Master's Thesis of Engineering

Eco-friendly Ultra-High Performance Concrete (UHPC) with Bottom Ash

석탄 바닥재를 사용한
친환경 초고성능 콘크리트

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Graduate School of Engineering
Seoul National University
Architecture and Architectural Engineering

Ji Eun Choi

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Advisor : Sung Gul Hong

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Chair __________________________ (Seal)

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Abstract

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Choi, Ji Eun
Department of Architecture and Architectural Engineering
College of Engineering
Seoul National University

Unlike the fly ash, which is produced with materials generated in the process of burning coal in thermal power plants to produce energy, bottom ash is mostly buried because its use is unclear. This treatment method has become many environmental problems, and research to recycle bottom ash as a construction material is being actively conducted. Research is being conducted mainly on the use of concrete materials at the aggregate level, but its application is limited due to the physical characteristics of bottom ash. Bottom ash is a material produced by burying coal, so it is not chemically stable because of its high metal component, and it cannot exhibit sufficient physical properties because it is a porous material. Therefore, this study intends to replace bottom ash with fine aggregates, a material of UHPC. To determine the effect of these characteristics of bottom ash on UHPC, the mix design was selected and experimented by setting aggregate replacement of bottom ash (0% 10%, 25%, 50%) as a variable. As a result of the experiment, as the replacement rate of the bottom ash increased, all mechanical properties, thermal properties, durability decreased, and some durability tended to increase slightly when the replacement rate was 10%. Considering the mechanical properties and durability, is judged the optimal mix design is to replacement 10% of the weight of fine aggregate. To solve the high metal components that is a disadvantage of bottom ash, based on a mixture of 10% replacement rate against the weight of the fine aggregate, which can maximize the performance of bottom ash, X-ray diffraction analysis (XRD analysis), mechanical properties, durability, and thermal properties were confirmed using bottom ash. The measurement and evaluation showed that a large amount of metal components and organic matter in bottom ash applied with washing, heat and chemical treatment were removed, and thus their mechanical properties and durability increased compared to raw bottom ash.

In other words, if bottom ash is used as a material for UHPC, it is eco-friendly in that bottom ash can be recycled and thermal conductivity can be reduced, and the performance of bottom ash can be improved through pre-treatment, so the use of bottom ash is considered appropriate for produce eco-friendly UHPC.

Keywords: Ultra-High Performance Concrete (UHPC), Eco-Friendly, Pre-treatment Method, Bottom Ash

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List of Abbreviation

UHPC	**Ultra-High Performance Concrete**
S	**Silica Sand**
C-S-H	**Calcium Silicate Hydrate**
W	**Washing**
H	**Heat**
C	**Chemical treatment**
XRD	**X-ray diffraction analysis**
RCMT	**Rapid Chloride Migration Test**
BA	**Bottom Ash**
PSD	**Particle Size Distribution**
SP	**Superplasticizer**
OPC	**Ordinary Portland Cement**

Chapter 1. Introduction

1.1 Background

1.1.1 Status of recycling of Bottom ash

Bottom ash is an industrial by-product produced by burning coal to use as an energy source in a thermal power plant. Recently, various environmental problems have arisen due to the reclamation of the ground after the bottom ash is generated. In addition to environmental pollution caused by the buried bottom ash, it is considered a problem in that the land where the bottom has been buried or the land that will be bury.

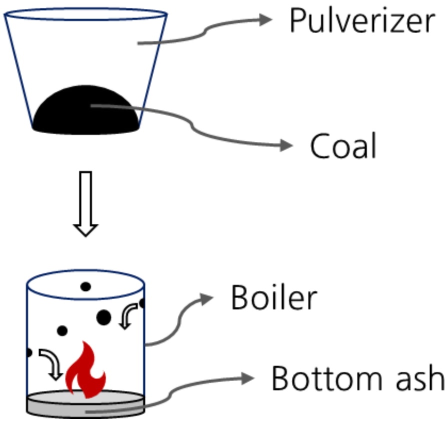


Figure 1-1 Simple image of thermal power plant

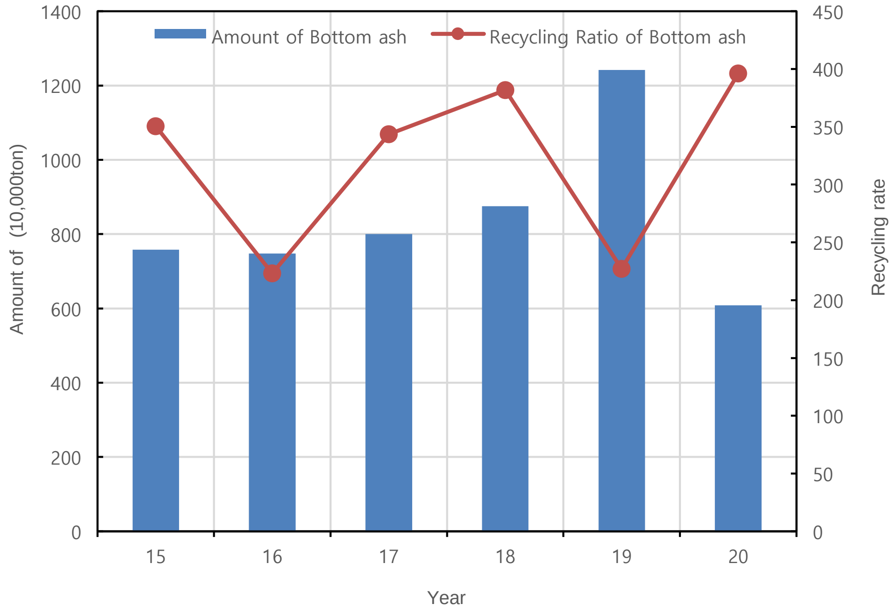


Figure 1-2 Amount and recycling ration of bottom ash in South Korea

Over the past five years, the average amount of bottom ash generated in Korea has been 838,500 tons, resulting in a significant amount of bottom ash, and the recycling rate of is also increasing. However, this is calculated by adding the ratio of recycled bottom ash that was already buried, not only the generated bottom ash, and the recycling rate for the actual generation is expected to be lower than the statistics.

So, using bottom ash a material for ultra-high performance (UHPC) concrete, can help reduce the content of buried bottom ash and increase the recycling rate of bottom ash.

1.2 Scope and Objectives

Research continues to be conducted to recycle bottom ash as a building material to solve environmental and economic problems and natural aggregate supply and demand problems caused by the increase in emissions of bottom a sh.

(1) A study on the use of bottom ash as fine aggregate and coarse aggregate of normal concrete [6, 7, 8, 9, 10, 11, 12, 13, 14, 15]

(2) A study on the use of bottom ash as quartz powder of Ultra-high performance concrete (UHPC) and High strength concrete (HSC) [16, 18]

(3) A study on the use of bottom ash as fine aggregate of Ultra-high performance concrete (UHPC) [1]

Bottom ash is composed of various sizes without a specified particle size, so it can be used as a construction material in various ways, from quartz powder as fine particles to coarse aggregates as large particles. Through a physical treatment such as sieving.

Therefore, in this paper, we will analyze the characteristics of concrete that changes accordingly by replacing bottom ash according to a certain ratio after preprocessing so that it can be used as a fine aggregate for UHPC.

Chapter 2. Literature Review

Chapter 2 introduces the characteristics of bottom ash and UHPC, and a summary of the literature using bottom ash for normal concrete and UHPC. Then, the comparison of silica sand and bottom ash is explained

2.1 Bottom Ash

2.1.1 Characteristics of bottom ash

As an industrial by-product generated by thermal power plants, about 90%~85% of coal is burned as fly ash, and 10%~15% is generated as bottom ash. Fly ash has been actively used as a material for concrete since various studies have been conducted for many years, but bottom ash has a lower recycling rate than fly ash because impurities from processing after obtained.

The bottom ash in this paper is obtained from the Korea Western Power Plant, and the power plant uses a wet method of cooling the failing bottom ash using seawater. Accordingly, it was determined that the bottom ash used in this paper would contain high impurities from seawater and require pre-treatment.

Additionally, the particles of bottom ash vary from fine particles to large particles. Therefore, in this paper, to use bottom ash as a fine aggregate for UHPC, sieve analysis test was carried out and used according to the size of No.6 silica sand used in the laboratory.

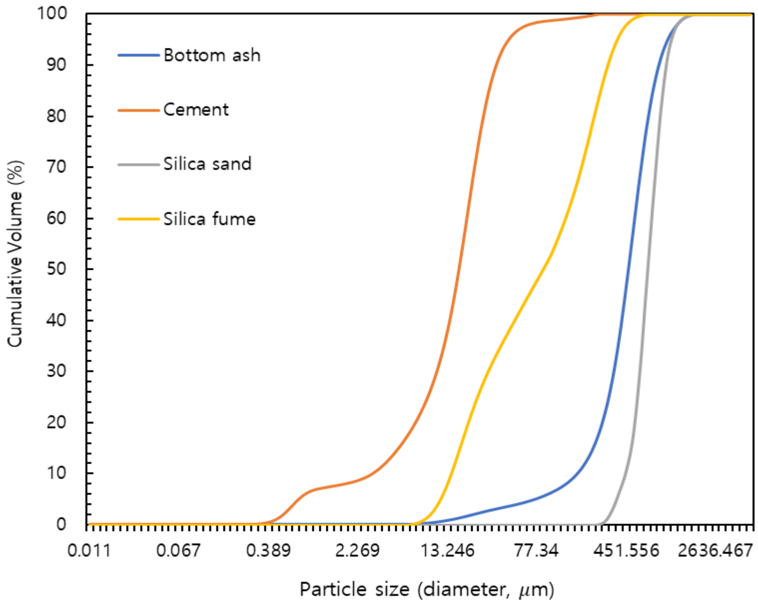


Figure 2-1 Cumulative particle size distribution

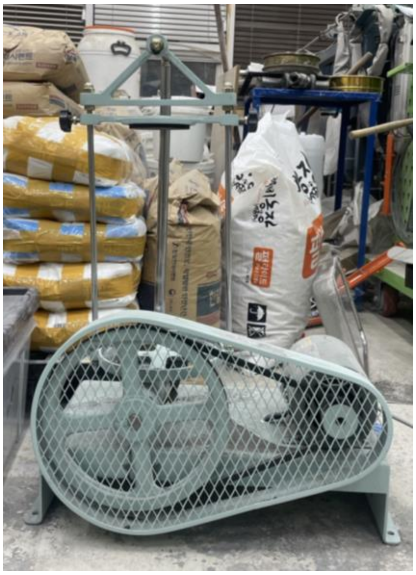


Figure 2-2 Picture of sieve machine

In Table 2-1 and Table 2-2, bottom ash shows the following chemical components and has a high content of $SiO_2, Al_2O_3, Fe_2O_3, CaO$. In particular, since the content of silica, alumina, and ion has been exceeding 70% and the loss of ignition does not exceed 6%, it can be classified as a pozzolanic material of Class C or F according to ASTM C618-22.

Table 2-1 Chemical composition of bottom ash

Component	Percentage (%)
SiO_2	50.20
Al_2O_3	22.25
Fe_2O_3	13.36
MgO	1.84
CaO	3.27
Na_2O	1.44
K_2O	1.97
MnO	0.05
P_2O_5	0.24
TiO_2	0.50
Loss of Ignition (LOI)	5.23

Table 2-2 Comparing standard (ASTM C1761/C1761M, ASTM C618-22)

	ASTM C1761/C1761M, ASTM C618-22	Test result
Density	$1.12\mathrm{g}/cm^3$	$1.039\mathrm{g}/cm^3$
Water absorption	Not less than 5%	4.52%
Silica + Alumina	Minimum 50%	85.82%
Loss of ignition (LOI)	Maximum 5% or 6%	5.23%

According to ASTM C1761, the bottom ash is classified for pozzolanic material because of the high content of silica and alumina. Silica in the bottom ash formed the C-S-H gel as react with portlandite of the cement and water. C-S-H gel is an important for concrete strength formation.

The chemical equation of pozzolanic reaction is

$$SiO_2 + Ca(OH)_2 + H_2O \rightarrow C-S-H$$

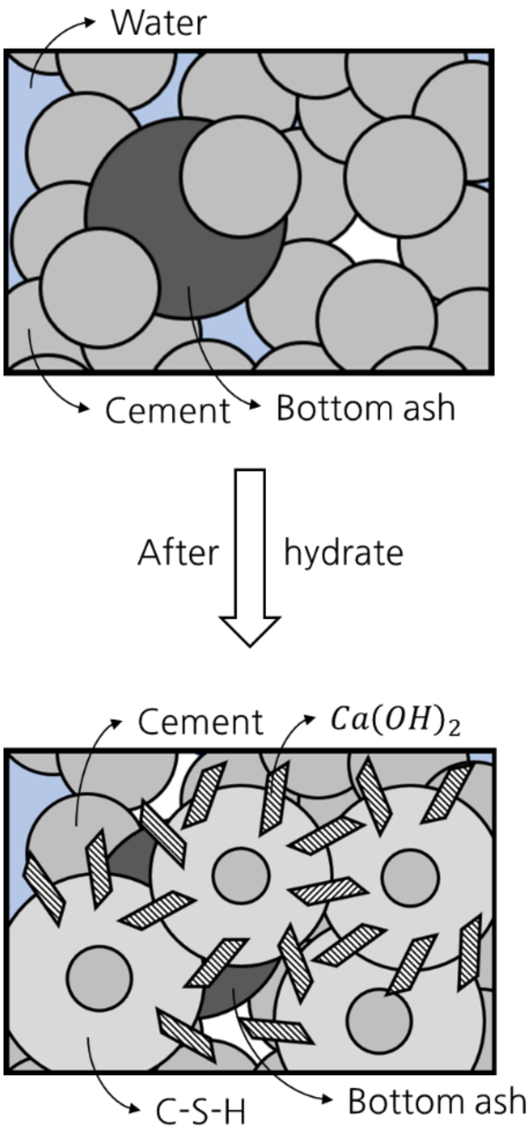


Figure 2-3 Schematic illustration of the pozzolanic reaction

2.1.2 Bottom ash as fine aggregate in normal concrete

Research using bottom ash as a replacement for fine aggregates of concrete is still actively. To use bottom ash as concrete material, the particle size of bottom ash is mostly 5mm.

The particle size of the bottom ash used in each study was different, so the workability was different, but most of the compressive strength and flexural strength tended to decrease regardless of the replacement rate. However, in some papers, the compressive strength and flexural strength tended to increase when cured for a long time up to a certain replacement rate (10%~25%). In addition, the durability test results also show that the tendency to increase as the usage of bottom ash increases, especially in the case of chloride penetration resistance.

It was judged that silica in bottom ash was caused by the pozzolanic reaction that a chemical reaction with $Ca(OH)_2$, and the remaining C-S-H caused the strength of the concrete to increase.

2.1.3 Bottom ash as quartz powder in Ultra-High Performance Concrete

Research using the bottom ash as quartz powder for UHPC is not as active as the fine aggregate replacement paper, but it is progressing slowly.

In this study, an experiment was conducted by replacing bottom ash with the whole quartz powder. In the case of the fresh property, there was little change in the slump by aligning the particle range of the bottom ash as much as possible with the particle range of the quartz powder.

The compressive strength was also little different from the control specimen. So, it can be seen that the generation rate of C-S-H product by the pozzolanic reaction of bottom ash is almost similar to the porosity of UHPC. Additionally, considering that there is no change in the setting time when both the reference setting time and specimen that bottom ash are replaced with quartz powder, it was determined that bottom ash can be used as a concrete material by performing a pozzolanic reaction.

If bottom ash is used as a material for concrete in the same way as replacing fine aggregates with bottom ash, it is expected that the pozzolanic reaction can be expected due to the high silica content of bottom ash.

2.1.4 Bottom ash as silica sand in Ultra-High-Performance Concrete

Studies using bottom ash as a silica sand for UHPC are also being studied as slowly as quartz powder.

In this study, an experiment was conducted by replacing bottom ash with silica sand. Considering the high absorption rate of bottom ash, in this study, bottom ash in a dry state was used after being immersed in water for 24hours.

As a result, the compressive strength of UHPC increased to a replacement rate of 25%. However, when the replacement rate of bottom ash increased to 100%, the strength decreased, but it was determined that the strength was sufficiently manifested as UHPC over 130MPa. In this study, since bottom ash was immersed and used in water, the cumulative hydration heat also tended to increase when the replacement rate of bottom ash increased. This is due to the internal curing in which the water initially contained in the bottom ash is discharged to the concrete by osmosis, and the strength can also be increased by this internal curing.

Therefore, it was judged that the strength of the 25% replacement rate was higher by the inside of the concrete is dense by internal curing than the high porosity by bottom ash.

In other words, it was determined that bottom ash could be sufficiently used as a fine aggregate for UHPC.

2.2 Ultra-High-Performance Concrete (UHPC)

UHPC has a higher performance than other concrete such as compressive strength, flexural strength, and durability, and has a very high flowability.

Therefore, when replacing the constituent materials of the UHPC with other materials, the performance should be evaluated with attention to strength and flow.

① High strength: UHPC usually exhibits compressive strength exceeding 150MPa. This strength is further increased when heat curing is performed at a high temperature.

② High density: The density of UHPC is high, ranging from 2.4 to 2.5 g/cm^3. Due to the high density, durability also shows high characteristics, and accordingly, chloride penetration can be prevented, which has a good environmental effect.

③ High fluidity: This feature has the advantage of having a wider range of use than normal concrete because various types of buildings and structures can be made using UHPC.

UHPC is concrete that is greatly influenced by the curing method, and it is usually carried out using two methods. Usually, two way applied normal curing and heat curing. The hydration reaction in UHPC is accelerated when curing at high temperature, and heat curing can be used to produce UHPC with excellent performance.

In this paper, white cement (Union white cement, Korea), Quartz powder (S-SIL 10, Korea), silica sand (No.6, Korea), silica fume (Grade 940U, Elkem, Norway), superplasticizer are used to produce UHPC.

2.3 Comparing of Silica sand with Bottom Ash

Comparing of silica sand with bottom ash is important things. Because silica sand is replaced by bottom ash in UHPC.

(1) Formation

- Silica sand

Figure 2-4 Picture of silica sand

- Bottom ash

Figure 2-5 Picture of raw bottom ash and pre-treatment bottom ash

(2) Price

- Silica sand: 760₩/kg
- Bottom ash: 0₩/kg
- Distilled water: 216.67₩/L
- Sodium carbonate: 10,000₩/kg

Bottom ash is an industrial by-product thrown away from thermal power plants and can be obtained free from thermal power plants. If bottom ash is used without pre-treatment, it may be economically beneficial than silica.

However, when pre-treatment is applied to improve the performance of bottom ash, 39.75g of sodium carbonate to match 0.25M with 1.5L of distilled water is consumed additionally in addition to bottom ash to chemically treat 1 kg of bottom ash based on the chemical treatment method that consumes the most processes.

This amount is 325₩ for 1.5L of distilled water, 397.5₩ for 39.75g of sodium carbonate, and a total of 722.5₩, indicating that it is a little more economical than using silica sand. Therefore, while silica sand is 760₩/kg, the total cost of the pre-treatment bottom ash is 722.5₩, so it can be used the bottom ash at a slightly lower cost than that of silica sand.

In the results, if bottom ash is used as a material for UHPC, it is environmentally beneficial in that if recycles the discarded material, and is economical in that it can save money.

Table 2-3 Comparing of silica sand and bottom ash

	Picture	Material	Pre-treatment		Total
S		760₩/kg	-		760₩/kg
BA_ raw		0₩/kg	-		0₩/kg
BA_ WHC		0₩/kg	Distilled water	Sodium carbonate	722.5₩/kg
			325₩/1.5L	397.5₩/53g	

Chapter 3. Experiment Plan

3.1 Test Outline

3.1.1 Bottom Ash

Particle Size of Bottom Ash: UHPC uses only fine aggregates, not coarse aggregates, so various sizes of bottom ash were used to measure the size of fine aggregates. It was shifted to a size between 0.3mm and 0.7mm, the particle size of the no.6 silica sand used for the production of UHPC.

Replacement Ratio: According to various previous studies conducted earlier, fine aggregates are replaced by maximum 50% of the volume and mass of fine aggregates. Accordingly, the experiment was conducted by applying a replacement ratio of 0%, 10%, 25%, and 50% to the weight of fine aggregates.

Pre-treatment method: Proper pre-treatment method has to be performed to remove several impurities in bottom ash obtained by different methods. In this paper, the method of pre-treatments are 3 methods washing, heat, chemical treatment is performed only or together. Pre-treatment method: Washing (W), Heat (H), Heat after washing (WH), and chemical treatment after washing and heat (WHC) were used.

Chemical changes in the bottom ash aggregate itself are expected due to pre-treatment through physical and chemical methods, and accordingly, physical, chemical, and temperature changes when bottom ash is replaced with fine aggregates of UHPC are expected.

Therefore, compressive, flexural strength test, water absorption test, and rapid chloride migration test (RCMT) were performed to confirm physical properties, and x-ray diffraction analysis (XRD) was performed to confirm chemical properties. Finally, in order to check the change in thermal properties, the thermal conductivity was measured and the results were compared.

3.1.2 Outline

The figure 3-1 is an overall outline of this paper. The purpose of this study is to find an optimal mix design for manufacture of UHPC using bottom ash and to find a pre-treatment method that minimizes the performance degradation of UHPC due to the use of bottom ash.

Therefore, experiments and analysis were conducted for this purpose according to the description below.

First, the mechanical properties, thermal properties and durability of the reference UHPC and UHPC with bottom ash were checked, and an experiment was conducted to fix the mix design.

The experiment was conducted again based on the mix design obtained through the experiment. The per-treatment methods mentioned above were applied to confirm the change in bottom ash according to the pre-treatment method. Mechanical tests, thermal tests, durability tests and XRD analysis were conducted in the same manner to verify the performance of UHPC using bottom ash with pre-treatment.

As a result, it was possible to determine whether it is appropriate to use bottom ash as a material for UHPC by checking and determining an appropriate replacement rate of bottom ash and pre-treatment method through experiments, and eco-friendly UHPC could be made using bottom ash

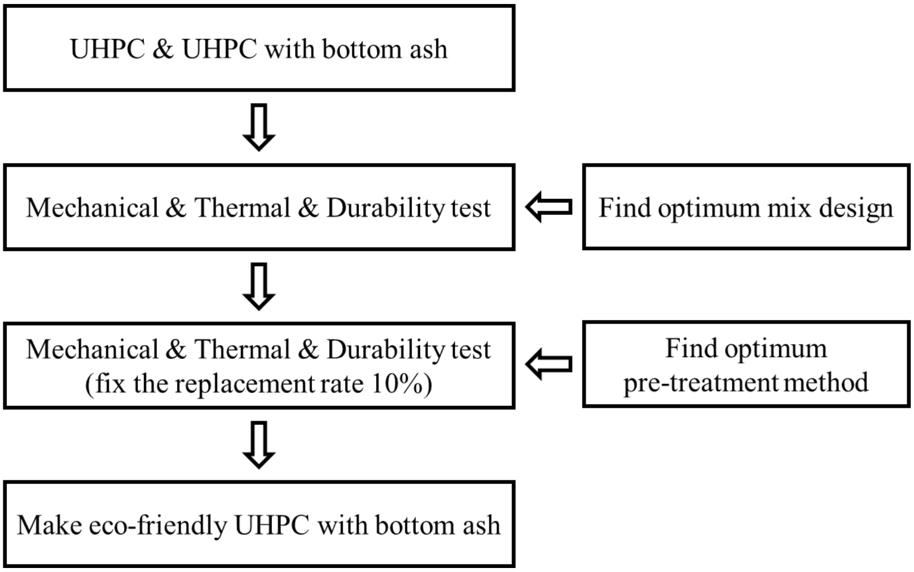


Figure 3-1 Outline of the study

3.2 Pre-treatment Method

3.2.1 Washing(W)

After immersing the bottom ash in water for 72 hours, stir the bottom ash once a day to allow it to be evenly immersed. After 72 hours, it was dried in an electric furnace at 105℃ for 24 hours.

Washing can be used by removing Al by the chemical reaction below by increasing the pH concentration of water.

$$Al + 2OH^{-} \rightarrow [AlO(OH)_2]^{-} + H_2$$

$$[AlO(OH)_2]^{-} + H_2O \rightarrow Al(OH)_3 + OH^{-}$$

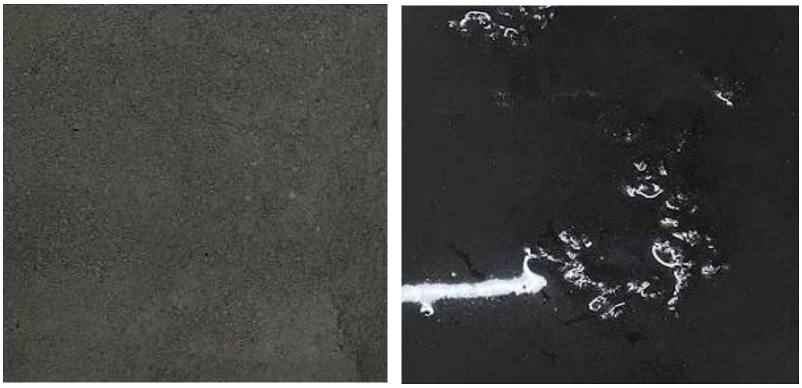


Figure 3-2 Picture of bottom ash (before and after washing)

3.2.2 Heat(H)

It is a method of firing the raw bottom ash at a high temperature in an electric furnace, and the target temperature was set to 700℃ and the temperature increase time was set to 6 hours. Through this process, unnecessary organic matters in the bottom ash is removed.

Figure 3-3 Bottom ash (before heat and after heat)

3.2.3 Chemical treatment (Saturated in Na_2CO_3, C)

In the same way as the washing method, soak raw bottom ash in 0.25M Na_2CO_3 solution for 72 hours, and stir the bottom ash immersed in the solution once a day to soak it evenly. After 72 hours, it was washed minimum three times in distributed water, dried in an electric furnace at 105°C for 24 hours, and used.

Al is removed by increasing the pH concentration in the same mechanism as washing, and Na_2CO_3 reacts with $CaSO_4$ in bottom ash and sulfate in Na_2SO_4 can be removed as shown in the following formula.

$$Na_2CO_3 + CaSO_4 \rightarrow Na_2SO_4 + CaCO_3$$

Figure 3-4 bottom ash (before and after chemical treatment)

3.3 Mechanical Properties

3.3.1 Flowability

Flow test was conducted in accordance with ASTM C1856/1856M.

The mold of flow table is 70mm diameter of top, 100mm diameter of bottom and 50mm height. After pouring UHPC in the mold, lifting it immediately. After pouring UHPC according to the test method of UHPC, flow table was used without bouncing.

The results of the flow test used the average of the width and length.

Figure 3-5 Flow table

3.3.2 Compressive strength

For the compressive strength test, six $50 \times 50 \times 50$mm cube specimens manufactured according to ASTM C1856/1856M were measured for compressive strength according to ASTM C39/C39M and the average value was used. Specimen were measured normal curing, heat curing, respectively.

The experiment was measured by placing the specimen in the center of the universal test machine (UTM) device plate and applying a vertical load. The initial load was set to be 1000kN and the load speed was set to be 1mm per minute at the displacement speed.

Figure 3-6 Compressive strength test

3.3.3 Flexural strength

The Flexural strength test was conducted using six $40 \times 40 \times 160$mm specimens manufactured in accordance with ASTM C1856/1856M. In the experiment, the flexural strength was measured according to C1609/C1609M, and the average value was used. The strength was measured at heat curing, normal curing, in the same way as the compressive strength test.

The experimental method is similar to the compressive strength experimental method, but the experiment was conducted by setting the load speed to be 1.5mm displacement per minute based on the displacement speed.

Flexural strength is calculated by the following equation.

$$\sigma = \frac{3FL}{2bd^2} \qquad (3.1)$$

$\sigma = Flexural\ \ strength$

$F = load$

$L = length\ \ of\ \ specimen$

$b = width\ \ of\ \ specimen$

$d = thick\ \ of\ \ specimen$

Figure 3-7 Flexural strength test

3.4 Thermal Properties

3.4.1 Thermal conductivity

The thermal conductivity experiment is an experiment that measures the thermal conductivity of concrete, and the energy performance of concrete can be determined through the experimental results.

The thermal conductivity test method is as follows.

In the thermal conductivity experiment, the specimen after curing was cut in half, and then washed in alcohol for 10 seconds. After cutting and installing the sensor to contact the flat surface, the sensor was fixed. The thermal conductivity was measured by applying heat of 350mW to each specimen for 40 seconds.

As for the measurement value of thermal conductivity, three specimens were produced for each variable and their average value was used.

Figure 3-8 Thermal conductivity test

3.5 Durability

An experiment was conducted to confirm the durability change according to each replacement rate and pre-treatment method of bottom ash used in UHPC.

3.5.1 Water absorption test

The water absorption test is the most basic method for checking the durability of concrete, and it is an experiment to check the voids in the concrete through weight change after immersing the concrete in water. The method of the experiment is to first measure the weight of the specimen, which has been cured at heat curing and normal curing, dried in an oven at 105℃ for 24hours and cooled to 20℃ in accordance with KS F 2518. After the measurement is completed, distilled water and specimens are put in a sealed plastic container and immersed at room temperature for 48hours. After 48hours, wipe the outside of the specimen lightly with a wiper, measure its weight, and set the ratio as the absorption rate compared to the first weight measured.

The equation for determining the result value of the absorption rate experiment is as follows.

$$Water\ \ absorption\ \ rate\,(\%) = \frac{A-B}{B} \times 100 \qquad (3.2)$$

$A = Water\ \ saturated\ \ mass$

$B = Oven\ \ dried\ \ mass$

(a) (b)

Figure 3-9 Water absorption test:

(a) drying specimens, (b) immersing specimens into distilled water

3.5.2 Rapid chloride migration test (RCMT)

The chloride migration test is a method to check the degrees of migration of chloride in concrete through a migration coefficient, and it can be known whether the pretreatment was sufficiently performed by verifying the chloride migration rate through experiments.

The experiment was conducted in accordance with NT BUILD 492. First, a cylindrical specimen with a diameter of 100mm and a height of 50mm is produced and cured. The curing method applies both heat curing and normal curing as in cube specimens. After curing, the specimen is immersed in a $Ca(OH)_2$ saturated solution at room temperature for 20hours, then immersed in a $NaCl$ solution with a concentration of 2N, and the upper part of the specimen is charged with a concentration of 0.3M for 6 to 96hours. Finally, take out the specimen and cut it, sprinkle silver nitrate solution with a concentration of 0.1M on the surface and leave it at room temperature for 10 minutes. Then, as shown in Figure 3-10, the length of the surface color change is measured, and the average value is substituted into the following equation to obtain the coefficient.

The chloride migration coefficient obtained through the equation determined the resistance according to the classification in Table 3-1.

$$D_{nssm} = \frac{0.0239(273+T)}{(U-2)t} \times (x_d - 0.0238)\sqrt{\frac{(273+T)Lx_d}{U-2}} \qquad (3.3)$$

$$D_{nssm}(\times 10^{-12}\, m^2/s) = non-steady-state\ coefficient$$

$$U(V) = average\ \ value\ of\ the\ applied\ voltage$$

$$T(^\circ C) = average\ value\ of\ \ the\ initial\ and\ \ final\ temperature\ in\ the\ anolyte\ solution$$

$$L(mm) = thickness\ of\ \ the\ specimen$$

$$x_d(mm) = average\ value\ of\ \ the\ \ penetration\ depths$$

$$t(hour) = test\ duration$$

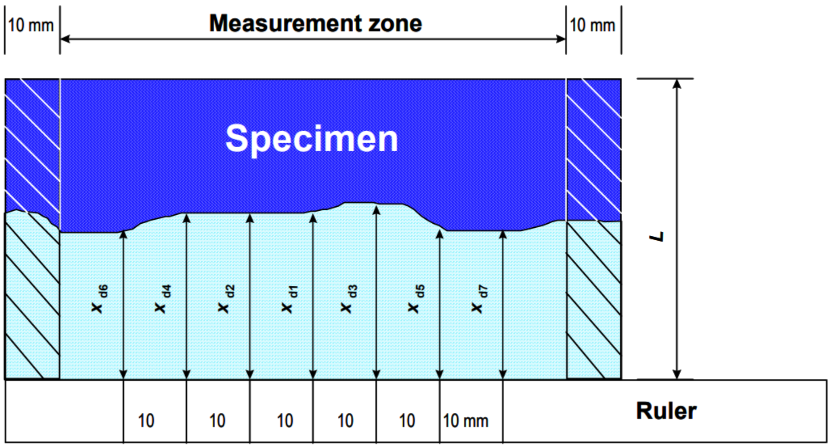
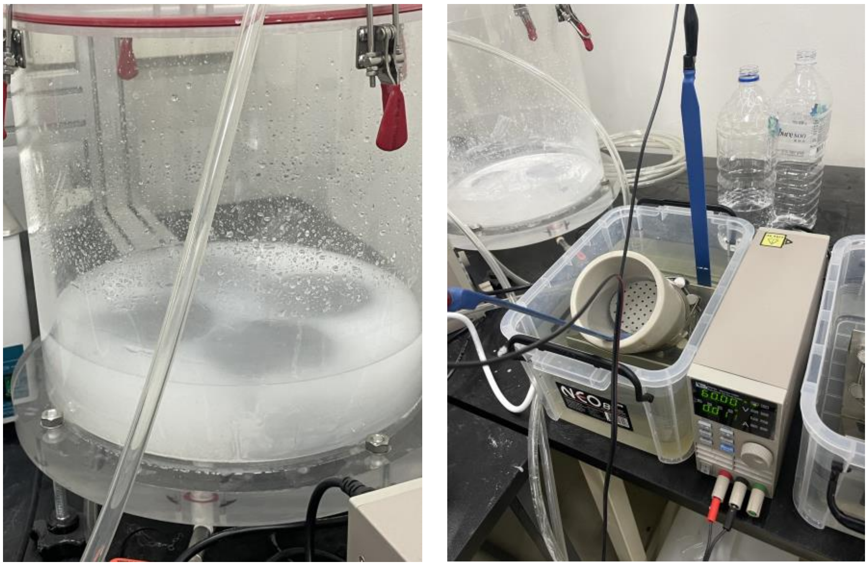


Figure 3-10 Measurement for chloride migration depths



(a) (b)

Figure 3-11 Rapid Chloride Migration Test (RCMT): (a) immersing specimens into $Ca(OH)_2$ solution, (b) applied voltage to specimens

Table 3-1 Classification of resistance to chloride penetration

Chloride migration coefficient $[D_{nssm}\ (\times 10^{-12}\ m^2/s)]$	Classification of resistance to chloride penetration
< 15	Low
10 - 15	Moderate
5 - 10	High
2.5 - 5	Very high
< 2.5	Extremely high

3.6 X-ray Diffraction (XRD)

XRD analysis is an experiment performed for quantitative analysis of crystalline materials, and in this experiment, it was conducted to confirm chemical changes in bottom ash that were pretreated by different methods through qualitative analysis rather than quantitative analysis.

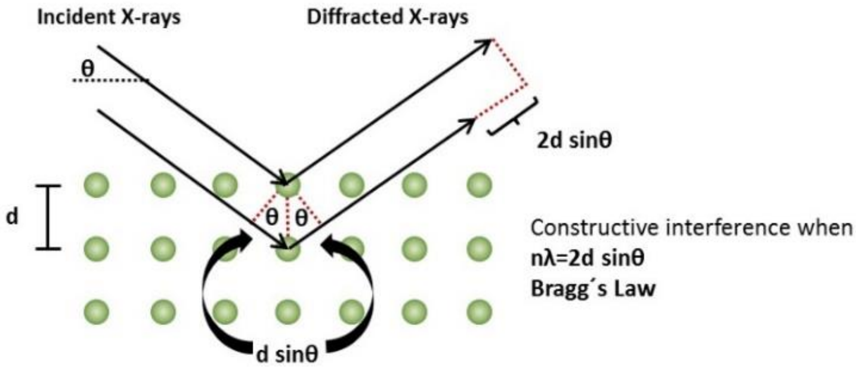


Figure 3-12 Principle of X-ray Diffraction analysis

The principles of XRD analysis are as follows. Crystalline materials have a lattice shape with a constant atomic interval in a crystalline state. In this case, when the x-ray is headed at a constant angle toward the crystal, it is scattered in various directions by atoms in the crystal structure.

At this time, as the wave lengths of the scattered X-rays overlap and interfere with each other, the peak value can be taken by the detector according to Bragg's Law. The XRD spectrum is a graph of peak values according to such a constant incident angle in the form of a spectrum.

The angle of incidence and the intensity of peak at this time are unique characteristics of each material. Therefore, it is possible to identify and analyze the chemical components that make up the substances based on these spectra.

For the experimental method, the sample is finely ground using a mortar for XRD analysis and then filled in the fillet. After putting the sample in the machine, the XRD spectrum can be obtained through an experiment for 1 hour and 40 minutes per sample.

The obtained XRD spectrum was used to identify the chemical components in each bottom ash and compare and analyze the changes.

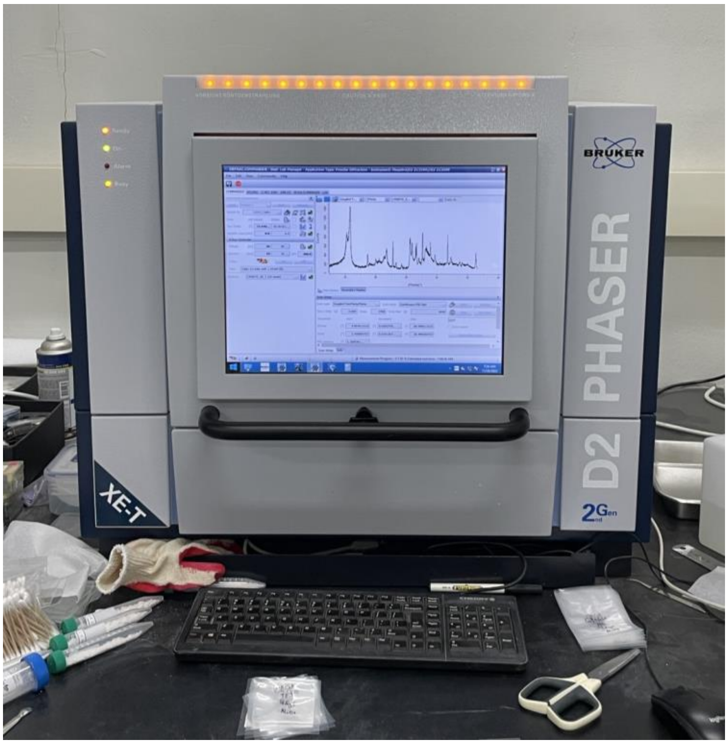


Figure 3-13 Picture of X-ray diffraction machine

Chapter 4. Effects of Bottom Ash on UHPC

4.1 Introduction

Chapter 4 confirms the properties of concrete when the fine aggregate of UHPC is replaced with raw bottom ash, and compares and analyzes the performance difference with reference UHPC.

At this time, as the replacement rate of the bottom ash increases, the mechanical performance and thermal conductivity decrease, and the durability also decreases overall.

The more bottom ash is used, the lower the performance of UHPC, but it is economically beneficial for the environment because it recycles bottom ash, which is discarded as an industrial by-product.

4.2 Mix Design

The mix design used in the experiment for raw bottom ash is the same mix design that of for UHPC as shown in Table 4-1. It is a mixture table prepared based on weight, and bottom ash was replaced with 10%, 25%, and 50% of the weight of silica sand. This is a mix design table based on weight, and blending was performed under the same conditions without variables other than the pre-treatment method of bottom ash.

Table 4-1 Mix design of reference UHPC and UHPC with bottom ash

	Binder		Quartz powder	Silica sand	Bottom ash	Water (w/b)	SP (Superplasticizer)
	Cement	Silica fume					
Ref	1	0.25	0.35	1.1	0	0.22	0.04
BA-10%				0.99	0.11		
BA-25%				0.825	0.275		
BA-50%				0.55	0.55		
W_10%				0.99	0.11		
H_10%							
WH_10%							
WHC_10%							

First, improve the silica fume and silica sand for 5 min at a low speed, and then improve cement and quartz powder in a bowl where quartz powder and cement have been mixed, and mix them again at a low speed for 5 min. Afterwards, remove 1/3 of the premix and add the solution mixed with water and SP at a low speed for 3 min, and add the remaining premix together. After adding it all, mix it once more at a low speed for 1 min, mixed at a medium speed for 1 minute, and finally at a low speed for 1 min.

The placed UHPC is demolded after 24 h, and heat curing is carried out for 90℃ and 50 h during heat curing, and usually curing is carried out for 28 days in an environment that temperature of 20℃ , 60% of humidity.


(a) (b)

(c)

Figure 4-1 Mix design :

(a) mixing machine, (b) temperature and humidity chamber, (c) water bath

4.3 X-ray Diffraction analysis (XRD analysis)

An XRD analysis was used to analyze the chemical composition of the bottom ash applied pre-treatment.

Table 4-2 Chemical compounds of mineral in bottom ash

Mineral	Quartz	Mullite	Hematite	Organic
Chemical compound	SiO_2	$3Al_2O_32SiO_2$	Fe_2O_3	*Pyrazole*

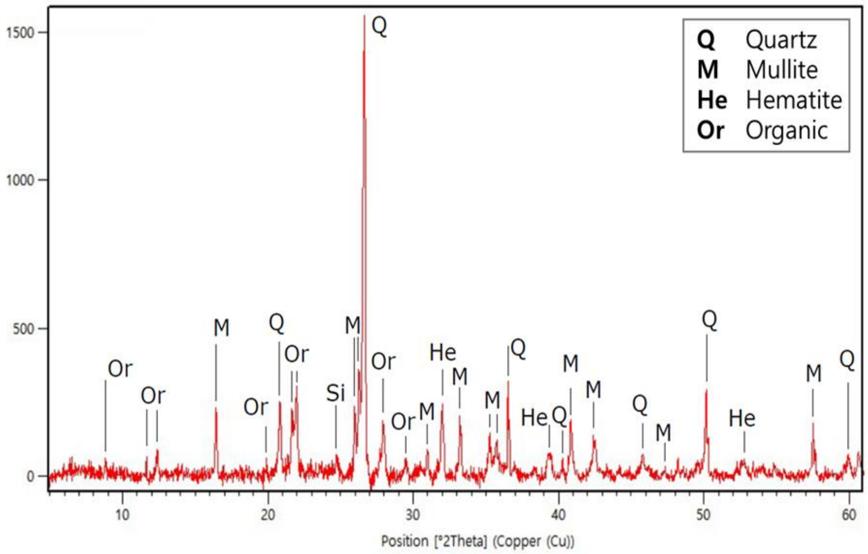


Figure 4-2 XRD spectrum of raw bottom ash

In Figure 4-2, XRD analysis of raw bottom ash shows that most of them are composed of Quartz and Mullite, as well as Hematite and organic compounds such as pyrazole. In particular, Mullite and Hematite are iron components such as Al and Fe, respectively, which reduce the durability of bottom ash and organic compounds reduce the strength of bottom ash, so a process of removing these components is needed.

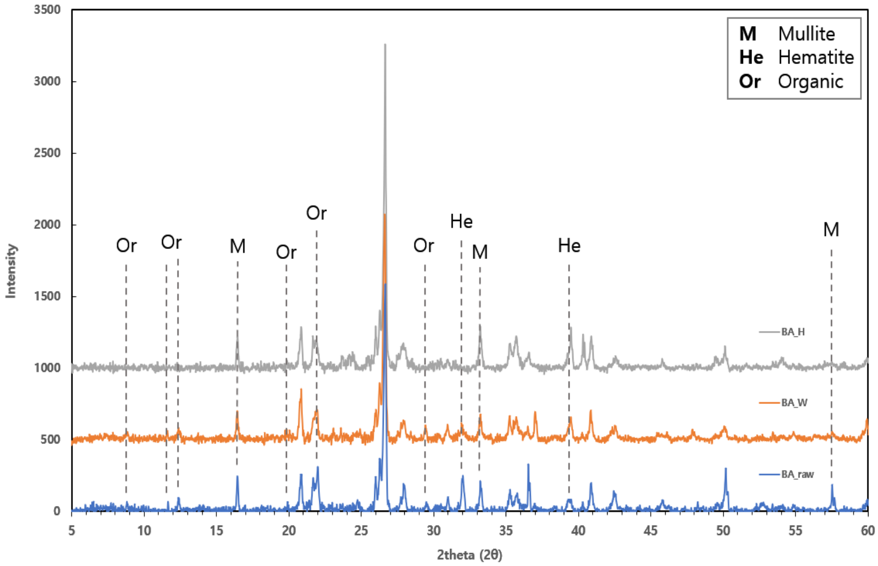


Figure 4-3 XRD spectrum of BA_raw, BA_W, BA_H

In Figure 4-3, when comparing the spectrum of bottom ash after washing only with the XRD spectrum of raw bottom ash, it may be seen that there is little change with respect to the organic compound, and the hematite and mullite peaks increase and decrease.

In the case of heat, compared to the XRD spectrum of raw bottom ash and washing bottom ash, it may be seen that the peak by the organic compound seen in the washing and raw bottom ash disappeared during the heat process and the metal component increased.

Therefore, it was judged that an additional treatment process was needed to remove the metal component that was increased due to such heat.

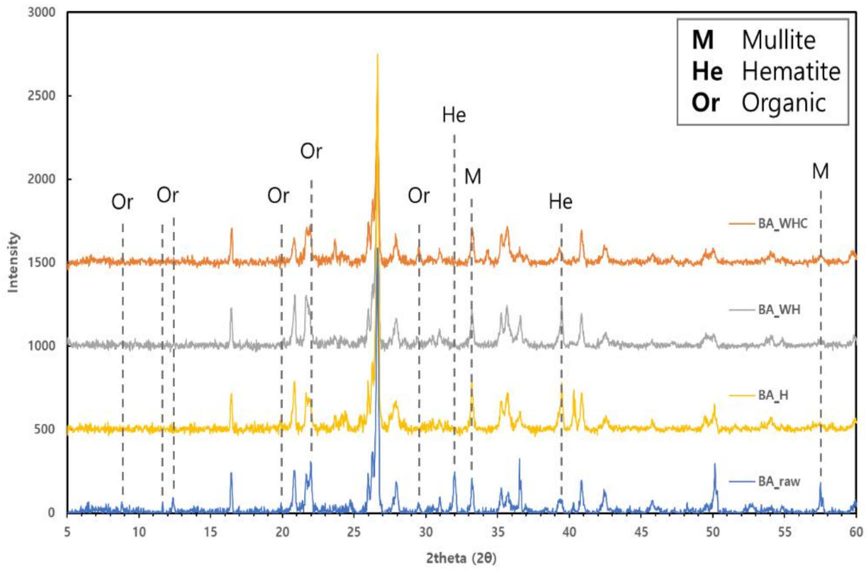


Figure 4-4 XRD spectrum of BA_raw, BA_H, BA_WH, BA_WHC

In Figure 4-4, when washing and heat were treated together, there was no significant difference from the method to which only washing and heat were applied, but many organic compounds were removed in the same way as the heat method, and the hematite peak also increased.

Finally, the method of chemical treatment using heat and sodium carbonate after washing could remove high aluminate and iron components seen after heat, and organic materials were also removed through heat.

In other words, since pretreatment methods using all methods can remove iron components and organic matter, it can be expected that the durability and mechanical properties of concrete will increase when using the pretreated bottom ash.

4.4 Mechanical Properties

4.4.1 Flowability

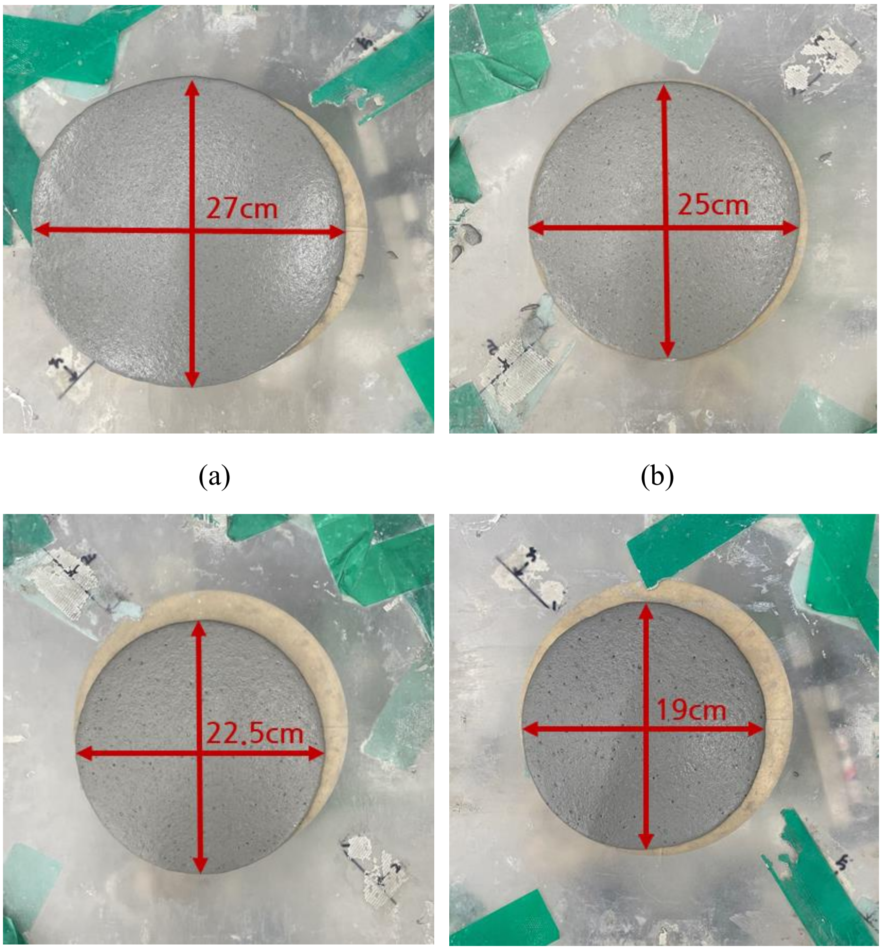
Flow test is conducted by Chapter 3. The results of flow test are shown in Table 4-3 and Figure 4-5.

In the case of UHPC replaced to 10% and 25% of the weight of fine aggregate, the flow length was 20 cm or more, but in the case of 50% of the replacement rate, the flow length was less than 20cm, and compared to the reference UHPC, the length showed a significant flow reduction of 70%.

The flow of UHPC decreases as the replacement rate increases, which shows a lower flow than the existing UHPC because bottom ash, a porous material, has a high absorption rate.

Table 4-3 Flow test result of reference UHPC and UHPC with bottom ash

Sample name	Mean length (cm)	Relative ratio
Reference UHPC	27	1
10% Raw BA	25	0.926
25% Raw BA	22.5	0.833
50% Raw BA	19	0.704



(a) (b)

(c) (d)

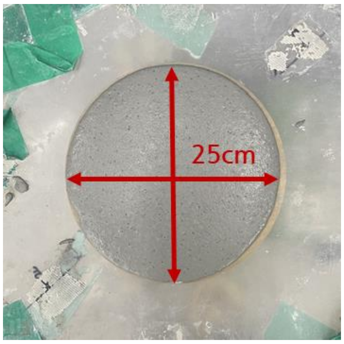
Figure 4-5 Flow test results : (a) Reference flow, (b) Raw_10% flow, (c) Raw_25% flow, (d) Raw_50% flow

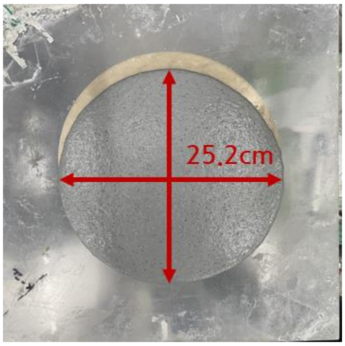
As shown in Table 4-4, The flow difference of UHPC using bottom ash that has applied pretreatment is not significantly different from that of UHPC using raw bottom ash.

There is no difference in the particle size of bottom ash used, and the pre-treatment process does not affect the factors that may affect the flow, such as voids in the bottom ash. That is, it may be determined that the bottom ash that has applied pre-treatment does not affect the flow of UHPC.

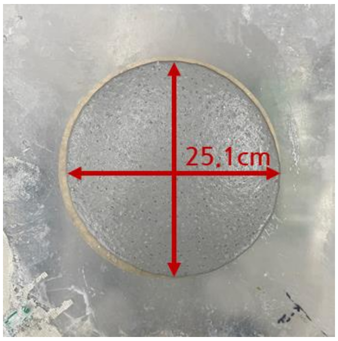
Table 4-4 Flow results of UHPC with raw bottom ash and pre-treatment bottom ash

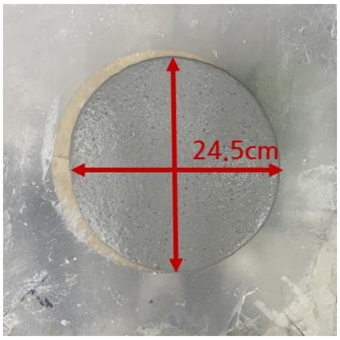
Sample name	Mean length (cm)	Relative ratio
Raw_10	25	1
W_10	25.2	1.008
H_10	25.1	1.004
WH_10	24.5	0.98
WHC_10	25.3	1.012



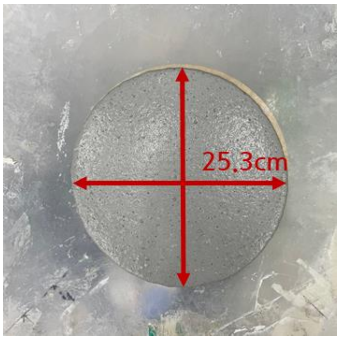


(a) (b)





(c) (d)



(e)

Figure 4-6 Picture of flow test results :

(a) Raw_10% flow, (b) W_10% flow, (c) H_10% flow, (d) WH_10% flow, (e) WHC_10% flow

4.4.2 Compressive strength

The compressive strength test is conducted, as shown in Chapter 3 and the results of compressive strength test are shown in Table 4-5 and Figure 4-7.

As result of heat curing, the replacement rate was up to 25%, 90.9% of the performance of the reference UHPC, and in the case of normal curing, the replacement rate was 82.7% of the reference UHPC. In addition, in the case of the specimen with replacement rate of 50% was only 79.45% of the reference UHPC performance in the case of heat curing, and in the case of normal curing, only 73.7% of the reference UHPC performance was shown.

In other words, as in the flow test results, replacing the bottom ash up to 50% of the fine aggregate does not sufficiently demonstrate the performance of UHPC, so it can be judged that it is inefficient to replace the bottom ash with the silica sand by applying a 50% replacement rate.

The results of the compressive strength show a tendency to decrease as the replacement rate of the bottom ash increases regardless of curing method. This is because bottom ash, which is a porous material, is used instead of fine aggregate, so the porosity in concrete is increased compared to the reference UHPC that uses fine aggregate.

Table 4-5 Compressive strength of reference UHPC and UHPC with raw bottom ash

Sample name	Compressive strength (MPa)		Relative ratio	
	28d curing	Heat curing	28d curing	Heat curing
Reference UHPC	133	166	1	1
10% raw BA	121	158	0.910	0.952
25% raw BA	110	151	0.827	0.909
50% raw BA	98	132	0.737	0.795

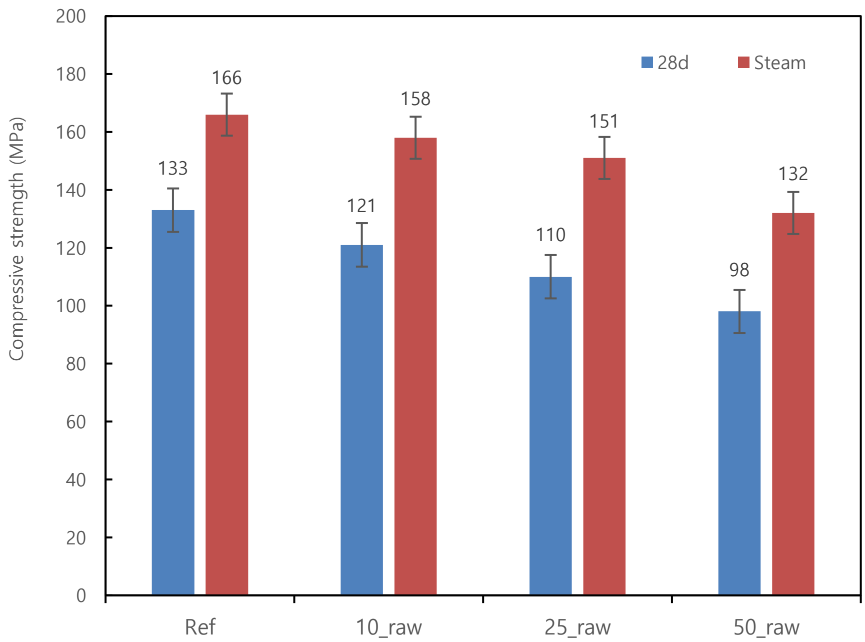


Figure 4-7 Compressive strength of reference UHPC and UHPC with raw bottom ash

The compressive strength results of UHPC using the pre-treatment bottom ash are shown in Table 4-6 and figure 4-8.

As a result of the experiment of UHPC using bottom ash that has only applied washing method and heating method, it tends to increase slightly to about 101.3% and 104.1% compared to UHPC using raw bottom ash in normal curing, and to about 98.7% and 98.3% compared to UHPC using raw bottom ash in heat curing.

However, the results of washing and heat together, the results of the UHPC experiments using bottom ash to which washing, heat and chemical treatment are applied in normal curing and heat curing show that the compressive strength is all higher than that of the UHPC using raw bottom ash.

In other words, when washing and heat are applied to the bottom ash alone, it hardly affects the bottom ash itself as in the analysis results of previous XRD, so the UHPC using the bottom ash is also hardly affected, so the compressive strength seems to have increased or decreased slightly. However, when all pre-treatment methods are applied, organic compounds are removed at high temperature through heating, and metal components in the bottom ash increased due to heat are removed through chemical treatment, thereby improving the performance of the bottom ash and the performance of UHPC.

Table 4-6 Compressive strength results of UHPC with raw bottom ash and pre-treatment bottom ash

Sample name	Compressive strength (MPa)		Relative ratio	
	28d curing	Heat curing	28d curing	Heat curing
Raw_10	121	158	1	1
W_10	122.667	156	1.013	0.987
H_10	126	155.33	1.041	0.983
WH_10	129.5	159.12	1.07	1.007
WHC_10	130.25	163.33	1.076	1.034

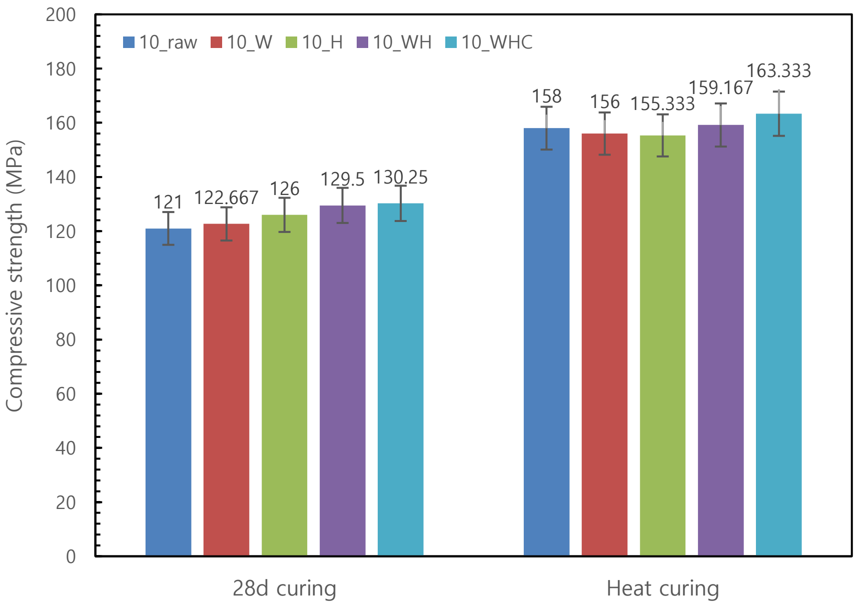


Figure 4-8 Compressive strength results of UHPC with raw bottom ash and pre-treatment bottom ash

4.4.3 Flexural strength

The flexural strength test is conducted by Chapter 3 and the results of flexural strength are shown in Table 4-7 and Figure 4-9.

Compared to the reference UHPC, the heat curing method shows 99% flexural strength of replacement rate 10% and little reduction in flexural strength, while flexural strength of replacement rate 25% and 50% shows only 77.5% and 62.8% performance of the reference UHPC. In addition, as a result of normal curing, the flexural strength of replacement rate 10% UHPC is 94.4%, which is not significantly degraded, but in the case of 25% and 50%, the performance is almost half degraded to 64.4% and 52.7%, respectively. As can be seen from the experiment results, it can also be confirmed that the performance degradation of the flexural strength occurs more than the compressive strength.

Similar to the results of the compressive strength test and the flow test, it was confirmed that the strength of UHPC decreased as the replacement rate of bottom ash increased. This is because the porosity in the UHPC also increases as the amount of bottom ash used increases, and the strength decreases, so the same tendency is shown regardless of the curing method.

When 10% of silica sand is replaced with bottom ash, the performance of UHPC is almost similar to that of reference UHPC, while the performance of UHPC decreases rapidly as it increases to 25% and 50%. Therefore, it is not appropriate to replace silica sand with bottom ash up to 25%, 50%, and it is most appropriate to replace silica sand with 10% rate.

Table 4-7 Flexural strength of reference UHPC and UHPC with raw bottom ash

Sample name	Flexural strength (MPa)		Relative ratio	
	28d curing	Heat curing	28d curing	Heat curing
Reference UHPC	24.438	24.688	1	1
10% raw BA	23.063	24.45	0.944	0.99
25% raw BA	15.75	19.125	0.644	0.775
50% raw BA	12.875	15.5	0.527	0.628

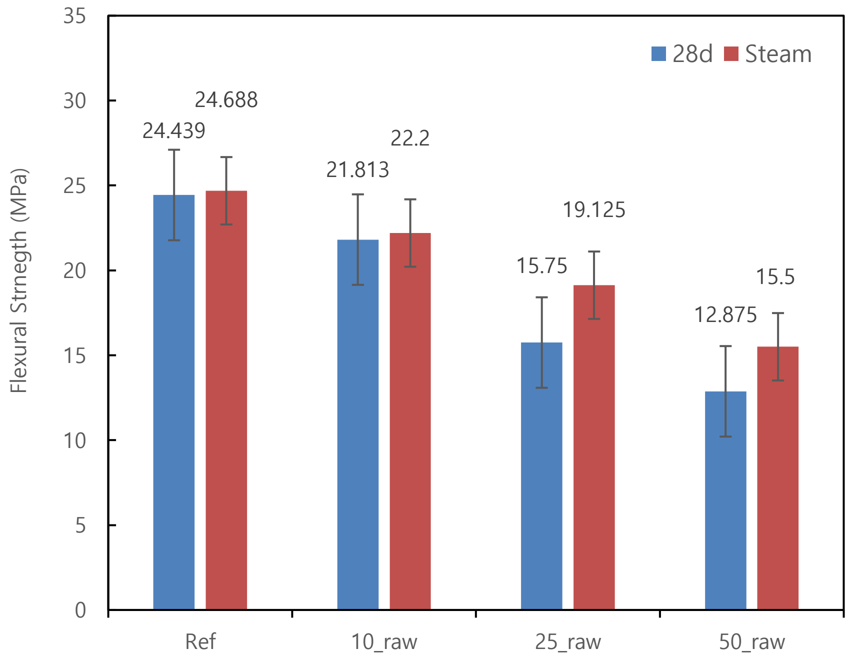


Figure 4-9 Flexural strength of reference UHPC and UHPC with raw bottom ash

The flexural strength results of UHPC using the pre-treatment bottom ash are shown in table 4-8 and figure 4-10.

As a result of the UHPC using bottom ash applied only with washing and heat method, there was a tendency to increase or decrease slightly. In the normal curing, the flexural strength of UHPC using washing bottom ash was slightly increased to 102.6% with respect to the UHPC using raw bottom ash, and the UHPC using bottom ash applied heat method was also increased to 103.1% with respect to the UHPC using raw bottom ash. In heat curing, the UHPC using washing bottom ash increased to 100.9% and the UHPC using bottom ash applied heat method slightly decreased to 98.5%, showing no significant change in flexural strength.

However, when washing and heat method were applied together or the washing, heat and chemical treatment methods were applied, the normal curing method increased by 108.3% and 111.2% compared to the reference UHPC, and the heat curing also increased to 105.4% and 105.9% respectively.

As explained in the results of the compressive strength, strength degradation was minimized by removing organic compounds in the bottom ash through heat, and increased metal components due to the heat method were removed chemical treatment to improve the performance of the bottom ash and then used as a material of UHPC, thereby increasing strength.

Table 4-8 Flexural strength results of UHPC with raw bottom ash and pre-treatment bottom ash

Sample name	Flexural strength (MPa)		Relative ratio	
	28d curing	Heat curing	28d curing	Heat curing
Raw_10	21.813	22.95	1	1
W_10	22.375	23.156	1.026	1.009
H_10	22.5	22.625	1.031	0.985
WH_10	23.625	24.188	1.083	1.054
WHC_10	24.25	24.313	1.112	1.059

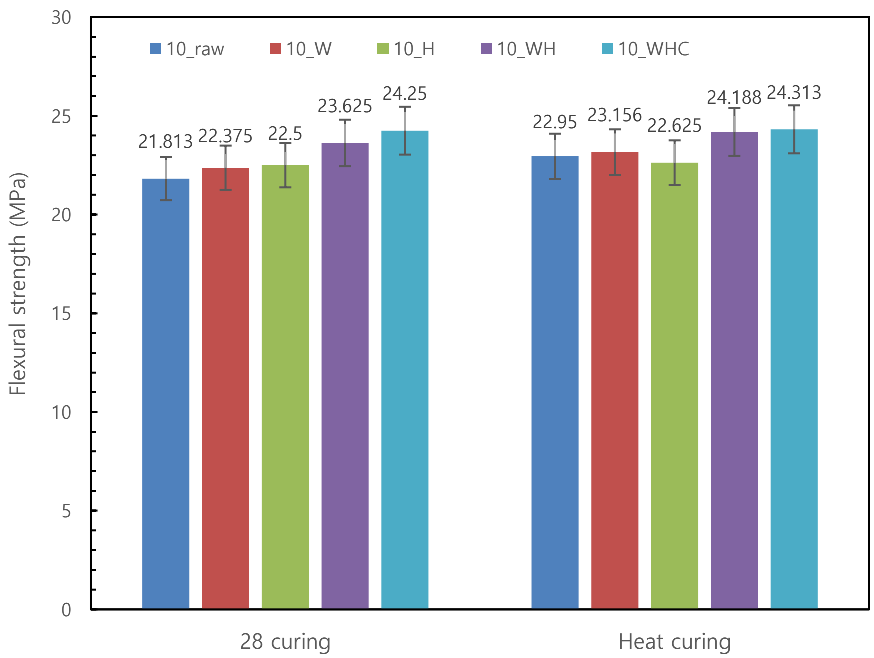


Figure 4-10 Flexural strength results of UHPC with raw bottom ash and pre-treatment bottom ash

4.5 Thermal Properties

4.5.1 Thermal conductivity

The thermal conductivity test is conducted, as shown in Chapter 3 and the results of thermal conductivity test are shown in Table 4-9 and Figure 4-11, 4-12.

In the case of normal curing, the thermal conductivity of replacement 10%, 25%, 50% was 1.814W/mK, 1.447W/mK and 1.144W/mK, respectively, which decreased to 86.6%, 69.1%, and 54.6%, respectively, compared to the thermal conductivity of reference UHPC of 2.095W/mK, and in the case of heat curing, the thermal conductivity of 1.862W/mK, 1.55W/mK, and 1.36W/mK, respectively, which decreased to 87%, 72.6%, and 63.6%, respectively, compared to the thermal conductivity of reference UHPC.

The thermal conductivity measurement results show that the thermal conductivity of UHPC tends to decreases as the amount of bottom ash used increases. In the case of replacement rate 10%, the thermal conductivity both heat curing and normal curing are not much different from reference UHPC, but the thermal conductivity decreases significantly as the replacement rate increases to 25% and 50%. In addition, as can be seen from figure 4-12, when comparing the relationship between the density and thermal conductivity during heat curing, as the amount of bottom ash increases, the porosity of UHPC increases, thereby decreasing the thermal conductivity of UHPC as well.

In this case, since the thermal conductivity is reduced, when UHPC is applied to a building, reactivity of the internal temperature to the external temperature is lowed, thereby saving energy. In other words, it can be seen that the use of bottom ash is eco-friendly and energy-friendly.

Table 4-9 Thermal conductivity results of reference UHPC and UHPC with raw bottom ash

Sample name	Thermal conductivity (W/mK)		Relative ratio	
	28d curing	Heat curing	28d curing	Heat curing
Reference UHPC	2.095	2.1403	1	1
10% raw BA	1.814	1.862	0.866	0.87
25% raw BA	1.447	1.554	0.691	0.726
50% raw BA	1.144	1.362	0.546	0.636

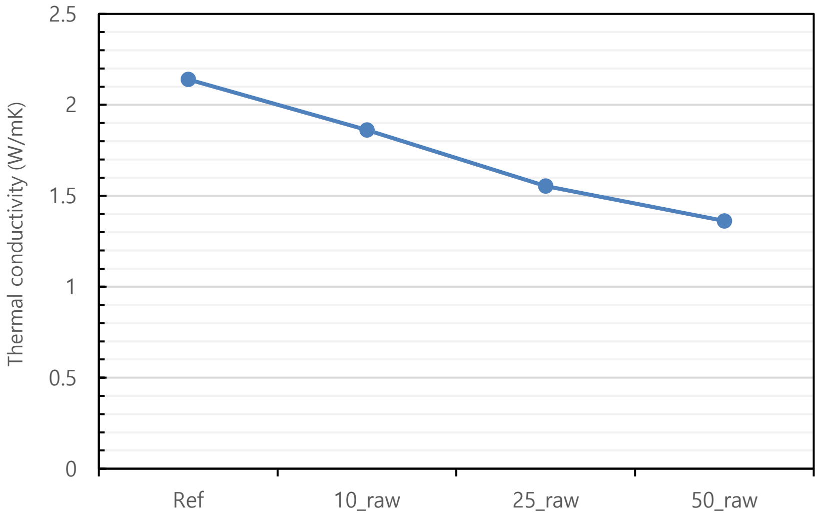


Figure 4-11 Thermal conductivity results of reference UHPC and UHPC with raw bottom ash (Heat curing)

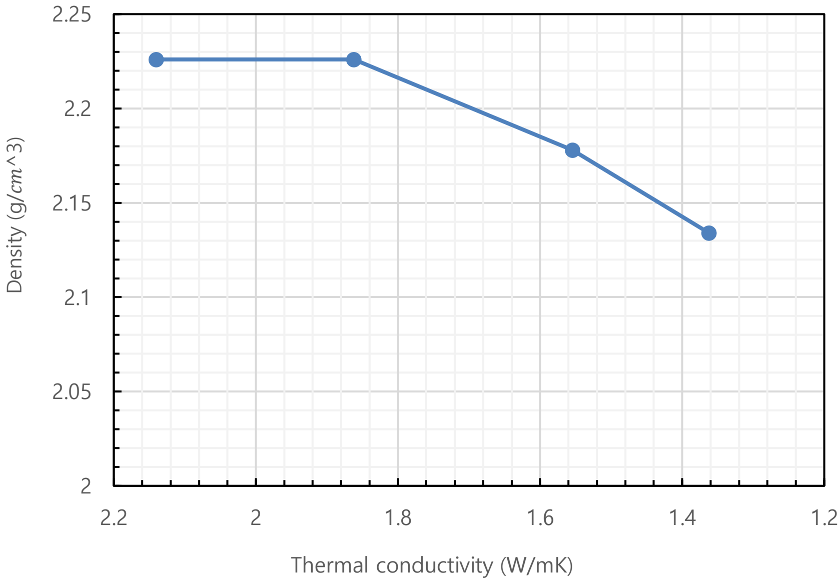


Figure 4-12 Comparing density and thermal conductivity results of reference UHPC and UHPC with raw bottom ash (Heat curing)

The results of thermal conductivity measurement of the UHPC according to the pre-treatment method are shown in tables 4-10, figure 4-13.

As a result of the experiment, normal curing was 98.5%, 99.8%, 99.6%, and 100.5% in the order of washing, heat, heat after washing, chemical treatment after washing and heat, and heat curing was 97.8%, 100.1%, 98.4%, and 100.2%, with a difference of about 5% from thermal conductivity of UHPC using raw bottom ash

This is because the pre-treatment method of bottom ash used in this study does not affect the porosity of bottom ash for the purpose of removing impurities in bottom ash such as organic matter and metal components, and does not affect the thermal conductivity because UHPC using bottom ash that pre-treatment is applied does not change.

Table 4-10 Thermal conductivity results of UHPC with raw bottom ash and pre-treatment bottom ash

Sample name	Thermal conductivity (W/mK)		Relative ratio	
	28d curing	Heat curing	28d curing	Heat curing
Raw_10	1.814	1.862	1	1
W_10	1.787	1.822	0.985	0.978
H_10	1.811	1.863	0.998	1.001
WH_10	1.807	1.832	0.996	0.984
WHN_10	1.824	1.866	1.005	1.002

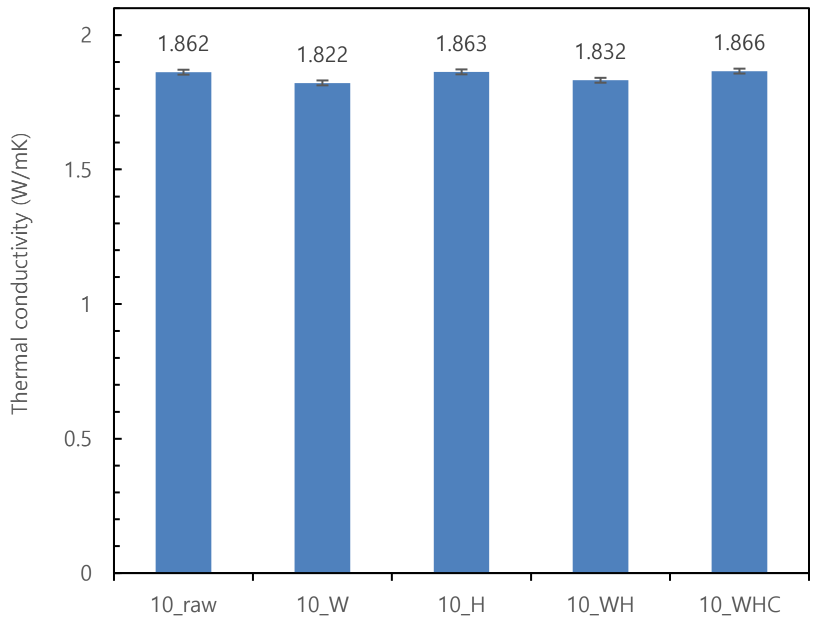


Figure 4-13 Thermal conductivity results of UHPC with raw bottom ash and pre-treatment bottom ash (Heat curing)

4.6 Durability

4.6.1 Water absorption

The water absorption test is conducted, as shown in Chapter 3, and the water absorption test results are shown in table 4-11 and figure 4-14.

Similar to the results of the strength test and the thermal conductivity test, the water absorption rate also tends to increases as the amount of bottom ash used increases. In the case of normal curing, the water absorption rate compared to reference UHPC increases to 102.2%, 225.4%, and 251.1% and in the case of heat curing, the water absorption rate decreases to 96% in replacement rate 10%, as the replacement rate increases, the water absorption rate also increases to 256% and 292%.

It may be seen that when 10% of silica sand is replaced to bottom ash in heat curing, the water absorption rate decreases by about 4%, It can be determined that the durability slightly increased by the pozzolanic reaction of the replaced bottom ash had a more influence on UHPC than the pores increased by the use of bottom ash.

In other words, when manufacturing UHPC by applying heat curing, the durability of UHPC is improved by the pozzolan effect of bottom ash by using a small amount of bottom ash of about 10%, so it is judged that bottom ash can be sufficiently used as a material for UHPC.

Table 4-11 Water absorption test results of reference UHPC and UHPC with raw bottom ash

Sample name	Water absorption (%)		Relative ratio	
	28d curing	Heat curing	28d curing	Heat curing
Reference UHPC	2.968	2.393	1	1
10% raw BA	3.034	2.295	1.022	0.96
25% raw BA	6.691	6.12	2.254	2.56
50% raw BA	7.454	6.984	2.511	2.92

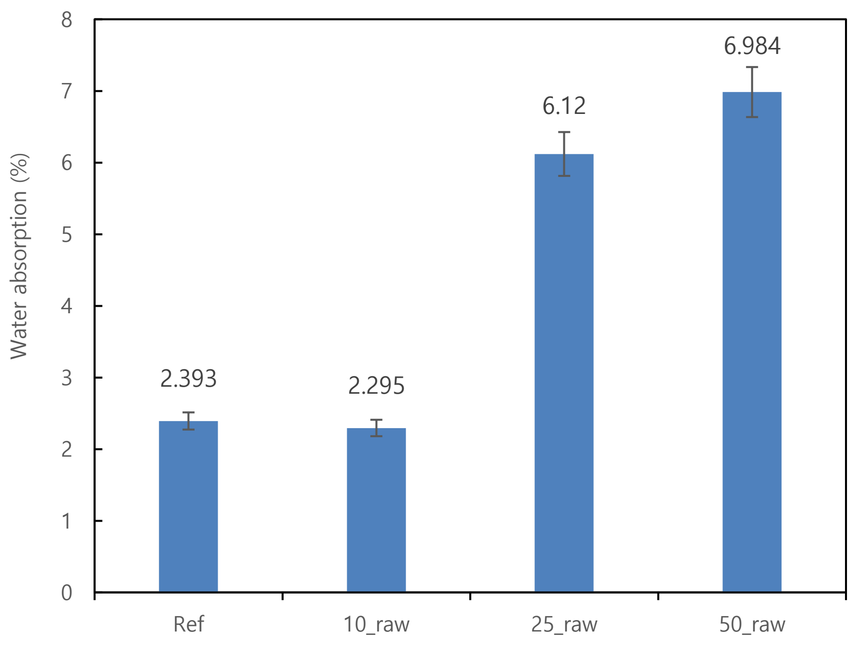


Figure 4-14 Water absorption results of reference UHPC and UHPC with raw bottom ash (Heat curing)

The results of water absorption test of the UHPC according to the pre-treatment method are shown in Table 4-12 and Figure 4-15. As a result of the water absorption measurement, there is no difference in water absorption rate of UHPC with raw bottom ash and UHPC with pre-treatment bottom ash.

In table 4-12, as a result of measuring the water absorption rate of UHPC using bottom ash according to the pre-treatment method, regardless of the curing method, the difference in water absorption rate of UHPC using raw bottom ash and pre-treatment bottom ash was very small as up to 5%, so the pre-treatment method did not affect the water absorption rate.

As mentioned in thermal conductivity test results, this is a method that the pre-treatment method applied in this study aims to improve performance by removing impurities in the bottom ash and does not affect the voids in the bottom ash. Therefore, it can be seen that the pre-treatment method does not affect the water absorption rate because there is no change in the porosity of the bottom ash even if the pre-treatment is applied.

Table 4-12 Water absorption test results of UHPC with raw bottom ash and pre-treatment bottom ash

Sample name	Water absorption rate (%)		Relative ratio	
	28d curing	Heat curing	28d curing	Heat curing
Raw_10	3.034	2.295	1	1
W_10	2.997	2.32	0.987	1.011
H_10	2.851	2.264	0.939	0.986
WH_10	3.125	2.241	1.03	0.976
WHC_10	3.005	2.2	0.991	0.959

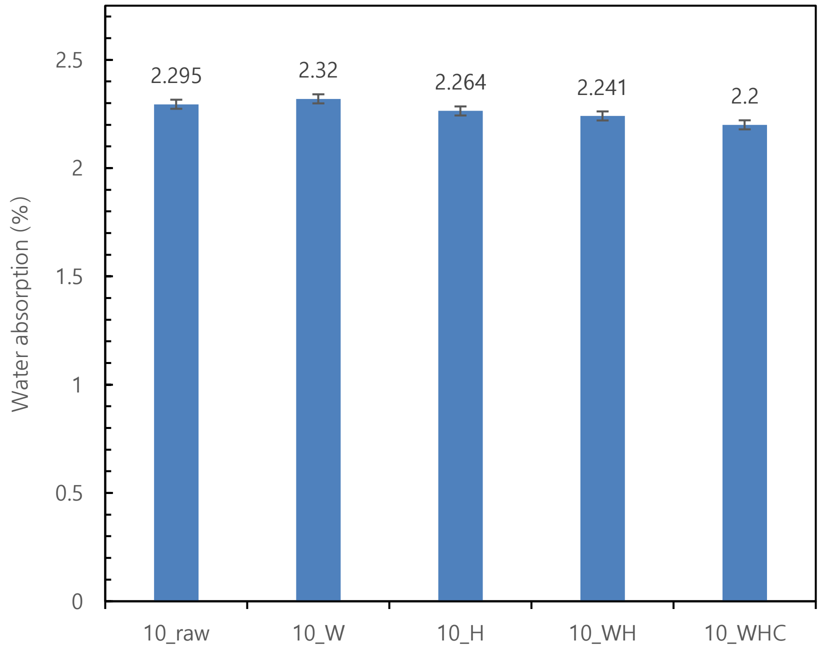


Figure 4-15 Water absorption test results of UHPC with raw bottom ash and pre-treatment bottom ash (Heat curing)

4.6.2 Rapid chloride migration test (RCMT)

RCMT is conducted by Chapter 3 and the results of RCMT are shown in Table 4-13, 4-14 and Figure 4-16, 4-17.

As a result of RCMT, the resistance of chloride was 'extremely high' because the chloride migration coefficient (D) was all less than 2.5, regardless of the curing method, especially when 10% of fine aggregates were replaced. In the case of normal curing, the chloride migration coefficient recorded the smallest value 0.2734 in the replacement rate 10%, and it can be seen that both 25% and 50% replacement rate were lower than the migration coefficient of reference UHPC. In addition, in the case of UHPC with heat curing, 10% of the weight of fine aggregate is replaced with bottom ash, the chloride penetration depth decreases from 1.482mm to 1.19mm, and the chloride migration coefficient decreases from 0.09 to 0.0718, as in normal curing.

It is judged that the chloride migration coefficient and penetration depth decreased as silica in the bottom ash used instead of silica sand reacts with $Ca(OH)_2$ and the pozzolanic reaction in which C-S-H gel is produced makes concrete matrix dense.

Table 4-13 Rapid chloride migration test (RCMT) results of reference UHPC and UHPC with raw bottom ash (Normal curing)

Sample name	Migration coefficient	Average of penetration depth	Classification of resistance to chloride ion
Reference UHPC	0.3954	3.214	Extremely high
10% raw BA	0.2734	4.428	Extremely high
25% raw BA	0.3227	5.2	Extremely high
50% raw BA	0.3438	5.55	Extremely high

Table 4-14 Rapid chloride migration test (RCMT) results of reference UHPC and UHPC with raw bottom ash (Heat curing)

Sample name	Migration coefficient	Average of penetration depth	Classification of resistance to chloride ion
Reference UHPC	0.09	1.482	Extremely high
10% raw BA	0.0733	1.19	Extremely high
25% raw BA	0.1036	1.714	Extremely high
50% raw BA	0.1707	2.8	Extremely high

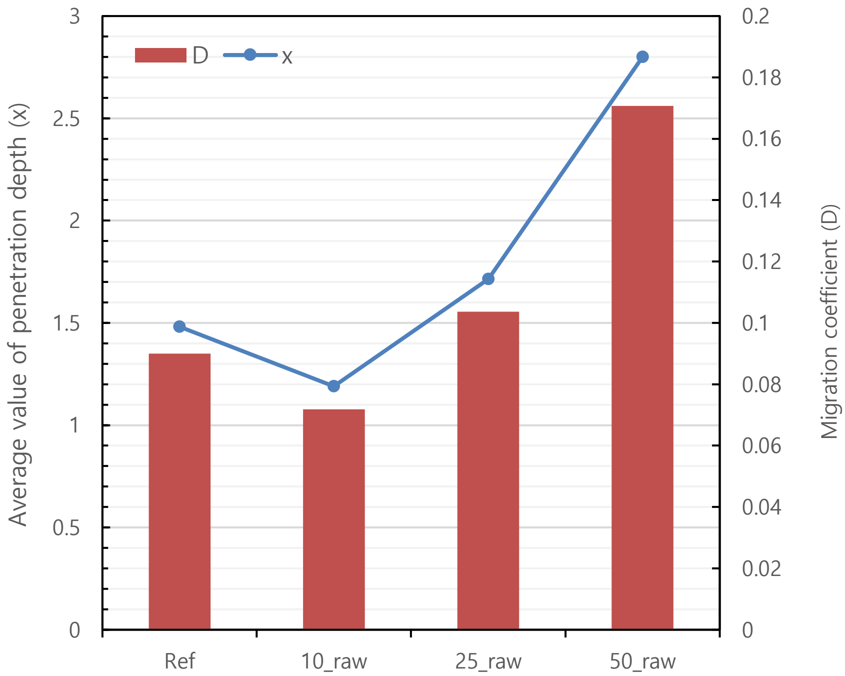
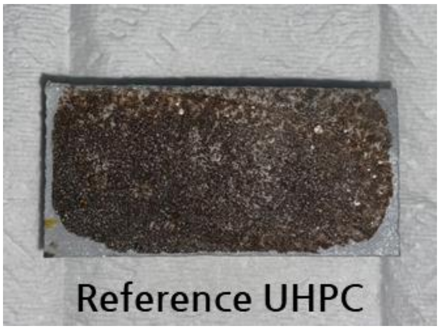


Figure 4-16 4-15 Rapid Chloride Migration Test (RCMT) results of reference UHPC and UHPC with raw bottom ash (Heat curing)



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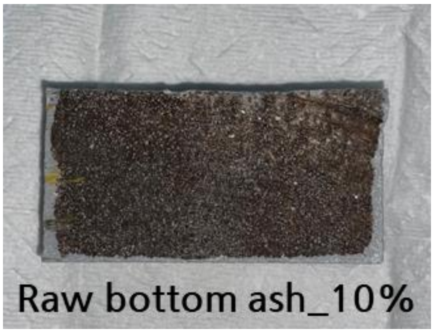
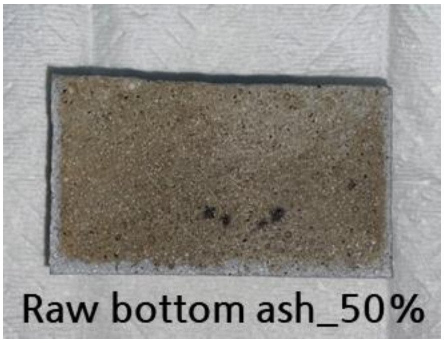


(b)

(c)



(d)

Figure 4-17 RCMT results : (a) Reference UHPC, (b) Raw_10%
(c) Raw _25%, (d) Raw_50% (Heat curing)

The results of RCMT of the UHPC according to the pre-treatment method are shown in Table 4-16, 4-17 and Figure 4-18, 4-19. All the chloride migration coefficient is less than 2.5, which is highly resistant to chloride as all are ‘extremely high’, and the chloride migration coefficient and depth decrease as the pre-treatment process progresses.

In particular, regardless of curing method, the durability of UHPC using bottom ash, which has applied only heat, is particularly poor, and the resistance to chloride of UHPC using bottom ash, which has been washed, heated, and chemical treated in order, is excellent.

This can be explained by comparing the results of the XRD analysis. When only heat method is applied to the bottom ash, the combined aluminum in the bottom ash is decomposed by heat, increasing the metal component in the bottom ash more than before the pre-treatment, and reducing the durability of the bottom ash, so when using bottom ash applied heat method only as a material of UHPC, the chloride resistance of UHPC also decreases.

However, when chemical treatment is performed on heat, metal components that have been increased due to heat can be removed through chemical treatment is performed, chloride resistance becomes stronger than bottom ash that has only applied heat. That is, the durability of UHPC using bottom ash that has applied all pre-treatment processes also increases. It can be judged that the durability of UHPC also increased by increasing the durability of the bottom ash itself by removing a large amount of hematite and mullite through chemical treatment after heat.

Table 4-16 RCMT results of UHPC with raw bottom ash and pre-treatment bottom ash (Normal curing)

Sample name	Migration coefficient	Average of penetration depth	Classification of resistance to chloride ion
Raw_10	0.2734	4.428	Extremely high
W_10	0.1977	3.215	Extremely high
H_10	0.2781	4.5	Extremely high
WH_10	0.1843	3	Extremely high
WHC_10	0.1487	2.428	Extremely high

Table 4-17 RCMT results of UHPC with raw bottom ash and pre-treatment bottom ash (Heat curing)

Sample name	Migration coefficient	Average of penetration depth	Classification of resistance to chloride ion
Raw_10	0.0718	1.19	Extremely high
W_10	0.0699	1.1667	Extremely high
H_10	0.0827	1.375	Extremely high
WH_10	0.0658	1.1	Extremely high
WHC_10	0.0556	0.9333	Extremely high

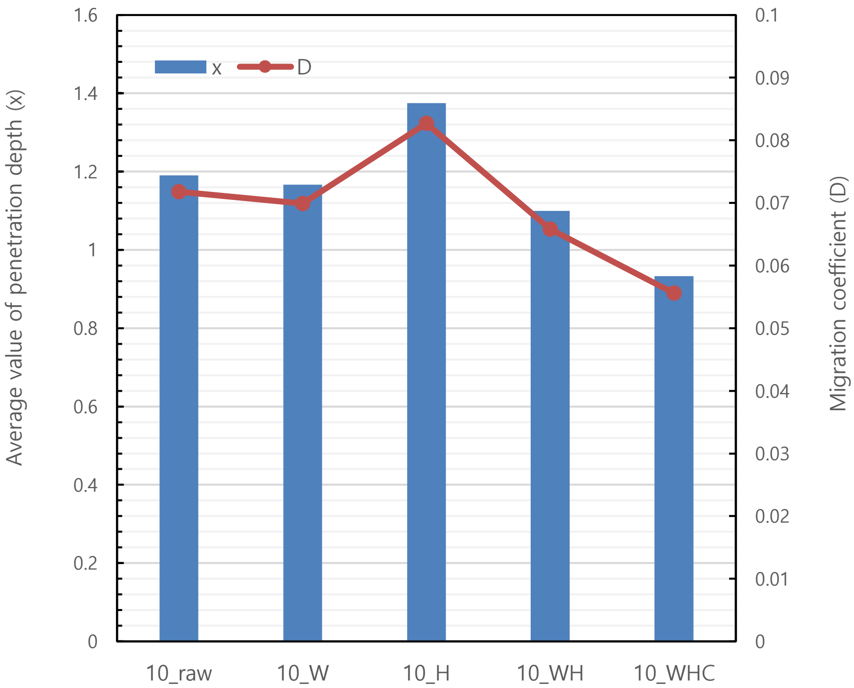
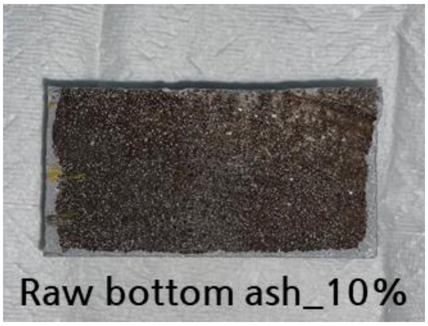
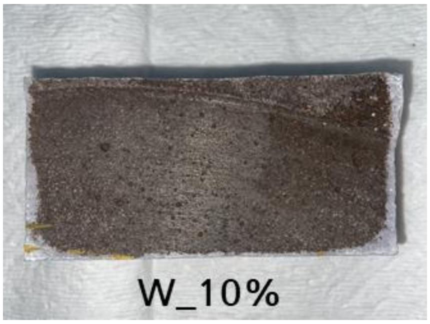


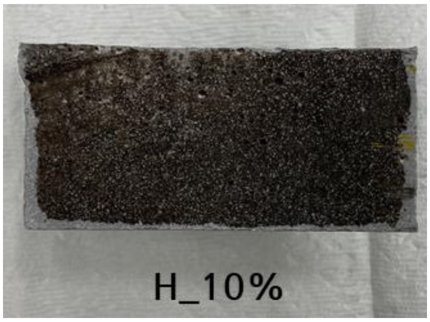
Figure 4-18 RCMT results of UHPC with raw bottom ash and pre-treatment bottom ash (Heat curing)



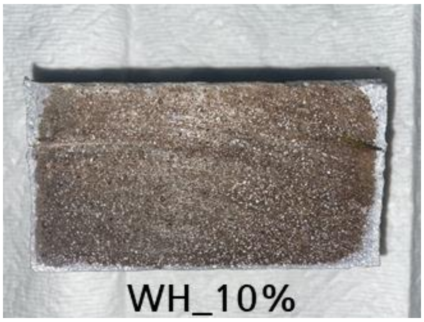
(a)



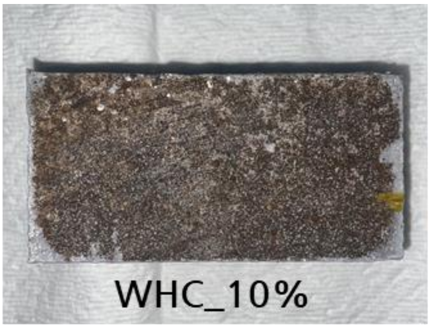
(b)



(c)



(d)



(e)

Figure 4-19 RCMT results (a) Raw_10%, (b) W_10% (c) H_25%, (d) WH_50% (Heat curing), (e) WHC_10%

4.7 Conclusion

This chapter confirmed the results of XRD analysis according to various pre-treatment methods applied to raw bottom ash, mechanical properties, thermal conductivity, and durability. To summarize this,

1. XRD analysis

   - Washing: It has a great advantage in that it can be easily performed, but as a result, there is no significant difference in raw bottom ash and XRD analysis, and there is no particular improvement overall.
   - Heat: Similar to washing, compared to raw bottom ash, there is no particular difference in mechanical, temperature, and durability, and XRD analysis shows that the metal component is higher than raw bottom ash.
   - Heat after washing: In terms of mechanical and durability, the performance of UHPC was improved compared to that of raw bottom ash, but it can be seen that the metal component that damages the durability of concrete is high.
   - Saturated in sodium carbonate after washing and heat: It can be seen that the performance of UHPC is improved in all aspects. It was confirmed that many metal components, which were highly measured in XRD analysis, were also removed through chemical treatment.

2. Mechanical properties

- As the replacement rate of bottom ash increases, the flowability also decreases. When the replacement rate is 10%, 25%, flowability is sufficient because the flowability is not significantly decreased. However, in the case of the replacement rate of 50%, the flow is less than 20cm, so it cannot be considered that the flowability is excellent as UHPC.

- The flow difference between the raw bottom ash and the pre-treatment bottom ash varies within 1cm, and although it tends to increase or decrease subtly, there is no significantly difference. This is because there is no difference in the particle size of bottom ash used, and the pre-treatment process does not affect the factors that may affect the flow, such as voids in the bottom ash. Therefore, the bottom ash that has applied the pre-treatment process has little effect on the flow of UHPC.

- As the replacement rate of bottom ash increases, the compressive strength decreases. In addition, when the specimen is in normal curing, its compressive strength is lower than when the heat curing is applied, and it can be seen that the compressive strength of the reference UHPC as well as the UHPC using bottom ash is also decreased. In heat curing results, the compressive strength of the replacement rate of 25%, 50% was 95% and 90% performance of the reference UHPC respectively, so it was judged that the replacement rate was sufficient as UHPC. But the compressive strength of the replacement rate 50% was only 80% performance of the reference UHPC.

- As the replacement rate of bottom ash increases, the flexural strength decreases. In the case of flexural strength, as the replacement rate of bottom ash increases compared to the compressive strength, the flexural strength decreases rapidly. In 10% replacement rate, both normal and heat curing have 94%, 99% performance, which is almost the same as reference UHPC. But as the replacement rate of bottom ash increases, its performance drops sharply to 70% and 60%.

- The results of compressive strength and flexural strength experiments show slightly difference depending on the pre-treatment method. In particular, the method of applying washing, heat, and chemical treatment together tends to increase slightly compared to when raw bottom ash is used. It was judged that the overall strength of UHPC increased by removing the organic matter in the bottom ash by removing the elements that harm the strength of the bottom ash.

3. Thermal properties

   - As the replacement rate of bottom ash increases, the thermal conductivity decreases. In replacement rate 10%, the thermal conductivity is almost the same as that of reference UHPC, but as the replacement rate increases, the thermal conductivity tends to decrease. When comparing the thermal conductivity and the density, like the thermal conductivity, the density also tends to decrease as the replacement rate of the bottom ash increases. As the amount of bottom ash used increases, as the result of the mechanical properties, it is determined that the porosity in the UHPC increases, thereby decreasing the density and thermal conductivity.

- The thermal conductivity test of UHPC using the bottom ash according to the pre-treatment method showed that the thermal conductivity was almost same, regardless of the pre-treatment method. It is determined that there is no change in the thermal conductivity of UHPC because the pre-treatment method is used as a method to remove impurities in the bottom ash, but the porosity of the bottom ash is not affected.

4. Durability

- As a result of measuring the water absorption rate, the water absorption rate tends to increase as the replacement rate increases with the replacement rate of 25% and 50% excluding the replacement rate of 10%. Like the previous experiment results, it can be judged that the water absorption rate also increased because the porosity of UHPC increased as the amount of bottom ash used increased.
- The water absorption rate of UHPC using bottom ash applied pre-treatment was the same as the result of the thermal conductivity test, and almost the same result regardless of the pre-treatment method. It was determined that the pre-treatment method did not change because the porosity of the bottom ash and UHPC was not affected by the pre-treatment method.
- As a result of RCMT of UHPC using the bottom ash after pre-treatment, the chloride penetration depth and migration coefficient to increase at the replacement rate of 25% and 50%, excluding the replacement rate 10%. In the case of 10% replacement rate, resistance of chloride is considered to have increased because the matrix of UHPC has become dense due to the pozzolanic reaction of using bottom ash, and as the

replacement rate increases to 25% and 50%, resistance to chloride decreases due to increased porosity of UHPC.

- The RCMT measurement of UHPC using bottom ash after the pre-treatment showed that bottom ash with only heat method showed the lowest chloride resistance, and it was confirmed that the bottom ash with all pre-treatment methods had excellent chloride resistance. As can be seen from the XRD analysis results, when only heat method is applied, the metal component inside the bottom ash is decomposed due to heat method, and thus the resistance to chloride is reduced, but when all pre-treatment is applied, the resistance of both the bottom ash and UHPC can be improved by chemical treatment.

That is, when the bottom ash is replaced by fine aggregate in UHPC, as the amount of bottom ash increases, the performance of UHPC also decreases. However, the compressive strength and flexural strength of the bottom ash increased as the pre-treatment was carried out sequentially on the bottom ash, and the performance of the UHPC improved.

Especially, in the case of durability, in the results of water absorption test and RCMT, the water absorption rate and chloride migration coefficient, penetration depth tends to decrease. After that, as the replacement rate to 50%, the results of water absorption test and RCMT also increases. This seems to have increased durability due to the formation of C-S-H gel due to the pozzolanic reaction of bottom ash, and 25% and 50% of the increase in porosity in concrete due to the voids in bottom ash than C-S-H produced by the reaction of bottom ash and $Ca(OH)_2$.

In the case of UHPC using bottom ash that has applied a pre-treatment process, the compressive strength and flexural strength increased as the pre-treatment progressed on another, because, as mentioned above, the performance was improved by removing impurities in the bottom ash.

And the thermal conductivity and water absorption rate showed almost similar results. The pre-treatment methods applied to bottom ash are method to remove the organic matters and metal components in bottom ash, and this is because they do not affect the pores of bottom ash, thus, they do not affect the pores of UHPC.

The RCMT measurement of UHPC using bottom ash without pre-treatment method showed that the chloride migration coefficient and depth of bottom ash after only heating increased significantly, and the penetration coefficient and depth decreased as the pre-treatment process progressed. When only heating is performed, a large amount of metal components is generated in the bottom ash, as can be seen from the XRD analysis results.

Therefore, durability is inevitably reduced, and when bottom ash applied with washing, heating, and chemical treatment is used, the metal components increased due to heating is removed through chemical treatment, so the durability of UHPC increased due to the performance of bottom ash.

Although the performance of UHPC may be degraded due to bottom ash, which is a porous material, if bottom ash is used at about 10%, durability can be expected to be improved due to the pozzolanic reaction of bottom ash, so it was judged that it is appropriate to use bottom ash as an eco-friendly UHPC.

And, it was judged that the overall strength of UHPC increased by removing the organic matter in the bottom ash by removing the elements that harm the strength of the bottom ash through heat, and durability was also improved as a large amount of metal components detected after heat were removed through chemical treatment.

Therefore, it can be seen that the raw bottom ash is used as a concrete material after pre-treatment by using a treatment method that can remove organic matter and metal components without using it as it is, it can exhibit the performance of reference UHPC.

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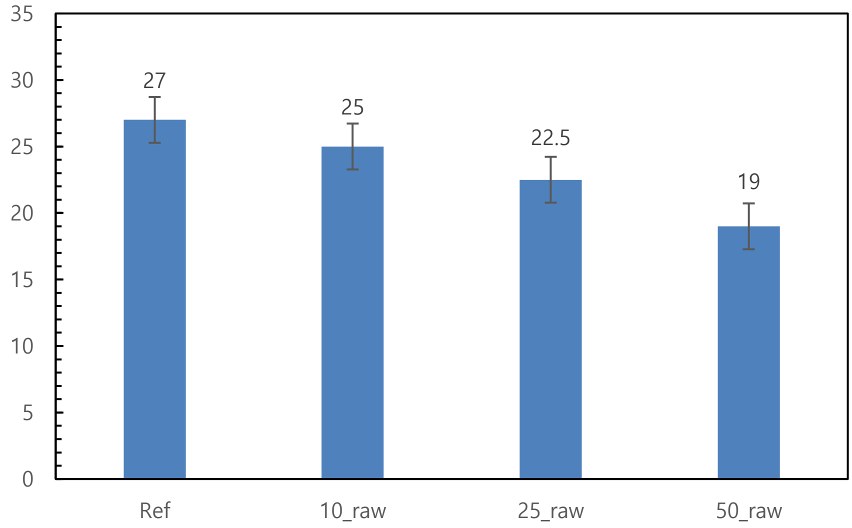
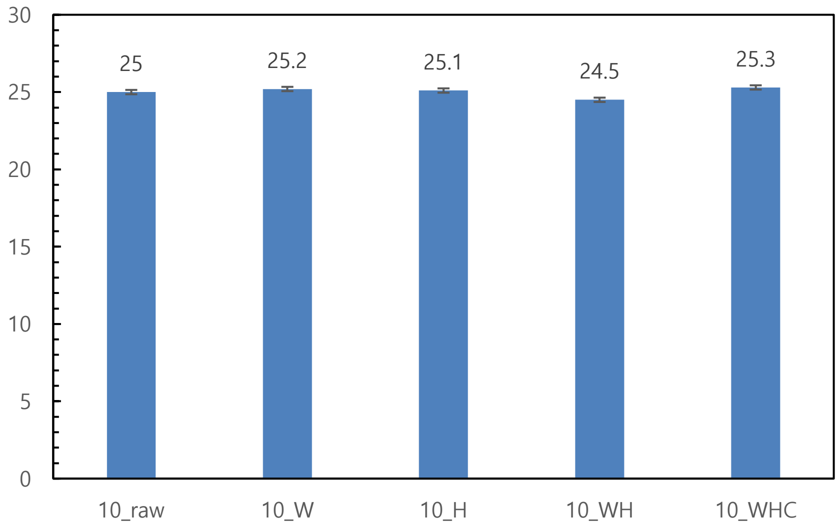
Appendix

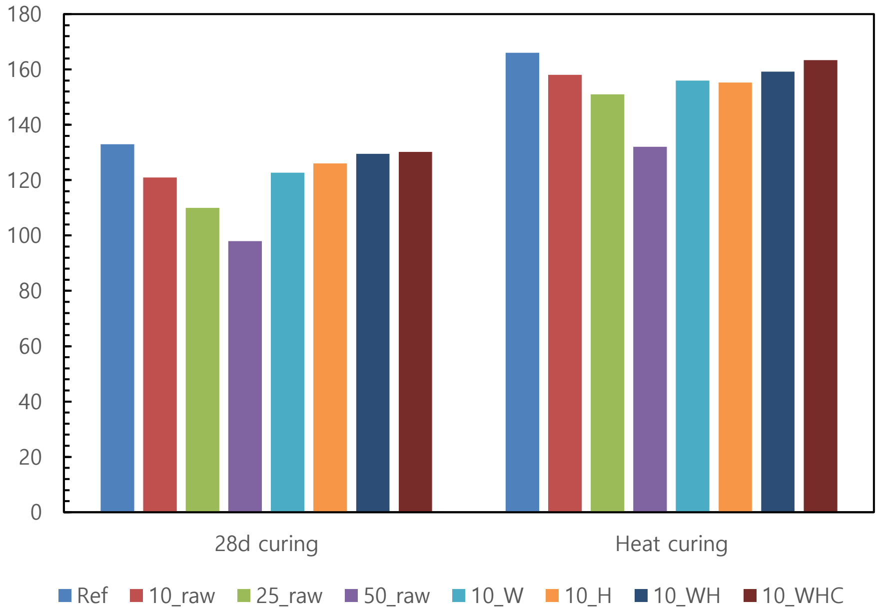
Appendix. A-1 Comparing flow test results of UHPC with raw bottom ash



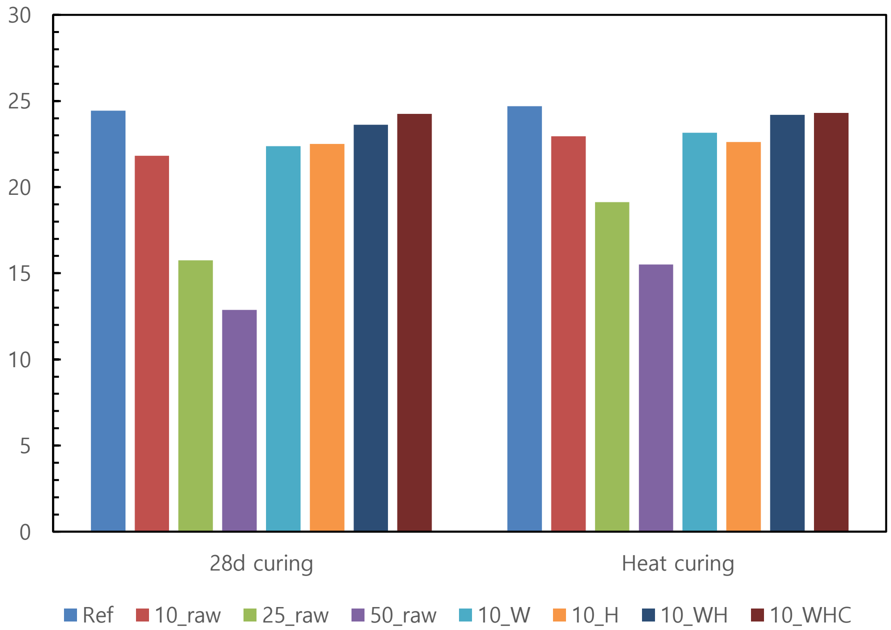
Appendix. A-2 Comparing flow test results of UHPC with pre-treatment bottom ash



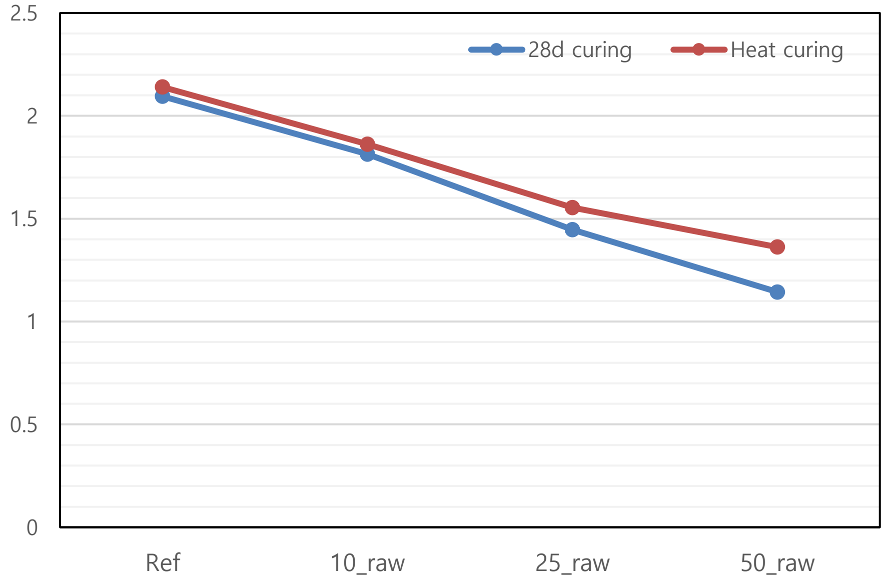
Appendix. A-3 Comparing the compressive strength of all specimens

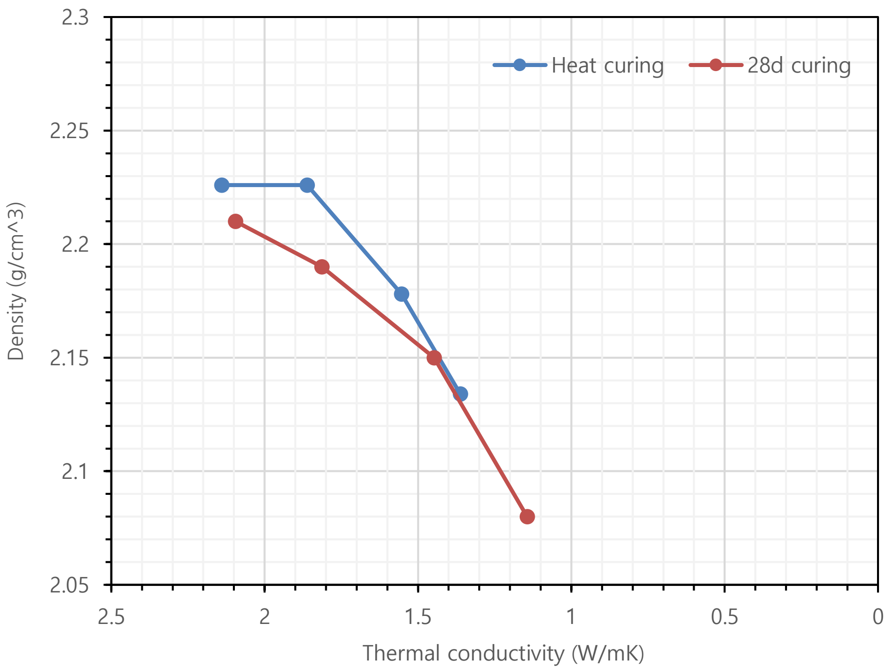


Appendix. A-4 Comparing the flexural strength of all specimens

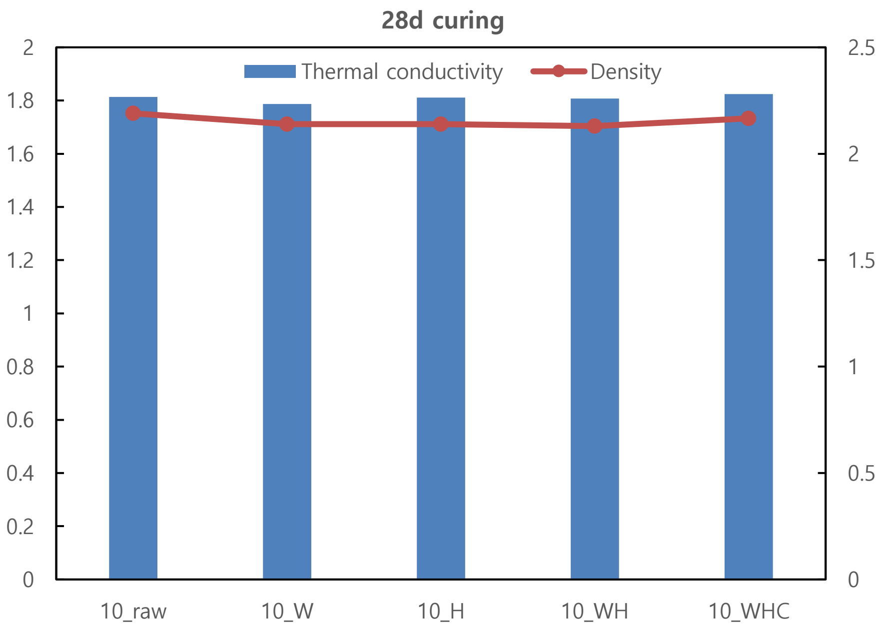


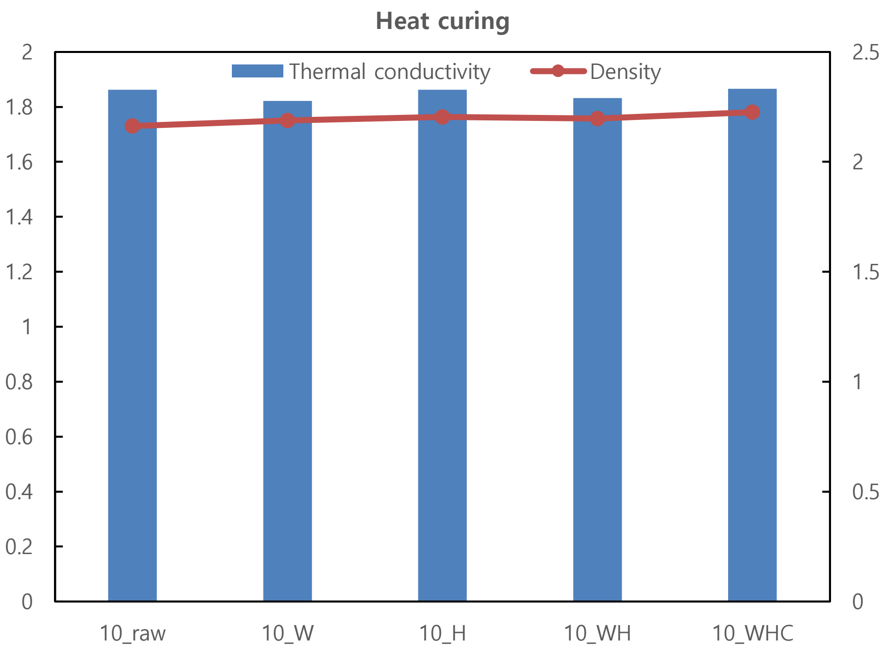
Appendix. A-5 Comparing Thermal conductivity of UHPC with raw bottom ash



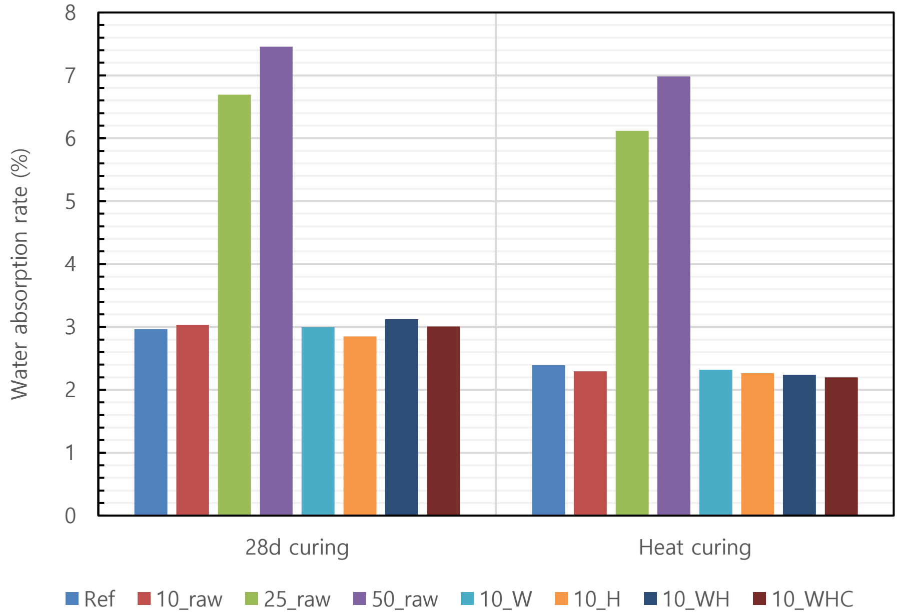


Appendix. A-6 Comparing thermal conductivity of UHPC with pre-treatment bottom ash

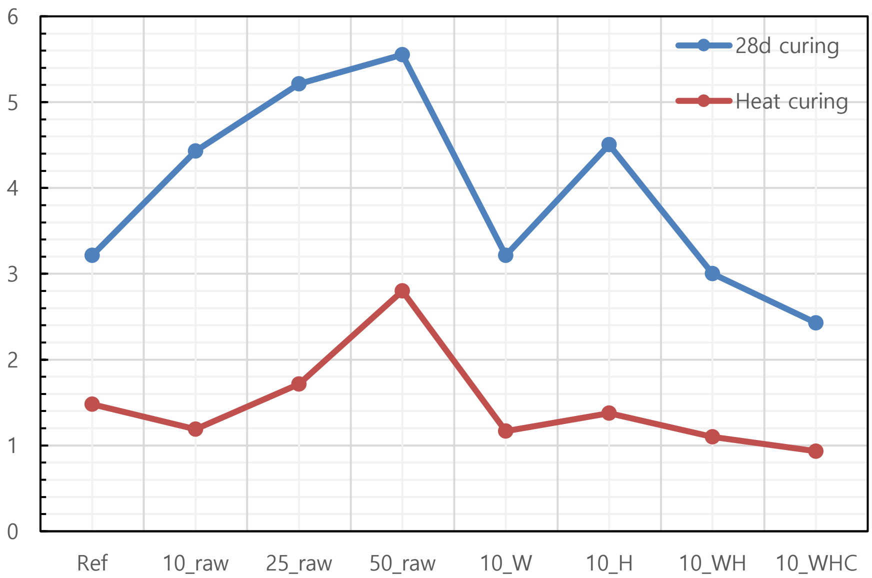




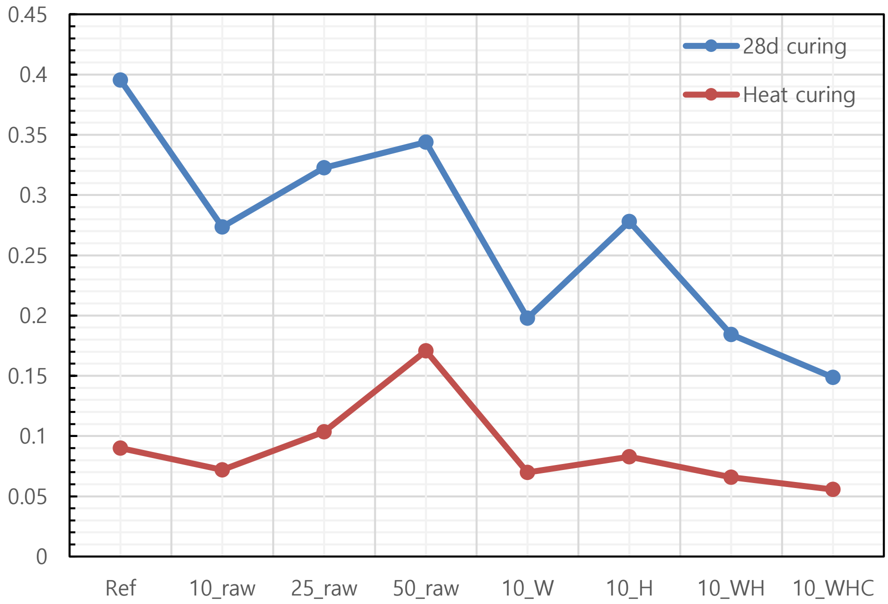
Appendix. A-7 Comparing water absorption rate of all specimens



Appendix. A-8 Comparing chloride penetration depth of all specimens



Appendix. A-9 Comparing chloride migration coefficient of all specimens



초 록

석탄 바닥재를 사용한 친환경 초고성능 콘크리트

최 지 은

서울대학교 건축학과 대학원

Bottom ash는 화력 발전소에서 석탄을 태워 에너지를 생산하는 과정에서 생성되는 재료로 함께 생성되는 fly ash와 달리 사용처가 명확하지 않아 대부분 매립되고 있다. 이런 처리 방식은 환경적으로 많은 문제가 되고 있어, Bottom ash를 건설 재료로 재활용하고자 하는 연구가 활발하게 진행되고 있다. 주로 골재 차원에서 콘크리트 재료로 사용하는 연구가 이루어지고 있지만 bottom ash의 물리적, 화학적 특성 때문에 그 적용에 한계가 있다. bottom ash는 석탄을 태워 생성되는 재료이기 때문에 높은 금속성분으로 인해 화학적으로 안정하지 못하며, 다공성 재료이기 때문에 충분한 물리적 특성을 발휘할 수 없다.

따라서 본 논문에서는 bottom ash를 UHPC의 재료 중 하나인 잔골재로 대체해 사용하고자 한다. 앞서 언급했듯 bottom ash는 다공성 재료이며, 재료 자체의 높은 금속 성분으로 인해 잔골재에

비해 성능이 떨어질 것으로 예상된다. Bottom ash의 특성이 UHPC에 미치는 영향에 대해 알아보기 위해 bottom ash의 골재 치환율 (0%, 10%, 25%, 50%)을 변수로 설정해 배합비를 선정하고 실험을 진행했다. 실험 결과 bottom ash의 치환율이 증가할수록 역학적 성능 및 내구성, 온도적 특성이 모두 감소했으며, 10% 치환 시 일부 내구성이 약간 증가하는 경향을 보였다. 역학적 성능, 내구성 등을 고려했을 때, 잔골재 중량 대비 10%를 치환하는 것이 최적의 배합인 것으로 판단된다.

Bottom ash의 성능을 최대한 발휘할 수 있는 배합인 잔골재 중량 대비 10% 치환의 배합을 바탕으로 bottom ash의 단점인 높은 금속 성분을 해결하기 위해, 세척, 소성, 화학적 처리 등의 전처리 과정을 거친 bottom ash를 사용해 추가로 XRD분석, 역학적 성능 및 내구성, 온도적 특성을 확인했다. 측정 및 평가 결과, 세척, 소성, 화학적 처리방법을 모두 적용한 bottom ash 내의 유기물 및 금속 성분이 다량 제거되어 역학적 성능과 내구성이 raw bottom ash를 사용했을 때보다 증가한 것을 확인할 수 있었다.

따라서 다공성 재료인 bottom ash를 사용할 경우, bottom ash의 사용량이 증가할수록 UHPC의 성능이 저하될 수밖에 없지만, UHPC의 잔골재의 10% 정도를 사용할 경우, bottom ash에 의한 포졸란 효과로 인한 내구성 증대를 기대할 수 있기 때문에 친환경 UHPC의 재료로 bottom ash의 사용이 적절하다고 판단했다.

이에 raw bottom ash에 차례로 전처리 과정을 적용할 경우,

전처리를 통해 bottom ash내의 금속성분 및 유기물이 제거되면서 bottom ash의 성능이 향상된다. 따라서 이런 bottom ash를 UHPC의 재료로 사용할 경우, 그 성능이 reference UHPC와 거의 동일해지며, 특히, 내구성은 reference UHPC보다도 더 뛰어난 것을 확인할 수 있다.

즉, bottom ash를 UHPC의 재료로 사용할 경우, bottom ash를 재활용하고 열전도율을 낮출 수 있다는 점에서 친환경적이며, bottom ash의 포졸란 효과 및 전처리를 통한 bottom ash의 성능 개선으로 UHPC의 성능 저하를 최소화할 수 있기 때문에 친환경 UHPC를 제작하는데 bottom ash의 사용이 적절하다고 판단된다.

Keywords : 초고성능 콘크리트(UHPC), 친환경, 전처리, bottom ash

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