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An Experimental Study on the Thermal Conductivity of Concrete Containing Coal Bottom Ash Aggregate

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Abstract. *Thermal conductivity plays a significant role in efficient energy usage, especially in the construction field. Low thermal conductivity is preferable because lower thermal conductivity will increase the thermal insulation provided by the concrete and reduce the heating and cooling costs for residential and commercial buildings. To accomplish this goal, porous materials can be considered for use in concrete. Additionally, researchers have had challenges producing high-strength concrete with low thermal conductivity. Therefore, this study aims to investigate the effects of replacing crushed fine aggregates with coal bottom ash (CBA) on the thermal conductivity and mechanical properties of high-strength concrete. The concrete properties, including unit weight, compressive strength, and thermal conductivity, were measured. The experimental results revealed that the thermal conductivity of the CBA concrete decreased as the unit weight of the CBA concrete decreased, and the thermal conductivity also decreased as the compressive strength decreased. Finally, the relationships between the thermal conductivity, unit weight, and compressive strength of the CBA concrete were also examined.*

Keywords: *Coal Bottom Ash, Thermal Conductivity, High-Strength Concrete, Porosity.*

1 Introduction

Currently, the demand for energy-efficient buildings is increasing to optimize the internal temperature of buildings (Najjar *et al.*, 2019). One of the key factors for optimizing energy efficiency is thermal conductivity. When a building is constructed from materials with higher thermal conductivity, to ensure the internal temperature of the building, a greater amount of energy must be consumed for cooling and heating. To address this issue, materials with low thermal conductivity are recommended during construction. Thus, considering concrete with low thermal conductivity is the most suitable choice.

To produce concrete with low thermal conductivity, Aghdam *et al.* (2019) carried an experimental study to estimate the effects of carbon nanotubes on the thermal conductivity of steel fiber-reinforced concrete. Their test results indicated that the agglomeration of carbon nanotubes caused a decline in the concrete thermal conductivity. However, the use of carbon nanotubes is expensive, and high-strength concrete is not considered.

Currently, coal-fired thermal power plants create a substantial amount of bottom ash and fly ash. Bottom ash is industrial waste produced at the bottom of coal furnaces. To develop concrete with low thermal conductivity for energy efficiency, an experimental study to investigate the effects of partial or total replacement of crushed fine aggregates with coal bottom ash (CBA) on the thermal properties of concrete is vitally necessary.

Therefore, in this experimental study, the thermal conductivity and mechanical properties of high-strength concrete specimens containing 25, 50, 75, and 100% replacement of crushed fine aggregates with CBA were investigated at a curing age of 28 days. The compressive strength, unit weight, and thermal conductivity of these specimens were measured. The relationships between the thermal conductivity, unit weight, and compressive strength of the CBA concrete were also examined.

2. Experimental Program

2.1 Materials

Figure 1. CBA aggregate.

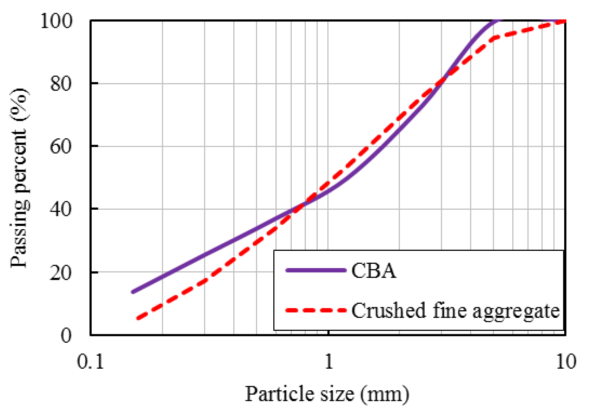


Figure 2. Grading curve of CBA and crushed fine aggregate.

Table 1. Physical properties of fine, coarse and coal bottom ash aggregate.

	Fineness modulus	Water absorption (%)	Unit weight (g/cm^3)
Crushed fine aggregate	3.17	0.69	2.60
Coarse aggregate	6.77	1.44	2.61
CBA	3.83	6.87	1.84

The coal bottom ash used in this study was collected from a thermal power plant company in Korea. The CBA aggregate was screened to remove particles greater than 5.0 mm and to retain the particles greater than 0.15 mm. The CBA used for this study is presented in Figure 1, and the particle size distribution of the CBA is also presented in Figure 2. The test results of the density and water absorption of the CBA are shown in Table 1. The particle size distribution of the crushed fine aggregates is illustrated in Figure 2. The unit weight, water absorption and fineness modulus results of the crushed fine and coarse aggregates are also shown in Table 1.

2.2 Mix Proportions

A concrete mix was designed with a target compressive strength of 60 MPa at a curing age of 28 days. The mixing proportions of the control concrete and coal bottom ash concrete are indicated in Table 2. The crushed fine aggregate was replaced with five different volume fractions (0, 25, 50, 75, and 100%) of coal bottom ash in the concrete.

Table 2. Mixing proportions of the coal bottom ash concrete.

Mixtures	Replacements of CBA (%)	W/C	Water	Unit content (kg/m^3)				
				Cement (OPC)[a]	Coarse aggregate	Fine aggregate	Coal bottom ash	HWRA[b] (0.6% × cement)
CBA00	0	0.3	178.5	595	878.5	663	0	3.6
CBA25	25	0.3	178.5	595	878.5	497.2	117.7	3.6
CBA50	50	0.3	178.5	595	878.5	331.5	235.3	3.6
CBA75	75	0.3	178.5	595	878.5	165.7	353	3.6
CBA100	100	0.3	178.5	595	878.5	0	470.7	3.6

a: OPC: ordinary Portland cement.
b: HRWA: high water reducing agent.

2.3 Specimens and Test Procedures

Cylindrical specimens with dimensions of 100 mm × 200 mm were cast to measure the unit weight, compressive strength, and thermal conductivity of the different samples. The unit weight, compressive strength, and thermal conductivity of the CBA concrete were measured at a curing age of 28 days. The thermal conductivity of each specimen was measured using a transient plane source (TPS) measurement system, as shown in Figure 3.

3 Test Results and Discussion

3.1 Unit weight

The unit weight results of the concrete specimens with different coal bottom ash ratios are shown in Figure 4. The figure indicates that the unit weight of the CBA concrete decreased as the replacement of crushed fine aggregate with CBA increased in the concrete. At a curing age of 28 days, the unit weight of the control mixture was 2,370 kg/m^3, whereas the unit weights of the coal bottom ash concrete mixtures CBA25, CBA50, CBA75, and CBA100 were reduced by 2.1, 3.2, 5.3, and 7.6%, respectively. The decrease in the unit weight of the CBA concrete mixtures is due to the replacement of coal bottom ash, which is a lighter fine aggregate than crushed fine aggregate, as shown in Table 1.

Figure 3. Test setup for thermal conductivity measurements.

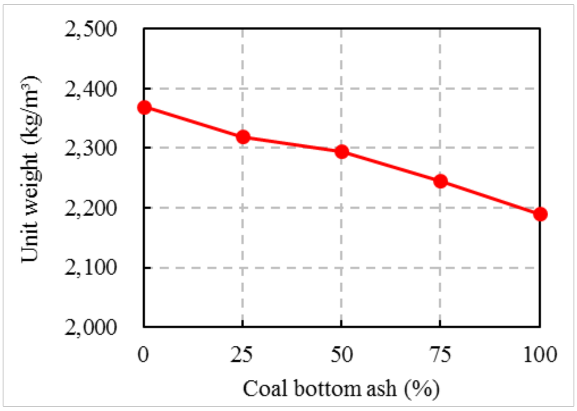


Figure 4. Effect of CBA replacements on unit weight of concrete.

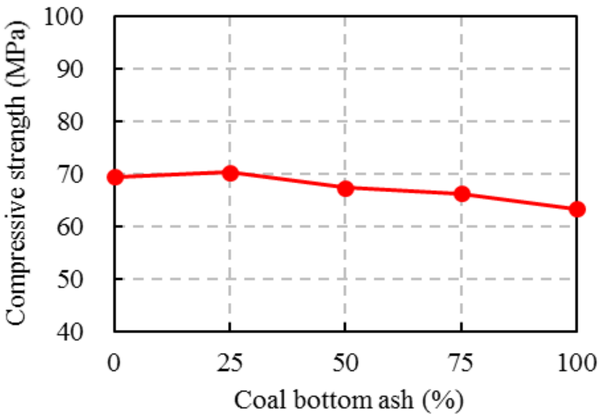


Figure 5. Effect of CBA replacement on compressive strength.

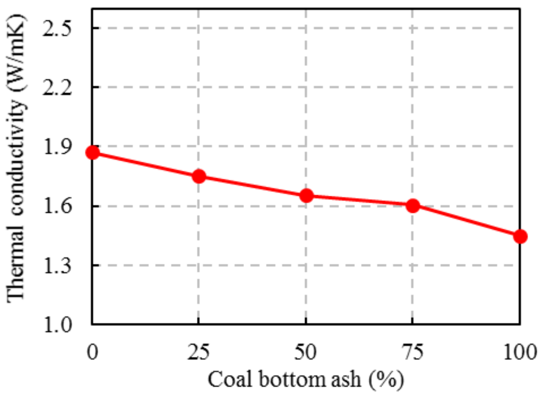


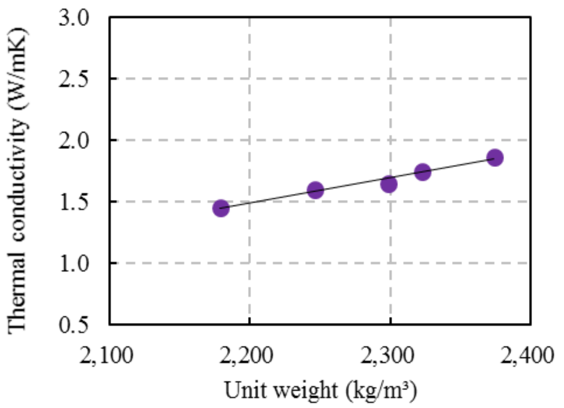
Figure 6. Effect of CBA replacement on thermal conductivity.

3.2 Compressive Strength

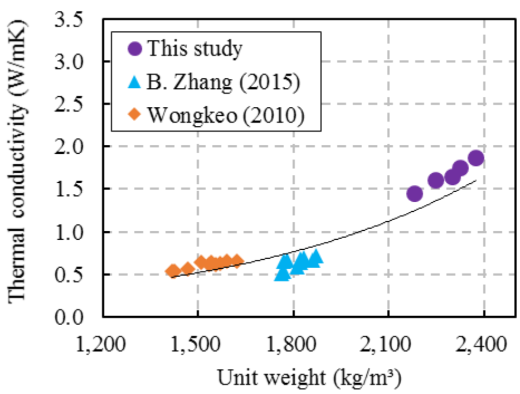
The test results of the compressive strength of the concrete specimens with different coal bottom ash contents are summarized in Figure 5. Generally, at a curing age of 28 days, the compressive strength of the CBA mixtures decreased as the CBA replacement increased. The compressive strength of the coal bottom ash concrete mixtures CBA50, CBA75, and CBA100 were 3.0, 4.6, and 8.8% less than that of the control concrete mixture (69.4 MPa), respectively. However, the compressive strength of the coal bottom ash concrete mixture CBA25 was insubstantially higher (1.2%) than that of the control concrete mixture. The compressive strength loss could be explained by the increase in the porosity of the concrete. These porosities cause negative impact on concrete matrix and reduce the compressive strength of the CBA concrete specimens [Singh *et al.*, 2014].

3.3 Thermal Conductivity

The thermal conductivities of the concrete specimens with different CBA contents are presented in Figure 6. At a 28-day curing age, the thermal conductivities of the CBA mixtures decreased as the CBA content increased. The thermal conductivities of the CBA concrete mixtures CBA25, CBA50, CBA75 and CBA100 were 6.4, 11.7, 14.2, and 22.5% less than that of the control concrete mixture (1.87 W/m·K), respectively. The thermal conductivity of the CBA concrete with a 100% CBA content was significantly less than that of the control concrete mixture. It is known that thermal conductivity highly depends on the lightweight aggregate pore structure, the concrete density and the cement paste. Hence, the pore structure was one of the key elements affecting thermal conductivity (Tasdemir *et al.*, 2017). For that reason, the observed decline in thermal conductivity could be explained by the increase in the CBA concrete in the concrete. As the CBA content increased, the total volume of porosity of the concrete increased, and the thermal conductivities of the concrete decreased. Reducing the thermal conductivity would increase the thermal insulation provided by the concrete and reduce the heating and cooling costs for buildings.



(a) Test results of this study

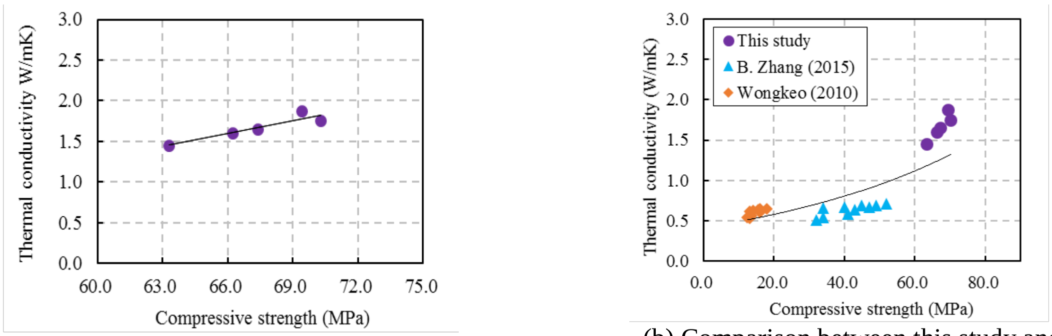


(b) Comparison between this study and previous studies

Figure 7. Relationship between the thermal conductivity and unit weight.

The relationship between the thermal conductivity and unit weight of the CBA concrete is demonstrated in Figure 7. As the unit weight of the CBA concrete increased, the thermal conductivity of the CBA concrete increased. Moreover, the thermal conductivity of the CBA concrete is nearly linearly proportional to the unit weight. Increasing the air voids or lightweight aggregate in concrete is a method to reduce unit weight and thermal conductivity. A similar trend was found when analyzing the test results of Wongkeo *et al.* (2010) and Zhang *et al.* (2015), in which the unit weights ranged from 1417 to 1621 kg/m^3 and from 1760 to 1870 kg/m^3, respectively, as shown in Figure 7(b).

The relationship between the thermal conductivity and the compressive strength is demonstrated in Figure 8. This relationship is similar to the relationship between the thermal conductivity and unit weight of the CBA concrete. Additionally, the thermal conductivity has a direct relationship with the compressive strength of the CBA concrete. Figure 8(b) shows a similar trend between the test results in the present research and those of other authors.



(a) Test results of this study

(b) Comparison between this study and previous studies

Figure 8. Relationship between the thermal conductivity and compressive strength.

4 Conclusions

In this research, an experimental study was performed on the low thermal conductivity of high-strength concrete specimens with different CBA replacement ratios. The research findings are summarized hereafter:

- The thermal conductivity of the CBA concrete is highly dependent on the porosity in the concrete specimens. For that reason, as the CBA content increased, the thermal conductivity of the CBA concrete decreased gradually. Remarkably, when replacing all the crushed fine aggregate with CBA, the thermal conductivity of the CBA concrete was 22.5% less than that of the control mixture.
- As the coal bottom ash content in the CBA concrete increased, the compressive strength of the CBA concrete decreased. In particular, the compressive strength of mixture CBA100 was 8.8% less than that of the control mixture CBA00.
- As the compressive strength of the CBA concrete decreased, the thermal conductivity of the CBA concrete also decreased.

Acknowledgments

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