An Experimental Study on the Calculation of Optimal Foam Content Ratio for Low-carbon Concrete

Jeyoung Park and Youngshik Park

***Abstract*—**Demand for energy-saving insulator technology development is increasing in South Korea as regulations on energy-efficiency improvement in response to global warming are applied to buildings. To meet this demand, studies on thermal insulation type panels are increasing; however, they merely aim to improve the performance of organic and inorganic insulation materials. In this study, experimental research was performed to find the optimal mix for concrete base in terms of insulation performance using aerated concrete and lightweight aggregates, which have received little attention in insulation research.

***Keywords*—**Thermal insulation, lightweight aggregates, aerated concrete, concrete panel, PC panel, sound insulation

I. Introduction

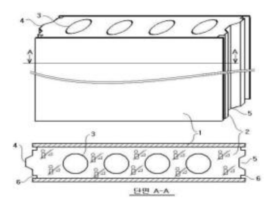
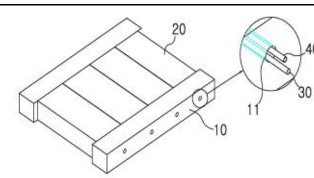
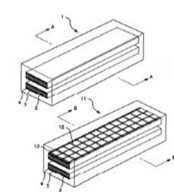
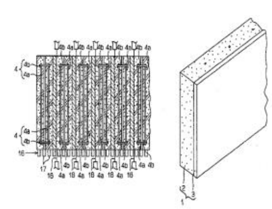
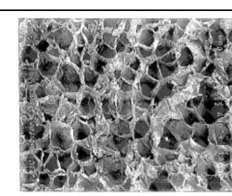
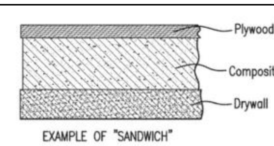
This study is a preliminary property test for a concrete mix for producing precast concrete panels applying a heat-metastructure. Thus, the objective of this study is to determine the optimal foam content ratio in the concrete. Going beyond the existing organic insulation materials, the possibility of commercializing inorganic insulation materials is explored, and a functional product is developed.

A. Domestic and overseas market trends and sizes

Demand for energy-saving insulator technology development is increasing in South Korea as regulations on energy-efficiency improvement in response to global warming are applied to buildings [1]. Organic insulation materials account for approximately 72% of the Korean domestic insulating materials market, and among them, EPS and PU-based insulating materials have more than 60% market share. The demand for organic insulating materials is expected to increase from 460,000 tons in 2014 to 620,000 tons in 2020 [2] [3], but their market share is expected to decrease gradually with the strengthening of fireproof certification [3]. In contrast, the domestic market share of inorganic insulation materials is approximately 15%, much lower than the global average share of 55%. Thus, there is not yet widespread use of inorganic insulation materials in Korea. However, the demand for inorganic insulation materials will increase in the future, and we need to prepare for this.

B. Domestic and overseas technology trends

TABLE I
Patent Trend for High Thermal Insulation Panel

Division	Prior art name	Technical drawing
Domestic	Manufacturing method of lightweight hollowed concrete panel for building wall and a lightweight hollowed concrete panel manufactured by the method	
Domestic	Lightweight concrete panel	
Domestic	High thermal insulation lightweight aerated concrete composite panel and the producing method of it	
Japan	Composite Panel and Manufacture Thereof	
USA	Lightweight concrete compositions	
USA	Methods for making aerogel composites	

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Domestic studies on PC panels have generally focused on evaluating the compressive strength performance and thermal conductivity of PC panels based on lightweight aggregate concrete or aerated concrete [5]–[7]. Furthermore, domestic studies on aerated concrete have mainly focused on evaluating the basic physical properties of concrete to achieve performance improvement and economic efficiency by applying industrial byproducts such as fly ash or blast furnace slag [8]–[9]. In contrast, domestic research on the combination of bubbles and bottom ash lightweight aggregate concrete is very insufficient [10].

Most overseas studies on aerated concrete concern ALC that has undergone high-temperature, high-pressure curing. Similar to domestic studies, they aimed to evaluate the basic physical properties and achieve performance improvement, environmental friendliness, and economic efficiency of aerated concrete by replacing industrial byproducts. A few overseas researchers have conducted studies on the fusion of bubbles and mortar [11], but there have been no studies aiming to improve thermal insulation at the concrete level.

Many studies have been conducted to improve the high unit volume weight and low thermal insulation of PC panels domestically and abroad. However, their main focus is on improving physical performance and securing economic efficiency, and the PC panels developed in these studies achieved only slight improvement in thermal insulation. Domestic and overseas patents related to lightweight aerated concrete panel, lightweight concrete panel, and foamed styrene panel mostly concern thermal and sound insulation and feature limited compressive strength and fire resistance. To improve fire resistance and insulation performance, patented technology considering a combination of components different from prior patents or a new manufacturing method is required. Therefore, continued research is necessary not only on the composition and manufacturing methods related to lightweight aerated concrete panel, lightweight concrete panel, and foamed styrene panel technologies, but also on the detailed structures using these technologies. In the present study, we attempted an experimental approach to achieve this.

II. Experimental Overview

The physical properties and chemical composition of the ordinary Portland cement (OPC), ground granulated blast-furnace slag (GGBS), and fly ash (FA) used in the mix are summarized below. The density and specific surface area of the OPC are 3.15 g/cm3 and 3,260 cm2/g, respectively, and the main chemical components are 62.4% CaO and 21.7% SiO2, which account for more than 80% of the total chemical components.

The density and specific surface area of GGBS are 2.94 g/cm3 and 4,355 cm2/g, respectively, and the major chemical components are 43.9% CaO and 33.5% SiO2, which account for more than 70% of the total chemical components. The density and specific surface area of FA are 2.20 g/cm3 and 4,170 cm2/g, respectively

A. Experimental Materials

The physical properties of major binders are listed in Table II.

TABLE II
Physical properties and chemical composition of GGBS and FA

Physical properties			
Material	Density (g/cm3)	Specific surface area (cm2/g)	Water content (%)
GGBS	2.94	4,355	0.23
FA	2.20	4,170	0.1

Chemical composition (%)							
Material	SiO2	Al2O3	Fe2O3	CaO	MgO	SO3	LOI
GGBS	33.5	15.2	0.5	43.9	2.6	2.5	3.9
FA	57.7	21.1	6.4	4.3	1.8	0.5	3.9

The physical properties of the bottom ash lightweight aggregates used in this study are outlined in Table III. To satisfy the particle size distribution of KS F 2527 for the fine aggregates, materials with particle sizes smaller than 2 mm and materials with particle sizes of 2–4 mm were mixed at a weight ratio of 7:3. The maximum sizes of the bottom ash lightweight fine aggregates and coarse aggregates are 4 mm and 13 mm, respectively, and the fineness moduli are 2.74 and 6.55, respectively. The absorptivity values of fine aggregates and coarse aggregates are 11.1% and 15.3%, respectively, and the dry air density values are 1.79 g/cm3 and 1.18 g/cm3, respectively. The surface and interior of the bottom ash lightweight aggregates have many air voids, as shown in Fig. 1. Their density ranged from 0.92 to 1.52 g/cm3, which corresponds to approximately 42–65% of that of general aggregates.

TABLE III
Physical properties of bottom ash lightweight aggregates

Aggregate type	Maximum size (mm)	Density (g/cm^3)	Absorptivity (%)	Fineness modulus
Fine aggregates	4	1.79	11.1	2.74
Coarse aggregates	13	1.18	15.3	6.55

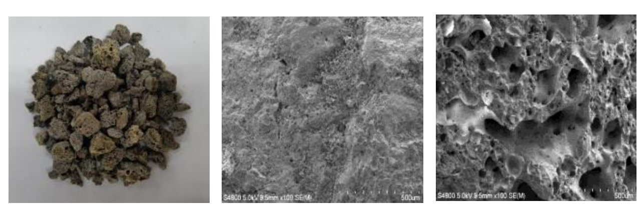

Fig. 1 Appearance and SEM images of bottom ash lightweight aggregates

For the foaming agent, a dark brown liquid animal foam agent with a density of 1.06 g/cm3 was used.

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TABLE IV
PHYSICAL PROPERTIES AND CHEMICAL COMPOSITION OF OPC

Physical properties				
Density (g/cm^3)	Specific surface area (cm^2/g)	Stability (%)	Setting time (min)	
			Initial set	Final set
3.15	3,260	0.05	230	345

Chemical composition (%)						
SiO2	Al2O3	Fe2O3	CaO	MgO	SO3	LOI
21.7	5.3	3.1	62.4	1.6	1.7	0.8

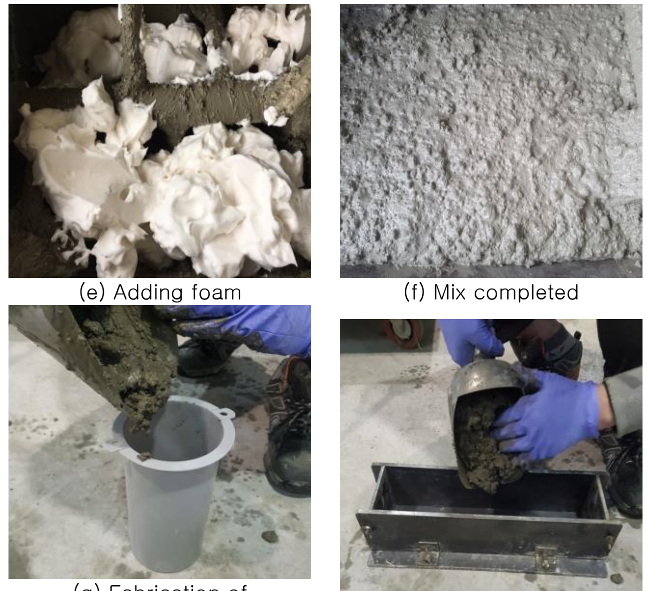
B. Mixing plan

The mixing details of the bottom ash lightweight aggregate concrete are described here. The main variable of groups 1 to 3 is foam content ratio (0%, 10%, and 25%, respectively). The unit binder quantity was changed to 450 kg/m3. The curing conditions of the mix were as follows: continuous curing at 20 ℃ after mixing, curing at 40 ℃ and 60 ℃ for 10 h, and constant temperature and humidity (20 ℃ and 60%, respectively).

The basic common conditions of the mix are the binder ratio (OPC 30%, GGBS 50%, and FB 20%) and 100% bottom ash lightweight aggregates (coarse aggregates and fine aggregates).

The main fabrication process of the concrete mix is shown in Fig. 2. To produce the concrete mix, bottom ash aggregates and binder were mixed in dry condition for approximately 2 min. Then wet mixing was performed by adding water, and then a water-reducing agent was added. The foam was added last by generating compressed air using a foaming agent diluted in water at a concentration of 2.5%.

(a) Adding aggregates (b) Dry mixing
(c) Adding mixing water (d) Generating foam



(e) Adding foam (f) Mix completed
(g) Fabrication of compressive strength specimen (h) Fabrication of specimen for coefficient of rupture

Fig. 2 Mix sequence of bottom ash lightweight aggregate concrete

C. Details of experimental mixes

The experimental mixes are outlined in Table V.

TABLE V
MIX DETAILS OF SPECIMENS

Specimens	*W/B* (%)	Foam (%)	Composition ratio of binder (wt %)		
			OPC	GGBS	FA
25-F0%	25	0	30	50	20
25-F10%		10			
25-F25%		25			
30-F0%	30	0	30	50	20
30-F10%		10			
30-F25%		25			

III. RESULTS

A. Uncured concrete

The mix could not be poured due to 0-mm slump. However, every other mix satisfied the target slump, and the slurry density exceeded the predicted value of ASTM C 567. Sedimentation due to a difference in specific gravity between the slurry and aggregates was not observed.

TABLE VI
EXPERIMENT RESULTS BY SPECIMEN

Specimen name	Foam content ratio (%)	Actual foam ratio (%)	Slurry density (kg/m^3) Measurement	Slump (mm)	Settlement depth (mm)
25-F0%	0	0	Filling is impossible due to 0mm slump		
25-F10%	10	12.5	1,582	210	0
25-F25%	25	20	1,366	205	0
30-F0%	0	0	1,620	50	0
30-F10%	10	7.5	1,541	150	0
30-F25%	25	17.5	1,320	165	0

B. Cured concrete

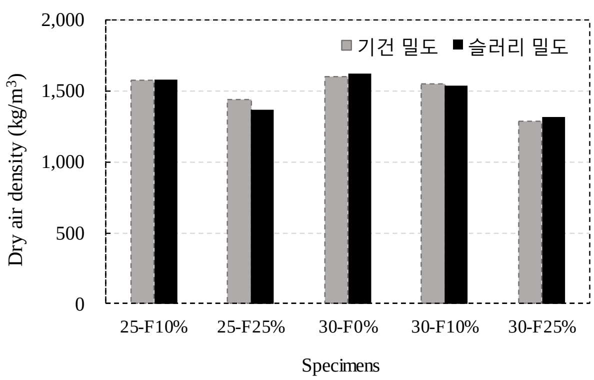


Fig. 3 Comparison of dry air density and slurry density

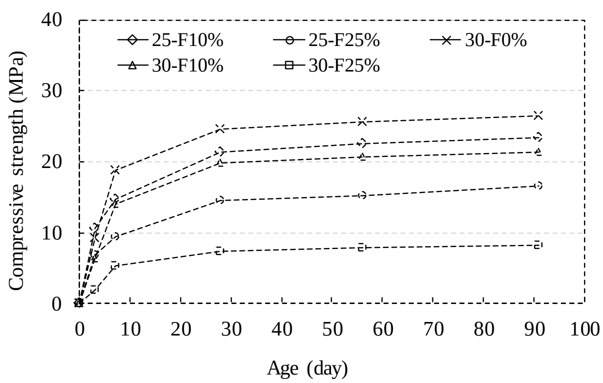


Fig. 4 Compressive strength by age for curing at room temperature

Every mix except for 30-F25% satisfied the target strength. The dry air density and compressive strength decreased with increasing foam content ratio.

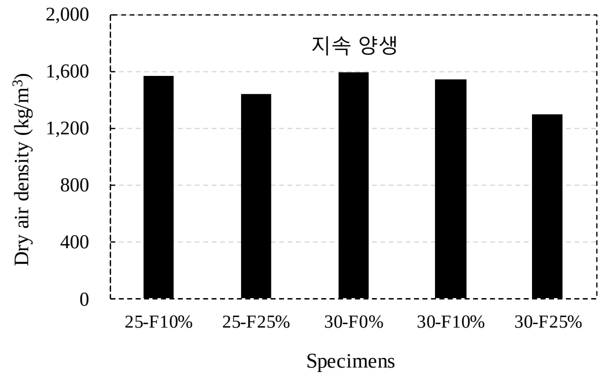


Fig. 5 Dry air density for curing at 60˚C

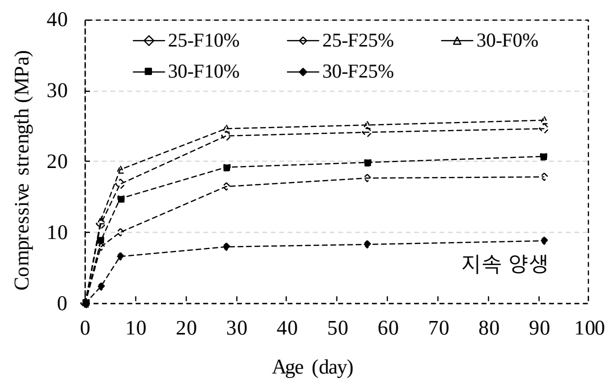


Fig. 6 Compressive strength and dry air density by age at 60˚C

TABLE VII
BENDING STRENGTH, SPLITTING TENSILE STRENGTH, AND DRYING SHRINKAGE

Specimen name	$f_{sp} / \sqrt{f_{ck}}$	$f_{r} / \sqrt{f_{ck}}$
25-F10%	0.335	0.574
25-F25%	0.303	0.548
30-F0%	0.350	0.667
30-F10%	0.305	0.555
30-F25%	0.288	0.500

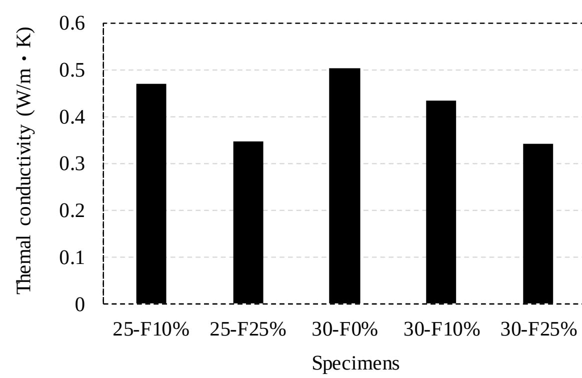


Fig. 7 Thermal conductivity

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TABLE VIII
THERMAL CONDUCTIVITY AND HEAT TRANSMISSION RATE

Specimen name	Thermal conductivity (W/m・K)	Converted heat transmission rate (W/m2・K)
25-F10%	0.471	0.288
25-F25%	0.347	0.278
30-F00%	0.505	0.290
30-F10%	0.434	0.286
30-F25%	0.342	0.278

The thermal conductivity and heat transmission rate decreased with increasing foam content ratio.

IV. Conclusions

The thermal conductivity of the specimens ranged from 0.342 to 0.505 W/m·K, approximately 83% compared to that of normal-weight concrete, 2.4 W/m·K. However, thermal conductivity must be lowered further, because it is still 40% higher than the target heat transmission rate, 0.2 W/m2·K.

(1) In every mix, the measured slurry density was higher than the predicted slurry density.

(2) The optimal mix conditions to satisfy the target compressive strength of 10MPa, the target dry air density of 1,300–1,600 kg/m3 and the target slump of 150mm are as follows: 25% foam content ratio, 25% W/B, 205mm slump, 91 days of age, 17.9MPa compressive strength, and 17.9MPa dry air density. The curing condition is continuous curing at a high temperature (60℃).

(3) The converted heat transmission rate was 0.274 W/m2·K (including heat-meta and insulating materials), which did not satisfy the target condition of 0.2 W/m2·K. The results of this experiment will be used as basic data for determining the optimal mix condition to meet this target.

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