shown in Table 1. The cover thickness (50 mm, 2 mm), span length (6.3 m, 7.8 m), and load (5.0 kN/m^2 , 4.0 kN/m^2) were used as the experimental factors in the experiment.

Table 1. Factor of fire test

Experiment factor	Level
Cover depth (mm)	50, 30
Loading (kN/m ²)	5.0, 4.0
Span length (m)	6.3, 7.8

Table 2. The condition of specimen shape

Specimen	Span Length (mm)	Length (mm)	Width (mm)	Depth (mm)	Covering Depth (mm)	Void	
S-1	300-50-E-7.8	7800	8500	3000	300	50	EPS
S-2	300-30-E-7.8	7800	8500	3000	300	30	EPS
S-3	300-50-E-6.3	6300	7000	3000	300	50	EPS
S-4	300-30-E-6.3	6300	7000	3000	300	30	EPS



2.2. Fabrication of Specimen

The specimen for the hollow slab with the 6.3 m and 7.8 m span was fabricated, as shown in Figure 3 and Figure 4. The lengths of the overall slab were 7.0 m and 8.5 m, and a 0.35 m supporting length was secured for loading on both sides. Also, there were 27 mm between both sides of the hollow sphere so it would be uniformly distributed; then it was embedded into the slab. The shape condition of the specimen is shown in Table 2.

Deformations were surveyed by installing an extensometer in the center of the slab. Also, a thermocouple was installed to survey the temperature change in each material, as shown in Table 3. In addition, concrete and the hollow sphere were installed at three points to be uniformly distanced from the heating point below, and reinforcement was installed at two major points below and above the parts. K-type was used for the thermocouple.

2.3. Experiment Method

Evaluation of this study was carried out in accordance with ISO 834-5 (Fire-resistance tests: Elements of building construction. Part 5: Specific

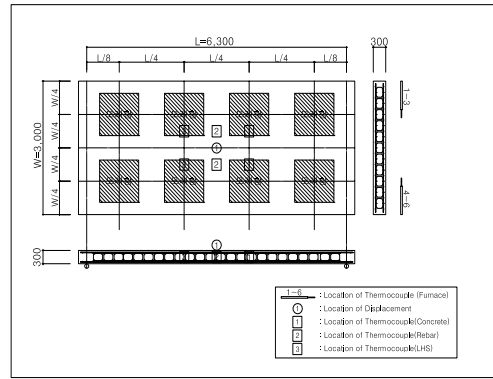


Figure 1. Drawing of specimen (7.0 m)

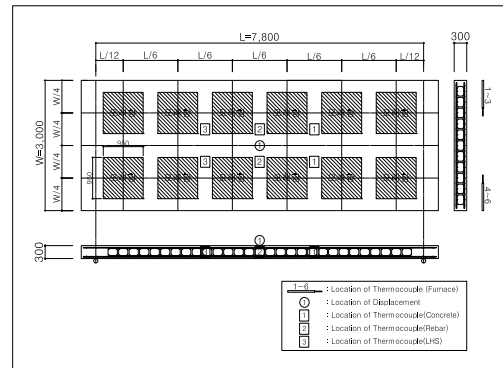
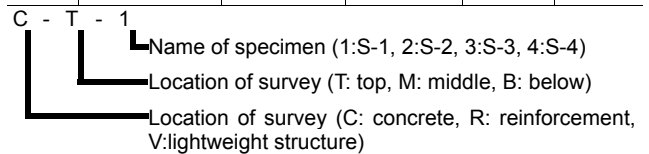


Figure 2. Drawing of specimen (8.5 m)

Table 3. The installation of thermocouple

Specimen	Concrete (mm)	Void (mm)	Rebar (mm)	이면 (mm)	
S-1	300-50-E-7.8	50,150,250	50,150,250	50,250	300
S-2	300-30-E-7.8	30,150,270	30,150,270	30,270	300
S-3	300-50-E-6.3	50,150,250	50,150,250	50,250	300
S-4	300-30-E-6.3	30,150,270	30,150,270	30,270	300



requirements for load bearing horizontal separating elements). Overall, the specimen lengths were 7.0 m and 8.5 m and the supporting length of load in the specimen were 6.3 m and 7.8 m. The specimen was simply supported. Uniform load was applied to the area where the live load occurred using a sand kit for the specimen, designed as shown in Table 4.

Table 4. The condition of loading specimen

Specimen	Slab Depth (mm)	Span (m)	Void Ratio (%)	D.L. (kN/m ²)	L.L. (kN/m ²)
S-1	300	7.8	32	5.88	2.0
S-2			34	5.88	2.0
S-3		6.3	32	5.88	5.0
S-4			34	5.88	4.0

Table 5. Standard of displacement and strain

Specimen	L/30 (mm)	Limiting displacement (mm)	Limiting rate of displacement (mm/min.)
S-1	260	608.4	27.0
S-2		563.3	25.0
S-3	210	396.9	17.6
S-4		367.5	16.3

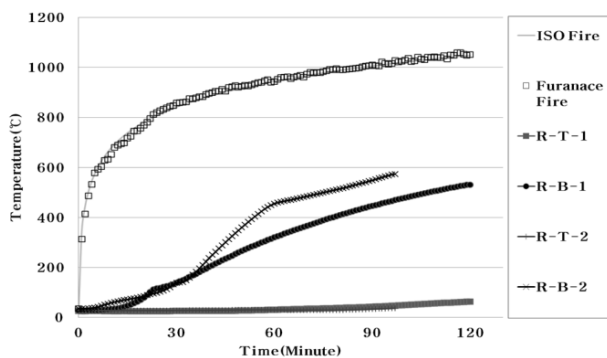


Figure 3. Temperature distribution of reinforcement based in each location based on cover depth(S-1, S-2)

Table 6. Average and maximum temperature of reinforcement in each location based on the cover depth (S-1, S-2)

Classification	Surveyed location (reinforcement)	Average temperature (°C) (at 97 min.)	Maximum temperature (°C) (at 97 min.)	Fire resistance performance (min.)
S-1	Top	47.5	53.9	120
	Bottom	469.5	476.7	
S-2	Top	37.5	46.1	97
	Bottom	574.3	606.8	

The standard of the fire resistance performance under the fire standard with a loading condition was evaluated based on the deformation and its rate in accordance with ISO 834-1 (Fire-resistance tests: Elements of building construction. Part 1: General requirements), and Table 5 shows the standard for the deformation and its rate.

3. EXPERIMENT RESULT

In the study, the fire resistance experiment was carried out in accordance with ISO 834-1 to analyze cover depth, span (lengthwise), fire resistance performance, and effectiveness of the fire behavior for the RC structure hollow slab using a lightweight sphere.

3.1. Internal Temperature Change in Each Experiment Factor

To compare the temperature characteristics depending on the cover depth, span (lengthwise), and loading of the hollow slab, the analysis was based on the temperature in each material affecting the fire behavior of the slab as follows.

3.1.1. Internal temperature change based on the cover depth (S-1 and S-2)

Temperature change of reinforcement:

Figure 3 displays the result of the temperature distribution in the upper and lower reinforcement depending on the cover depth. For S-1 and S-2, it was found that 120 minutes and 97 minutes, respectively, of fire resistance performances were secured based on the cover depth (50 mm ↔ 30 mm). Table 6 displays the minimum and maximum temperatures for both S-1 and S-2 at 97 minutes, since that was the shorter period of resistance performance from the test (from S-2). The temperature changes averaged 10°C with a maximum of 7.8°C in the top reinforcement and averaged 104.8°C with a maximum of 130.1°C in the reinforcement below based on the 20 mm difference of cover depth. For S-2, there was over a 100°C difference from S-1 in the below reinforcement temperature; the average temperature of the reinforcement was 574.3°C in the below reinforcement temperature which was over 538°C, the standard of the insulation heat performance for evaluating the fire resistance performance of the concrete structure. Therefore, it is considered that the deformation and its rate were over the limited value because the fire resistance performance reached the limit.

Temperature change of hollow sphere:

The results of the temperature distribution of the hollow sphere in each location are shown in Figure 4. For S-1 and S-2, it was shown that 120 minutes and 97 minutes fire resistance performances were

secured. The results of the survey of the temperature of the hollow sphere in each location based on the S-2 fire resistance performance (97 minutes), which had the lower performance of the two, are shown in Table 7. There were temperature changes that averaged 14.0°C with a maximum of 18.7°C for the top hollow sphere. There was an average of 1.0°C and maximum of 21.3°C in the center of the hollow sphere based on the 20 mm difference of cover depth. Therefore, for the hollow sphere, there was not a big change based on the cover depth regardless of the location. The temperature of the hollow sphere below was compared to the one in the below reinforcement and concrete, 77.8°C and 75.9°C were the average temperatures and 135.1°C and 130.3°C were the maximum temperatures, respectively. For the EPS hollow sphere applied to the specimen, 98% and 2% of the volume were composed of air and polystyrene, respectively.

The melting point of the ESP was 100°C, and it is considered that the section where the increase of the temperature was delayed was generated. In other words, it can be concluded that since the hollow sphere in the low temperature melted and disappeared and a mediator of heat transfer vanished, the temperature was lower than the temperature of the reinforcement and concrete.

3.1.2. Internal Temperature Change Based on the Cover Depth and Loading (S-3 and S-4)

Temperature change of reinforcement:

Figure 5 displays the results of the survey on the temperature distribution of the top and below reinforcement based on the cover depth and loading. Table 8 displays the results of the experiment for the cover depth (50 mm, 30 mm) and loading (5.0 kN/m², 4.0 kN/m²) for S-3 and S-4, 120 minutes were secured for all conditions. The temperature of reinforcement is shown in Table 8 based on the ending time of the fire resistance experiment (120 minutes) as a result of the survey on the temperature of reinforcement in each location. Since an average of 29.0°C and a maximum 25.6°C were shown for the temperature change depending on the 20 mm cover depth and 1.0 kN/m² differences in the top reinforcement, it was shown that there was no big change in the top reinforcement temperature. Although the 20 mm cover depth was reduced for the below reinforcement, an average of 206.9°C and a maximum of 214.2°C were lower as a result of the loading with the reduction of 1.0 kN/m². Therefore, it was shown that reducing 1.0 kN/m² loading affects the below reinforcement more than reducing the 20 mm cover depth.

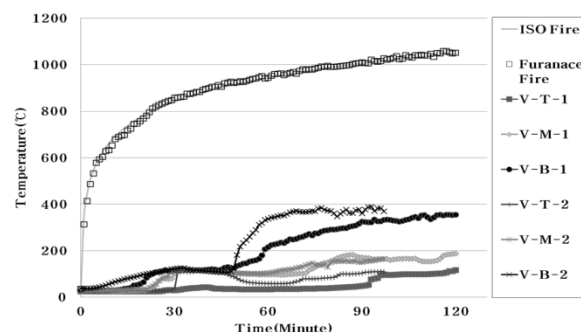


Figure 4. Temperature distribution of hollow sphere in each location based on the cover depth (S-1, S-2)

Table 7. Average and maximum temperature of reinforcement in each location based on the cover depth (S-1, S-2)

Classification	Surveyed location (Hollow sphere)	Average temperature (°C) (at 97 min.)	Max Temperature (°C) (at 97 min.)	Fire resistance performance (min.)
S-1	Top	95.7	96.7	120
	Middle	164.3	164.5	
	Bottom	332.6	391.9	
S-2	Top	109.7	115.4	97
	Middle	165.3	185.8	
	Bottom	370.2	376.0	

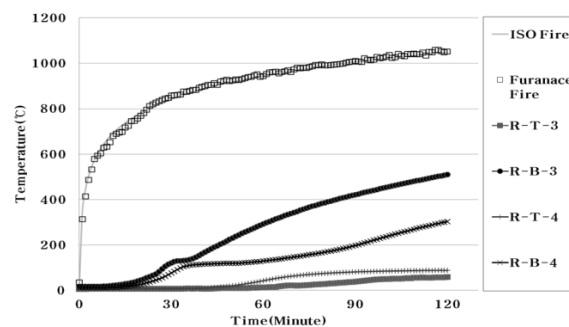


Figure 5. Rebar temperature of hollow slab depending on depth of concrete cover and loading condition

Table 8. Rebar temperature of hollow slab depending on depth of concrete cover and loading condition (at 120 min)

Specimen	Location of Thermocouples (Rebar)	Avg. Temp. (°C) (at 120 min.)	Max. Temp. (°C) (at 120 min.)	Fire resistance (min.)
S-3	Top	58.9	62.9	120
	Bottom	510.3	535.0	
S-4	Top	87.9	88.5	120
	Bottom	303.4	320.8	

Temperature change of hollow sphere:

Figure 6 displays the results of the survey on the temperature distribution in each location of the hollow sphere. Table 9 shows the results of the survey on the fire resistance experiment for the cover depth (50 mm, 30 mm) and loading (5.0 kN/m², 4.0 kN/m²) for S-3 and S-4 when 120 minutes were secured. The temperature of the hollow sphere is shown in Table 9 based on the ending time of the fire resistance experiment (120 minutes) as a result of the survey on the temperature in each location of the hollow sphere. There were temperature changes averaging 40.2°C with a maximum of 54.2°C in the top hollow sphere and averaging 43.6°C with a maximum of 26.8°C in the center of the hollow sphere based on the 20 mm difference of cover depth, respectively. For the below hollow sphere, an average of 93.8°C and a maximum of 206.0°C were shown for the change. In particular, the temperature in the below hollow sphere was shown to be lower than the one of reinforcement and concrete. It is considered that since the hollow sphere melted in the low temperature and then discharged through cracks of the concrete, the heat cannot be transferred.

3.1.3. Internal temperature Change Depending on the Span Length (S-1 and S-3)

Temperature change of reinforcement:

The results of the survey on the temperature distribution of the top and below reinforcement depending on the span length are shown in Figure 7. The fire resistance experiment based on the span length (7.8 m, 6.3 m) for S-1 and S-3 secured 120 minutes of fire resistance performance. The temperature of the reinforcement is shown in Table 10 based on the ending time of the fire resistance experiment (120 minutes) as a result of the survey on the reinforcement temperature in each location. There were temperature changes at average of 4.2°C and a maximum of 3.8°C in the top reinforcement and an average of 20.8°C and a maximum of 3.6°C in the below reinforcement based on the 1.5 mm difference of span length, respectively. Therefore, it is considered that the span length had a low effect on the temperature of the reinforcement.

Temperature change of hollow microsphere:

The results of the survey on the temperature distribution of the hollow sphere in each location are shown in Figure 8. As a result of the fire resistance experiment based on the span length (6.3 m, 7.8 m) for S-1 and S-3, 120 minutes of fire resistance performance were secured. The temperature of the hollow sphere is shown in Table 11 based on the ending time of the fire resistance experiment (120

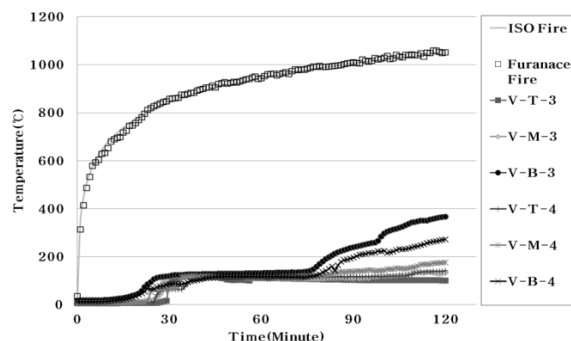


Figure 6. Hollow sphere temperature of void slab depend on depth of concrete cover and loading condition

Table 9. Hollow sphere temperature of void slab depend on depth of concrete cover and loading condition(at 120min)

Specimen	Location of Thermocouples (LHS*)	Avg. Temp. (°C) (at 120 min.)	Max. Temp. (°C) (at 120 min.)	Fire resistance (min.)
S-3	Top	101.0	102.2	120
	Middle	132.4	156.3	
	Bottom	366.5	482.7	
S-4	Top	141.2	156.4	120
	Middle	176.0	183.1	
	Bottom	272.7	276.7	

LHS* : Lightweight hollow sphere

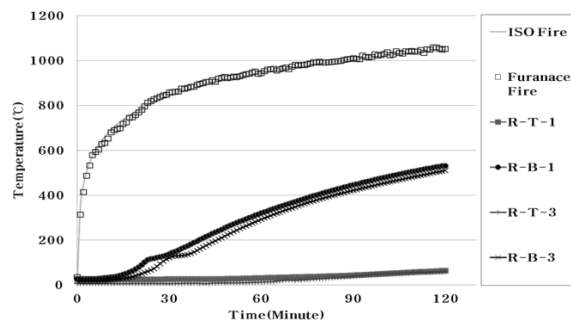


Figure 7. Rebar temperature of void slab depend on slab length

Table 10. Rebar temperature of void slab depend on slab length(at 120min)

Specimen	Location of Thermocouples (Rebar)	Avg. Temp. (°C) (at 120min.)	Max. Temp. (°C) (at 120min.)	Fire resistance (min.)
S-3	Top	58.9	62.9	120
	Bottom	510.3	535.0	
S-1	Top	63.1	66.7	120
	Bottom	531.1	538.6	

minutes) as a result of the survey on the temperature of the hollow sphere in each location. There were temperature changes averaging 15.5°C with a maximum of 22.8°C in the top hollow sphere and averaging 55.2°C with a maximum of 45.4°C in the center of the hollow sphere based on the 1.5 mm difference of span length, respectively. For the below hollow sphere, an average of 11.7°C and a maximum of 108.4°C were shown for the change. In addition, it is considered that since the melting point of the hollow sphere was low, the temperature in the below hollow sphere was lower than the one of reinforcement and concrete.

3.2. Fire Behavior Analysis in Each Experiment Variable of Hollow Slab

3.2.1. Analysis on the Fire Resistance Performance Depending on the Experiment Factors

As a result of the evaluation on the fire behavior of the cover depth of RC structure with a hollow slab, span (lengthwise), and using a lightweight hollow sphere, the fire resistance performance can be secured, as shown in Figure 9 and Table 12. For S-1 (7.8 m, 50 mm) and S-3 (6.5 m, 50 mm) securing 50 mm cover depth for 120 minutes, the minimum fire resistance performance to be applied to the actual site was secured regardless of the span (lengthwise). For S-3 (50 mm, 5.0 kN/m²) and S-4 (25 mm, 4.0 kN/m²) with the cover depth and loading as the experiment factors, 120 minutes fire resistance performance were secured for all conditions. Although the 20 mm cover depth was reduced for S-4, 1.0 kN/m² loading was reduced. Therefore, the deformation was generated to be as low as 95.6 mm. This means that its fire resistance performance is better than S-3. In general, the fire resistance performance was highly affected by the cover depth, and the fire resistance performance was increased depending on the increase of the cover depth. Although for the experiment, a 50 mm cover depth was secured and a 20mm cover depth was reduced compared to the S-3 which had 100% loading of the live load determined in the structure design; it was shown that S-4 with 80% loading of the live load had the high fire resistance performance.

4. CONCLUSION

As a result of the evaluation on the fire behavior of the cover depth of the RC structure with a hollow slab, span (lengthwise), and loading using the lightweight hollow sphere, it is concluded as follows.

1. For the 50 mm cover depth of the RC structure with a hollow slab secured, it was shown that 120 minutes of fire resistance performance could be secured regardless of the span (lengthwise) and loading.

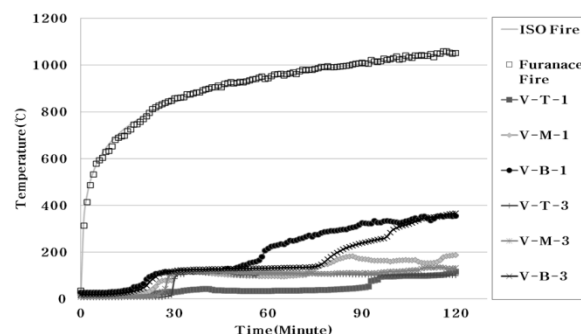


Figure 8. Hollow sphere temperature of void slab depend on slab length

Table 11. Hollow sphere temperature of void slab depend on slab length(at 120min).

Specimen	Location of Thermocouples (LHS*)	Avg. Temp. (°C) (at 120min.)	Max. Temp. (°C) (at 120min.)	Fire resistance (min.)
S-3	Top	101.0	102.2	120
	Middle	132.4	156.3	
	Bottom	366.5	482.7	
S-1	Top	116.5	125.0	120
	Middle	187.6	201.7	
	Bottom	354.8	374.3	

LHS* : Lightweight hollow sphere

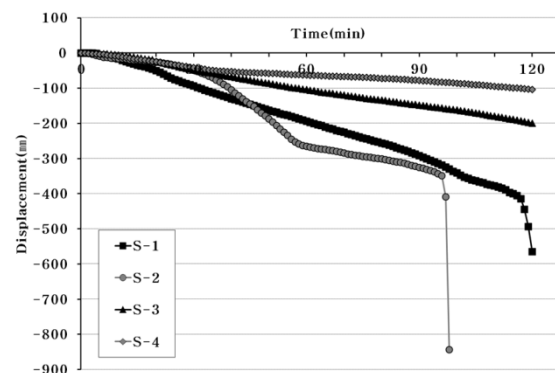


Figure 9. The analyze of fire behavior according to the variation of the void slab

Table 12. The deformation of void slab

Specimen	Deflection (mm)	Deformation ratio (mm/min.)	Fire resistance (min.)
S-1	565.2	71.8	120
S-2	409.3	60.6	97
S-3	199.8	2.0	120
S-4	104.2	1.2	120

2. As a result of the analysis on the fire resistance performance depending on the cover depth and loading, although a 50 mm cover depth was secured with 100% loading of the live load determined in the design and the cover depth was reduced to 30 mm, it was shown that the fire resistance performance with 80% loading is high. This means that the live load determined in the structure design of the RC structure with a hollow slab is a critical factor to secure the requirement of the fire resistance performance as well as structural performance.
3. As a result of the survey on the characteristics of the lightweight hollow sphere during high temperature which is not normally applied to the existing RC structure slab, the melting point was 100°C for the EPS which was applied in the hollow sphere. Therefore, the section where the increase of the temperature was delayed was generated depending on the shape change of the lightweight hollow sphere. The temperature of the hollow sphere was shown to be lower than the temperature of the reinforcement and concrete. In other words, it can be concluded that EPS melted in a low temperature and, therefore, has a low effect on the fire resistance performance of the hollow slab.

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