Master`s Thesis of Engineering

Effect of Waste Glass Aggregate on Mechanical and Durability Properties of Ultra High-Performance Concrete

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Abstract

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Waste glass is representing as an environmental problem all over the world. Since a lot of waste glass is buried in the landfill, it causes environmental pollution, and the recycling rate of waste glass has not reached the standard of the mandatory recycling amount. Therefore, as interest in the recycling of waste glass is increasing, the studies on the architectural use of waste glass have been actively progressed in recent years. Typically, waste glass is crushed into powder size to replace cement in concrete or into aggregate size to replace aggregate in concrete. However, in literature studies, the performance change according to the replacement rate of waste glass was not consistent. In addition, the ASR, which is a negative effect due to the waste glass, was not consistent too. While studies on the replacing of waste glass into normal concrete are in progress, only few studies have been progressed on the replacing of waste glass into Ultra High-Performance Concrete.

Therefore, this thesis focused on replacing fine aggregate of Ultra High-Performance Concrete with waste glass aggregate. The performance is evaluated by comparing the silica sand (fine aggregate of UHPC) with waste glass aggregate. Since the waste glass aggregate has a smoother surface than silica sand, slip phenomenon is expected to occur, and performance degradation is concerned. Therefore, the tests were conducted with the replacement rate of waste glass aggregate, which is expected to affect the performance, as a parameter. In addition, the tests were conducted by applying two developments of performance degradation. In conclusion, as the replacement rate of waste glass aggregate increased, the performance of UHPC decreased. However, when considering eco-friendliness and economic, the replacement rate was 10% as the optimal replacing rate (more than 95% of the performance of the UHPC). In addition, it was confirmed that the performance of UHPC, which applied two developments for alleviating performance degradation due to the replacement of waste glass (10%), was improved through mechanical and durability tests.

Keywords: Ultra High-Performance Concrete, Waste Glass Aggregate, Slip, ASR, Surface Modification

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List of Abbreviations

ASR	Alkali-Slica Reacion
C-S-H	Calcium-Silicate-Hydrates
MLIT	Minitry of Land, Infrastructure, Transport, tourism
MWGA	Modiciation Waste Glass Aggregate
OPC	Ordinary Portland Cement
PSD	Particle Size Distribution
SEM	Scanning Electron Microscope
SP	Superplasticizer
UHPC	Ultra High-Performance Concrete
UHPFRC	Ultra High-Performance Fiber-Reinforced Concrete
UTM	Universal Testing Machine
WGA	Waste Glass Aggregate

Chapter 1. Introduction

1.1 Background

1.1.1 Status of recycling of waste glass

Recently, most of the waste glass that cannot be recycled in Korea has been burried, and environmental problems have emerged. This material occupies huge parts of the landfill spaces, due to the causing serious environmental pollutions.

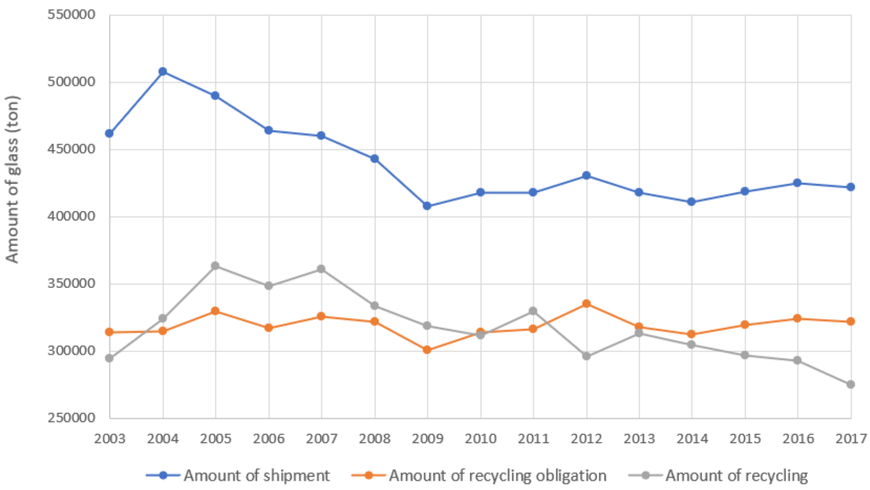


Figure 1-1 Delivery, recycling, and mandatory recycling amount of glass bottles in Korea

In the past five years, the amount of glass bottles in Korea have been shipped and imported about 420,000 tons. The recycling amount is about 308,000 tons. Therefore, the recycling performance rate is 30.8/42 = approximately 73.3 %.

However, the Ministry of Environment`s guideline for recycling waste glass bottles is 76.3 %, higher than recycling performance rate. Figure 1-1 shows that recycling amount is below the amount of recycling obligation [1].

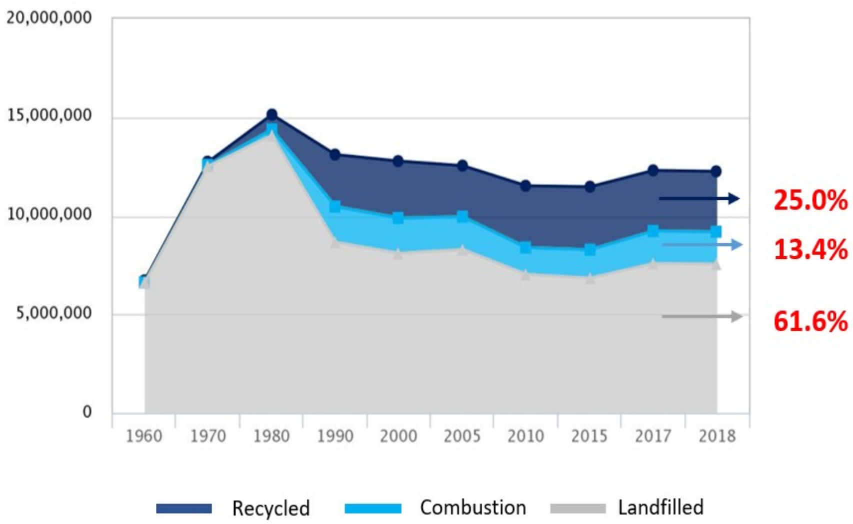


Figure 1-2 Waste glass recycling status of U.S

This problem has been a big issue not only domestically but also globally. The recycling rate of waste glass in the United States is significantly lower at 25 %, although it is gradually increasing. It is also a serious situation because more then 60% of waste glass is buried in landfill. Figure 1-2 shows it [2].

In Japan, the recycling rate of waste glass bottles is gradually increasing to 68.4 % in 2015, 68.9 % in 2018 and 71.6 % in 2019. In Europe Units, the recycling rate of waste glass bottles is also increasing to 73.1 % in 2015 and 74.7 % in 2018 [1]. This trend impies that the world is big interested in recycling waste glass and this problem is serious.

1.1.2 Research trend of concrete for waste glass aggregate

As this problem is getting worse and interest grows, ways to recycling waste glass are emerging. One of them is the architectural use of waste glass [3]. Recently, research has been actively conducted to use waste glass architecturally. It has already completed an analysis on the architectural use of waste glass bottles in Korea.

The Waste Management legislation and the legislation on the Promotion of Saving and Recycling of Resources suggest that aggregate, concrete, ready-mixed concrete, and ascon can be used directly by waste glass and waste glass bottles. Under the Resource Recycling legislation, waste glass is stipulated as civil and building materials in the recycling method and standards of waste glass bottles [4].

Table 1-1 Comparison of major qualities of recycled fine aggregate for concrete [4]

Category	Circulating fine aggregate quality standards		Results of tests	Note
	Recycled aggregate quality standards (MLIT)	Circulating aggregate for concrete (KS F 2573)		
Absolute Drying Density (g/cm^3)	Above 2.3	Above 2.2	2.45	OK
Absorption rate (%)	Below 4.0	Below 5.0	0.86	OK
Particle shape determination performance rate (%)	Above 53	Above 53	59	OK
Amount lost in 0.08mm sieve test (%)	Below 7.0	Below 7.0	2.0	OK

Alkali-Silica Reaction		Harmlessness	Harmlessness	Harmlessness	OK
Stability (%)		Below 10	Below 10	1.4	OK
Impurity rate	Organic impurity (%)	Below 1.0 (Volume)	Below 1.0 (Volume)	0.00	OK
	Inorganic impurity (%)	Below 1.0 (Volume)	Below 1.0 (Volume)	0.00	OK

Table 1-1 also shows that it is suitable for comparing the major qualities of recycled fine aggregate for concrete.

Existing research can be divided into two main parts.

First, it is a study in which waste glass is crushed into powder size and replaced with cement or quartz of concrete.

Second, it is a study that crushs waste glass into aggregate size and replaces it with aggregate of concrete.

These studies show that concrete performance decreases as increasing the replacement rate of waste glass because of surface of glass [5,6,7,8,9,10]. However, some studies show that concrete performance tends to improve if the replacement rate of waste glass is 10~20 % [11,12,13]. Thus, the performance of concrete following the replacement of waste glass is not generalized.

Some studies show that glass components cause harmful chemical reactions to concrete [14]. The reaction is Alkali-Silica Reaction (ASR). ASR is a phenomenon in which alkali components (Na, K) in cement are chemically reacted by alkali reactive silica minerals in water and aggregates, causing local volume expansion in concrete, which causes cracks in concrerte, which reduce the durability of concrete.

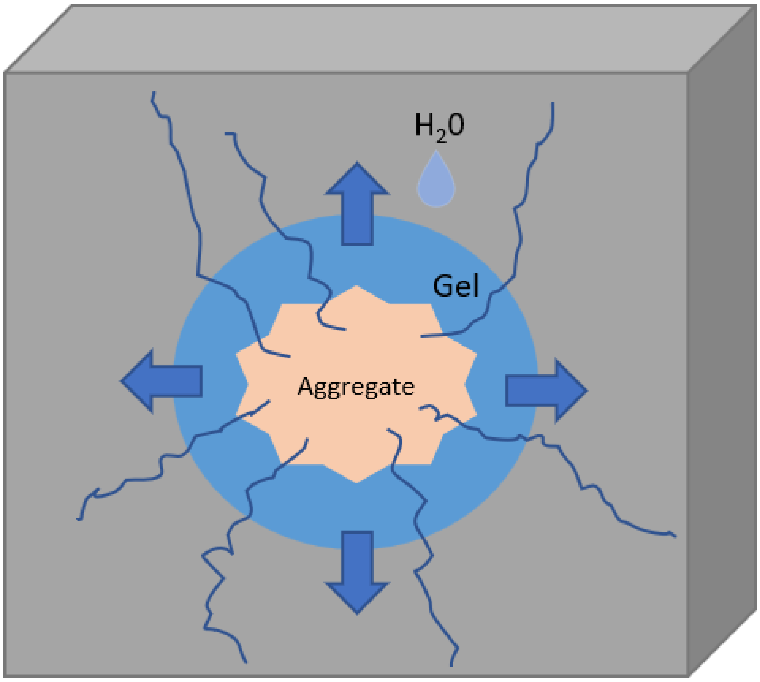


Figure 1-3 Schematic illustration of Alkali-Silica Reaction (ASR)

The ASR chemical equation is

$$SiO_2 \quad + \quad Na_2O \text{ or } K_2O \quad \rightarrow \quad \text{C-S-H}$$

SiO_2 is the main component of glass (above 70 %). Na_2O and K_2O are the alkali components of cement. C-S-H is a gel caused by ASR. C-S-H cause expansion.

The studies show that higher replacement rate of waste glass results in greater ASR responses. This greater ASR response, the greater the expansion. Therefore, the higher replacement rate of waste glass triggers the greater the expansion.

1.2 Scope and Objectives

As the environmental problems of glass are raised and the architectural use of waste glass is increasing, various studies of waste glass are being conducted.

① Replacing aggregate in normal concrete with waste glass aggregate [5,6,7,8,9,10,11,12,13].

② Replacing cement or quartz in normal concrete with waste glass powder [15,16,17].

③ Replacing cement or quartz in Ultra High-Performance Concrete with waste glass powder [18,19].

Literature studies can be divided into the three above specifically.

Therefore, in this study, waste glass crushed into fine aggregate size in Ultra High-Performance Concrete is replaced with silica sand to create new concrete and experiment and analyze the suitability of the concrete. In addition, the suitable replacement rate of waste glass aggregate is calculated because the performance of concrete decreases when the replacement rate of waste glass is increased. Apply the corresponding developments to the experiment and conduct mechanical and durability test.

The ultimate objective is the development of eco-friendly, economical, and new Ultra High-Performance Concrete.

Chapter 2. Preliminary Study

Chapter 2 introduces research cases referenced for writing this thesis and explains the characteristics of main meterials in this thesis and their correlations. Starting with the summary of several representative literature reviews conducted by replacing waste glass with normal concrete, the characteristics of UHPC and glass, which are the main materials in this thesis. And then the comparison of the two main materials is explained.

2.1 Literature review

2.1.1 Waste glass aggregate for Concrete

As described in Chapter 1, research on the architectural application of waste glass of general concrete is in progress. Due to the smooth surface of the waste glass aggregate, the performance of concrete is reduced, and since it is an amorphous silica mineral, it causes harmful expansion by ASR.

However, several studies show opposite results. Some studies describe that the performance of concrete is improved when the replacement rate of waste glass aggregate is 10~20%, but other studies explain that the performance decreases as the replacement rate of waste glass aggregate increases. In addition, some studies explain that the expansion rate due to ASR for waste glass aggregate is suitable for the standard, but other studies explain that it is not suitable. The reason for the improvement of concrete performance is not fully explained, but additional research is needed to generalize it.

2.1.2 Waste glass powder for Concrete

Waste glass powder, like waste glass aggregate, is aslo being actively studied. The chemical composition of glass power is very similar, and the materials could be declared as pozzolanic material. When waste glass is milled down to micro size particles, it is expected to undergo pozzolanic reactions with cement hydrates, forming Calcium Silicate Hydrate (C-S-H).

The fluidity increased as the waste glass powder replacement rate increased to 25%. Compressive strength decreased as the replacement rate increased when the curing period was less than 90 days, but compressive strength increased when the replacement rate was 10~20% over 90 days. It is because, as mentioned above, additional C-S-H was generated due to the beneficial pozzolanic reaction. Therefore, the compressive strength was enhanced.

The concrete made by replacing the cement by 10~20% the waste glass power showed a good effect.

2.1.3 Waste glass powder for UHPC

Waste glass powder is also being actively studied for Ultra High-Performance Concrete. The design of UHPC basically depends on the packing density and particle size distribution (PSD). The PSD of cement creates micro-scale gaps that need to be filled with finer materials such as silica fume. Therefore, the difference from normal concrete is the research on replacing quartz powder and silica fume, which are the main materials in UHPC, not replacing cement with waste glass powder. The pozzolanic reaction also gives positive effect on mechanical and microstructural poperties of UHPC.

A largest pore at micro-scale was eliminated due to the positive effect of an ASR. All compositions of UHPC had the highest concentration of pores at Nano-scale. When glass powder is substituted for silica fume, it shows better compressive strength.

Therefore, replacing glass powder is described as benefic method in thesises.

2.2 Ultra High-Performance Concrete (UHPC)

Ultra High-Performance Concrete has been developed since the mid-1990s. It is being studied a lot with good performances. Good performances can be divided into three main parts.

① Above 150 MPa compressive strength: UHPC has more than 150 MPa compressive strength in case of high – temperature steam curing because of the very low water/cement ratio. However, depending on the method of curing, the compressive strength may decrease.

② Good fluidity: UHPC has good fluidity. The better the fluidity, the better the workability, so it can be applied in various environments and conditions. It is more advantageous than other concrete.

③ High density: The high density of the UHPC means low permeability and meticulous matrix. It can prevent the harmful environment such as chlorides.

UHPC has various strength depending on curing method [20]. The ideal method is steam curing on 90℃ for 48h after curing in a mold for 24h at room temperature (20 ± 2℃, 60RH) because the high temperature accelerates hydration in concrete. When UHPC is cured at 20℃, 60RH for 28days, the compressive strength of the UHPC is less than 150MPa. Therefore, curing method is a big important point in UHPC.

The raw materials for the fabrication of UHPC in this study were Type Ⅰ white Ordinary Portland Cement (OPC, Union Cement Co., Ltd., Korean), Silica powder (S-SIL 10, SAC, Korea, mean particle size of 4.2μm), silica fume (Grade 940U, Elkem, Norway) and silica sand (Saeron Co., Ltd., Korea, with particle diameter in the range of 0.27~0.72mm).

2.3 Waste glass aggregate

The glass is an artificial material that is melted in a furnace of 1400~1500℃ after combining SiO_2 • $CaCO_3$ • Na_2CO_3 and metallic oxide (CuO or CuO_2 and $CoCO_3$) for adding color. The result is a hot liquid. When it can be cooled, it is and inorganic substance that is amorphous.

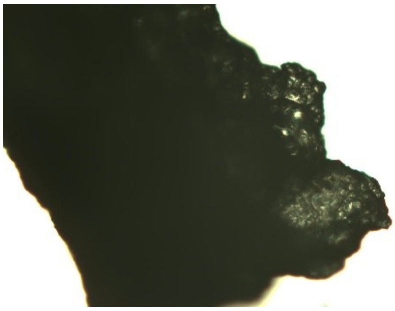
Table 2-1 Composition and compositional ratio of glass

Component	**SiO_2**	**Na_2O**	**K_2O**	**CaO**	**MgO**	**Al_2O_3**
Percent (%)	72.1	14.0	0.5	10.0	1.0	2.0

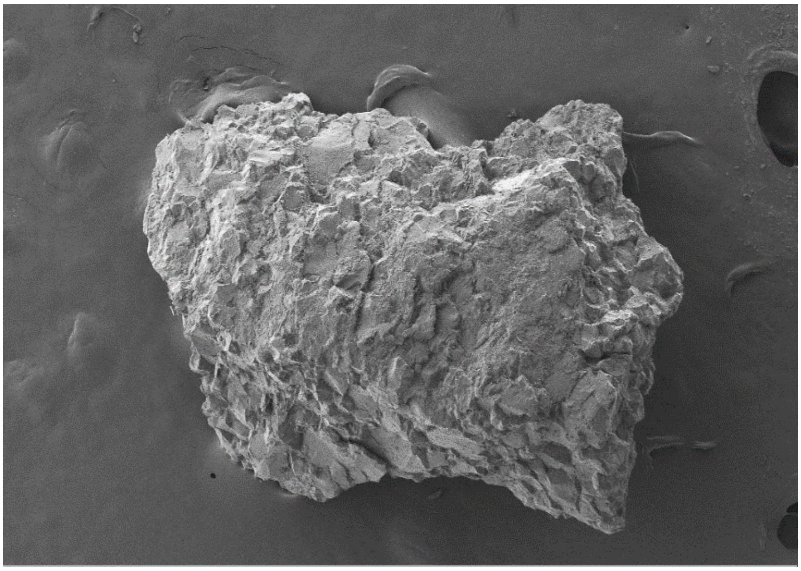
2.4 Comparing Silica sand with Waste glass aggregate

In this study, silica sand and waste glass aggregate should be compared because silica sand is replaced with waste glass aggregate.

① Surface

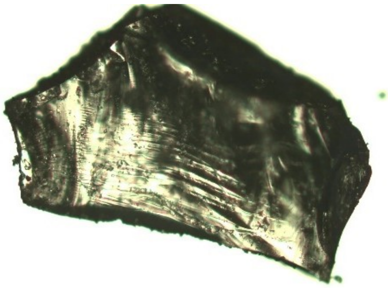
(a) (b)



(c)

Figure 2-1 Surface of silica sand: (a) silica sand, (b) by microscope, (c) by SEM

(a)



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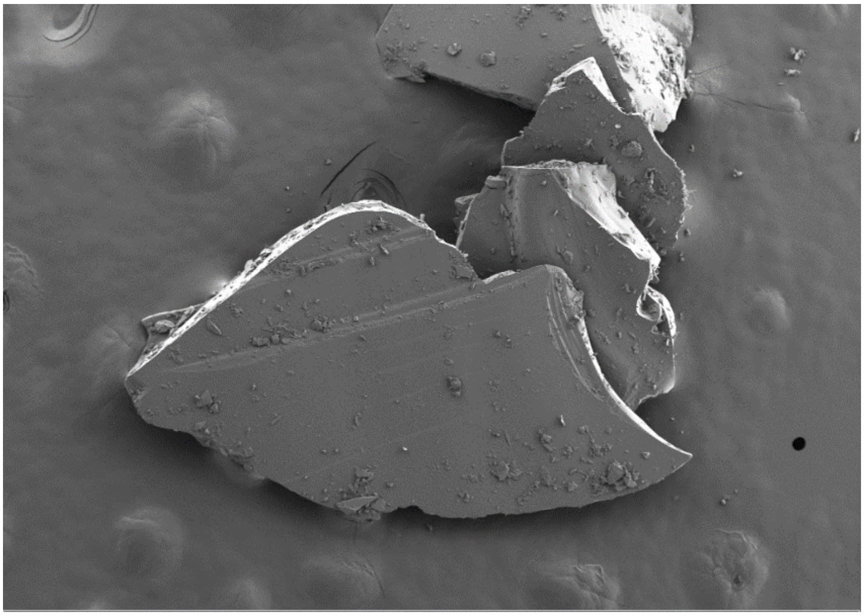


(c)

Figure 2-2 Surface of WGA: (a) waste glass aggregate, (b) by microscope, (c) by SEM

Figure 2-1, 2-2. (b) taken with microscope and (c) taken with SEM show that silica sand has a rougher surface compared with waste glass aggregates.

② Components

Silica sand consists of more than 98 % SiO_2 and table 2-1 shows components of glass. The common point is that they have high ratio of SiO_2. In Chapter 1.1.2, it is suggestd that ASR, where SiO_2 contact water and alkaline components of cement, is an important problem. However, when silica sand has a higher SiO_2 content than glass, why consider this problem more in waste glass aggregate? This is because silica sand is a crystalline substance and glass is a non-crystalline substance. An ASR is a chemical reaction in which amorphous substance SiO_2 contact alkaline component of cement. Therefore, more attention should be paid to ASR when using waste glass aggregates.

③ Price

- Price of silica sand: ₩ 267/kg
- Price of waste glass aggregate: ₩ 200/kg

Above price of waste glass aggregate is more expensive than actual price because infrastructure for crusing glass is not well established [21].

There are a few more things to consider. Recycling waste glass can save the cost of buried waste glass (₩ 15/kg). Additional cost saving can be expected as CO_2 from burning waste glass can be reduced. Therefore, considering this price, the cost of waste glass aggregate would be less than ₩ 200/kg.

As a result, waste glass aggregate is more economical and eco-friendly material than silica sand.

Chapter 3. Test Plan

3.1 Test outline

3.1.1 Waste glass aggregate size and replacement rate

One of the common principles applied in manufacturing Ultra High-Performance Concrete (UHPC) is not to use coarse aggregates. Such a combination composition principle is to construct a dense cement matrix by forming the optimal particle size and lowering the water cement ratio as much as possible to improve the mechanical properties. Since the length of microcracks is generally proportional to the particle size of aggregates, UHPC does not use coarse aggregates, and so small silica sand is typically used as fine aggregate of UHPC with an average size of less than 0.5mm [22].

Therefore, waste glass aggregate is also set to existing fine aggregate sizes suitable for UHPC. Particle size 0.3~0.5 mm of waste glass aggregate is used through sieve analysis test.

Figure 3-1 Seive analysis testing machine

As the replacement rate increases, the performance of concrete is decreasing. There are also some studies that show the performance of concrete increasing when replacement rate is 10~20 %.

Therefore, to optimize and generalize the replacement rate of waste glass aggregate, the replacement rate is set by 0, 10, 20 ,50 % as a parameter.

3.1.2 Outline

The outline of the test is as follows. The purpose of the test is to find optimal conditions for considering between eco-friendly and the performance degradation that occur when the fine aggregate of Ultra High-Performance Concrete is replaced with waste glass aggregate.

First, finding the optimization of the replacement rate of waste glass aggregate for UHPC based on mechanical properties tests.

Second, conducting mechincal properties and durability tests by applying developments according to the performance degradation.

In other words, determine the optimal replacement rate of waste glass aggregate, apply the developments against degradation, and compare them with UHPC. Slip phenomenon is caused by smooth surface of waste glass aggregate, so two methods have been devised.

① Steel fiber is added to increase adhesion and inhibit harmful ASR expansion caused by waste glass aggregate [23].

② Modify the surface of the waste glass aggregate. Through surface modification, as it is produced in C-S-H crystals on the surface of the waste glass aggregate, it prevents slip phenomenon and C-S-H crystals can also prevent performance degradation because they generate strength [24].

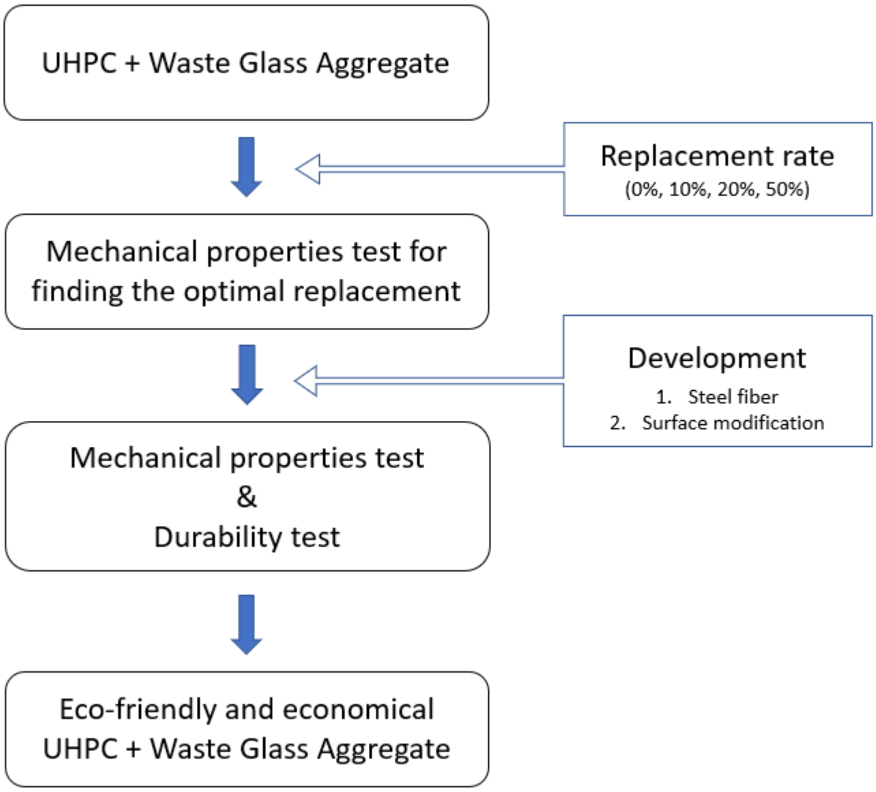


Figure 3-2 Algorithm of test outline

3.2 Mechanical properties test

3.2.1 Flow test

The flow test is conducted in accordance with KSL 5105 [25], and because UHPC has good fluidity, plastic plates were added to the flow test machine. The flow test is to drain the water off the flow table and put the mortar inside the mold. The mold is 70mm diameter on the top ,100mm diameter on the bottom and 50mm height. After putting the mortar inside the mold, lifting the mold immediately. And then, the table is dropped 25 times to measure the two diameters of the length from east to west, and from north to south. The average diameter value is the flow value.

Figure 3-3 Flow test machine

3.2.2 Compressive strength test

Compressive strength test can evaluate the performance of compressive stress. The compressive strength test is conducted in accordance with the KSL 5101 [26]. The specimens are tested after steam curing and normal curing 7, 28 days. The size of specimen is 50 x 50 x 50 mm and the number of specimens is six for each parameter.

Placing the specimens on the UTM (Universal Testing Machine) pressurization plate. The centerline of the specimen and the test machine is placed on the same vertical line and the top side of the specimen is completely parallel to the pressurized side of the test machine. The pressure speed is 500 KN with a displacement speed of 1 mm/min. The compressive strength is the average value excepting for the maximum and minimum values.

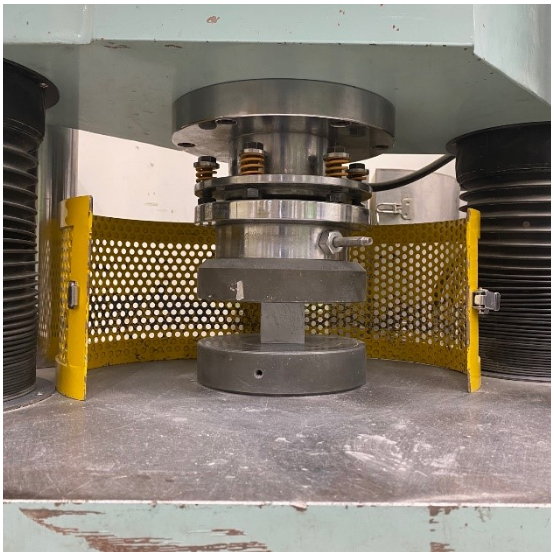


Figure 3-4 Compressive strength test

3.2.3 Flexural strength test

Concrete structures are vulnerable to tensile and flexural stress. If stress greater rthan the bending strength of the material occurs, cracks and delamination of the structure may occur. Therefore, the flexural strength is measured. The flexural strength test is conducted in accordance with KS F 2408 [27]. The specimens are tested after steam curing and normal curing 7, 28 days. The size of specimen is 40 x 40 x 160 mm and the number of specimens is six for each parameter.

The maximum load is obtained by loading the load in the center of the specimen. The flexural strength is the average value excepting for the maximum and minimum values. Flexural strength is calculated by the following equation.

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

σ = Flexural strength

F = load

L = span length

b = width of specimen

d = thick of specimen

(a)

(b)

Figure 3-5 Flexural strength test: (a) flexural strength test, (b) crack shape

3.3 Durability test

3.3.1 Alkali – Silica Reaction (ASR) test

Alkali – Silica Reaction test is so important test in waste glass aggregate for Ultra High-Performance Concrete. ASR test is conducted in accordance with ASTM C 1260 [28]. The size of specimen is 40 x 40 x 160 mm and the number of specimens is three for each parameter.

After specimens are placed, curing at 20℃, 60RH for 24hours. And then measure the initial length to 0.001 mm after mold is deformed. Then, immerse the specimens in distilled water and curing at 20℃ for 24 hours. Measure the length again (zero leading length). After that, measure the expansion length by immersing the specimens into 1N NaOH (aq) for 1, 2, 4, 6, 8, 10, 12, 14 and 16 days respectively.

(a)

(b)

(c)

(d)

Figure 3-6 ASR test: (a) immersing specimens, (b) 1N NaOH (aq), (c) measuring specimen length, (d) curing at 80°C

3.3.2 Absorption rate test

The absorption rate is the percentage of the ratio of the absorption amount to the absolute dry weight of absorption. Absorption rate is conducted in accordance with KS F 2518 [29]. The size of specimen is 50 x 50 x 50 mm and the number of specimens is six for each parameter.

The specimens are tested after steam curing and normal curing 28 days. After drying the specimens at 105±2 ℃ for 24 hours, cool the specimens for 30 minutes to measure the weight of the specimens and immerse distilled water at 20±5 ℃ for 48 hours. After that, the surface of specimens is cleaned with damp tower, and the weight is measured with a precision of 0.1g. The absorption rate is the average value except for the maximum and minimum values. It is calculated by the following equation.

$$\textit{Absorption rate (\%)} = \frac{A - B}{B} \times 100 \qquad (3.2)$$

A : weight of specimen after immersion (g)

B : weight of dry specimen (g)

(a)

(b)

(c)

Figure 3-7 Absorption test: (a) drying specimens, (b) measuring specimen weight, (c) immersing specimens

3.3.3 Acid resistance test

The acid rain due to recent urbanization and industrialization is fatal for buildings that are mainly exposed to outdoor environments. The definition of acid rain is below pH 5.6. As shown in Figure 3-8, acid rain range is between pH 4.0 and 6.0. The lowest value of acid rain is pH 4.3 in Daejeon, 2010. The highest value of acid rain is pH 6.0 in Gwangju, 2018.

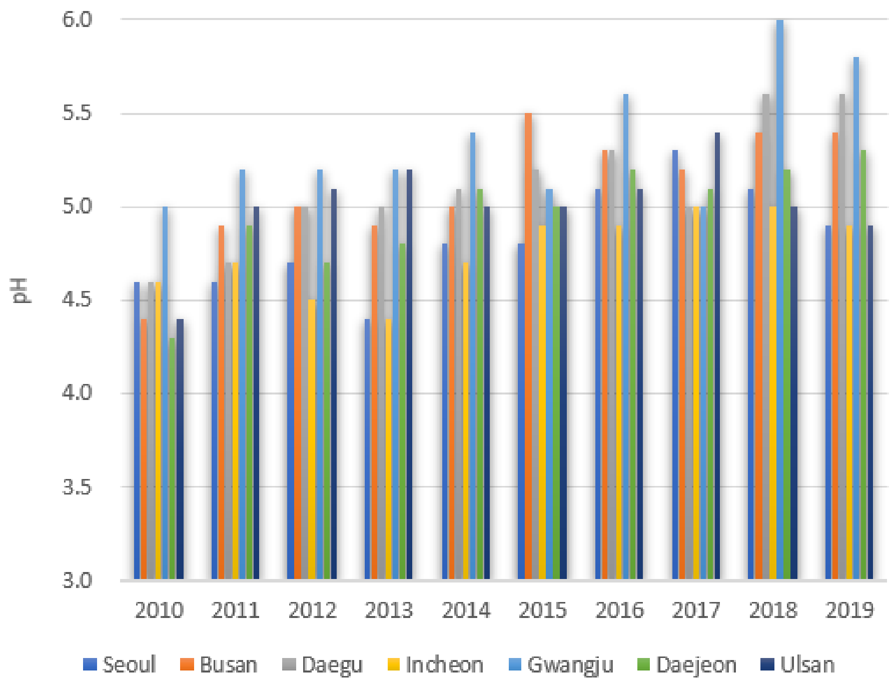


Figure 3-8 Acid rain average of domestic cities for 10 years

The acid resistance test is conducted in accordance with ASTM C 267 [30]. The size of specimen is 50 x 50 x 50 mm and the number of specimen is 6 for each parameter.

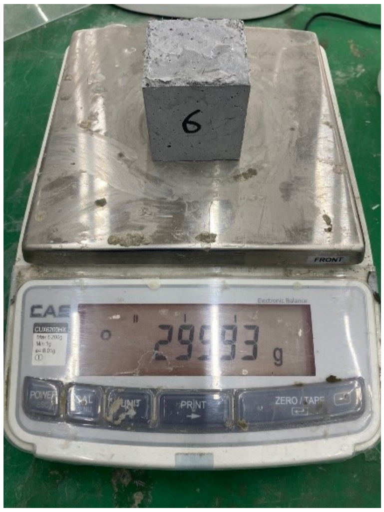
The specimens are immersed in an acidic solution on the 28 days of normal curing (20℃, 60RH), and then the weight change on the 7, 14 and 28 days is measured, and the appearance change is observed. As for the immersion solution, a 98% sulfuric acid (H_2SO_4) aqueous solution, which accounts for 84% of the acid rain, is diluted in distilled water to prepare pH 1, pH 3 and pH 5 solutions. As for the pH concentration, 0.1N aqueous sulfuric acid solution = pH 1 is used to obtain pH 1, and pH 1 is diluted 100 times to obtain pH 3, and pH 3 is diluted 100 times to obtain pH 5. Since UHPC has a strong alkalic surface, the neutralization rate is so fast when the speicmens are immersed in an acidic solution. Therefore, the acidity is maintained by measuring the concentration change every 24 hours for the first 2 weeks, and the solution is changed every 3 days for the remaining period. The Acid resistance rate is the average value except for the maximum and minimum values. It is calculated by the following equation.

$$\textit{Weight gain rate (\%)} = \frac{W_o - W_n}{W_n} \times 100 \qquad (3.3)$$

W_o : weight of specimen after immersion (g)

W_n : weight of specimen before immersion (g)

(a)



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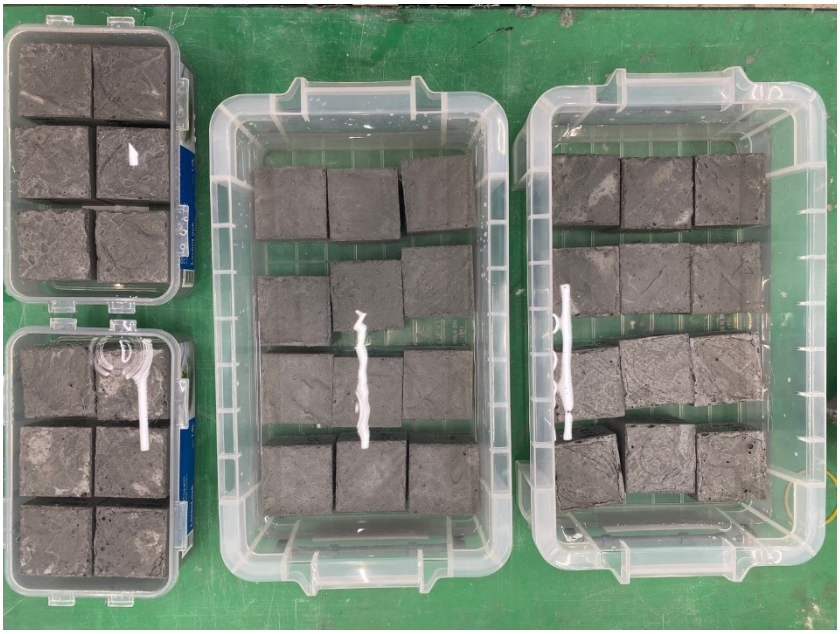


(c)

Figure 3-9 Acid resistance test: (a) measuring pH concentration, (b) measuring specimen weight, (c) immersing specimens into pH1,3,5 solution

3.4 Scanning Electron Microscrope (SEM)

Scanning Electron Microscope is a type of electron microscope that scans the surface of a specimen through an electron beam to image it. When high speed electrons are fired, the electrons collide with the surface of the specimen and interact, causing electron – like substances to pop out of the sample.

Electron microscope is fundamentally different from optical microscope in principle and structure. The main difference is that electron microscope uses electron beams instead of light. Optical microscope uses glass lenses to create images, and electrons are used because electron beams cannot pass through the glass. An electron lens is a device that creats a magnetic fiel with an electromagnet and uses it to converge or diverge electron beams. In particularly, SEM can know the surface shape and structure in three dimensions by deposition of dry metals in a specimen, injecting primary electron bin into the surface of the specimen, and scanning the emission secondary electron strength corresponding to the point. The resolution of the SEM is better than 1 nm and a vacuum environment is generally required.

SEM basically needs to be equipped with an electron optical system to produce the electrone probe (primary electron beam). Also referred to as an eletron gun, it creates, acceleratres, and supplies electrons that are used as light sources. It mainly uses a thermionic emission gun that emits electrons from a filament heated by heat. A detector for detecting and collecting secondary electrons (secondary electrons) reflected or reacted from one specimen is also essential. The scintillator, which is a component of the detector, is coated on the top of the detector and is a part that applies high voltage. Secondary electrons emitted from the specimen hit the scintillator by high voltage and emit light. This light passes through the photo – multiplier tube, transforms into an electron, amplifies, and turns into an electrical signal. The condenser lens and objective lens collect and focus electrons, and a magnetic lens that controls that electron beam by applting a magnetic field is sometimes used.

Speciment stage is a stage for placing a specimen, and since it is magnified at a so high rate by a microscope, it needs the ability to show the surfaces of the sample by moving it stably and smoothly. Horizontal movement (X, Y axis) and vertical movement (Z axis) should be possible, and both rotational movement (R) and tilt (T) should be possible too. Mainly horizontal movement is used to select the sesired field, and vertical movement is used to focus resolution and focus.

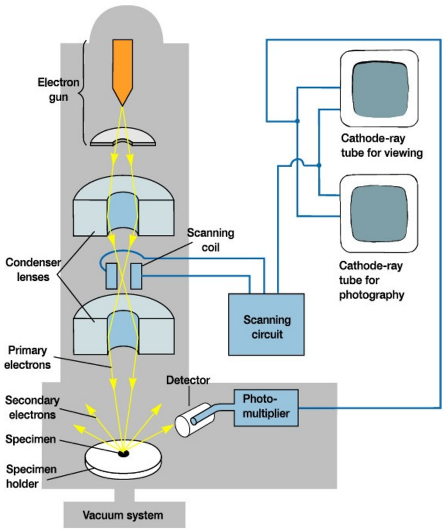
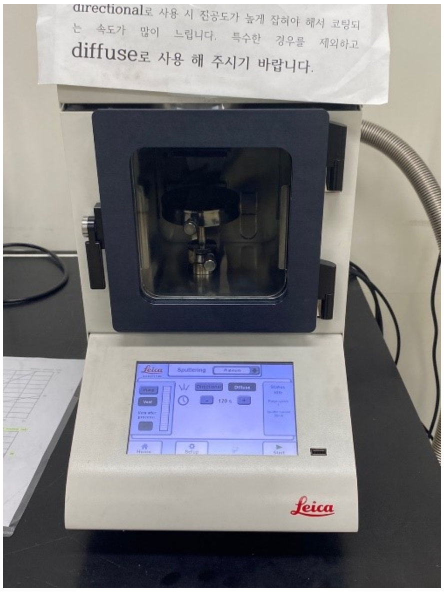
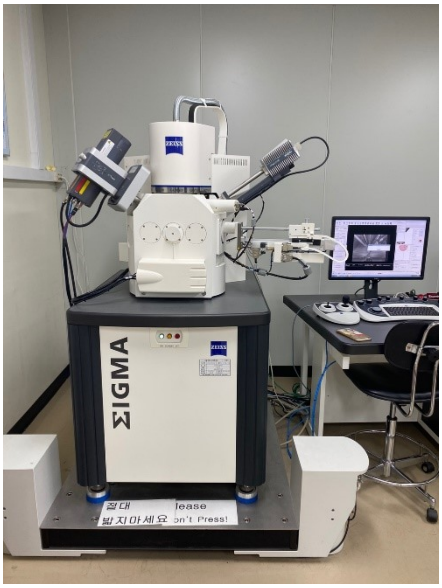


Figure 3-10 Principle of SEM



(a)



(b)

Figure 3-11 SEM machine: (a) diffuse vacuum machine, (b) SEM machine

Chapter 4. Effect of Waste Glass Aggregate on Mechanical Properties

4.1 Introduction

In this Chapter 4, it is a study through mechanical properties tests to see if the performance change occurs when silica sand, which is a fine aggregate in Ultra High-Performance Concrete, is replaced with waste glass aggregate.

Although the performance of UHPC decreases when the replacement rate of waste glass aggregate increases, as shown in Chapter 2, it is an advantage in economical and eco-friendly parts.

Therefore, by analyzing the tests data, the optimal waste glass aggregate replacement rate is derived in consideration of performance, eco-friendly and economical aspects.

4.2 Specimen study

The material proportion used in the tests is the same as that of the UHPC as shown in Table 4-1. The replacement rate of the waste glass aggregate is set to 0, 10, 20 and 50 %, as shown in Chapter 3.

Table 4-1 Material proportion of UHPC and waste glass aggregate

	Cement	Silica fume	Quartz	Silica sand	Waste glass aggregate (WGA)	Water	Superplacticizer (SP)
UHPC (Ref.)	1	0.25	0.35	1.1	0	0.24	0.04
UHPC-WGA (10%)	1	0.25	0.35	0.99	0.11	0.24	0.04
UHPC-WGA (20%)	1	0.25	0.35	0.88	0.22	0.24	0.04
UHPC-WGA (50%)	1	0.25	0.35	0.55	0.55	0.24	0.04

The mixing method is to first mix silica sand and silica fume for 5 minutes, then add cement and quartz, and mix them again for 5 minutes to prepare a premix. Using the mixer shown in Figure 4-1, add 2/3 of the premix to the bowl and start mixing in level 1 by adding distilled water and superplacticizer (SP). All materials should be added within 2~3 minutes. After that, mix for 2minutes in level 2. Next, start mixing again in level 1 for 1 minute to remove air inside the UHPC. And then, start pouring. Then, curing for 24 hours in a curing machine of 20℃, 60RH, and then demolding.

The performance of UHPC varies depending on the curing methods. The curing methods are divided into two. First, it is a high temperature steam curing. It is a method of curing for 48~72 hours in a water bath at 60~90℃ after demolding. Second, it is a basic curing method. It is a method of curing for 7, 28days in a 20℃, 60RH at curing machine.

(a)

(b)

(c)

Figure 4-1 Mixing and curing: (a) mixing machine, (b) basic curing machine, (c) water bath

4.3 Mechanical properties test

4.3.1 Flow test

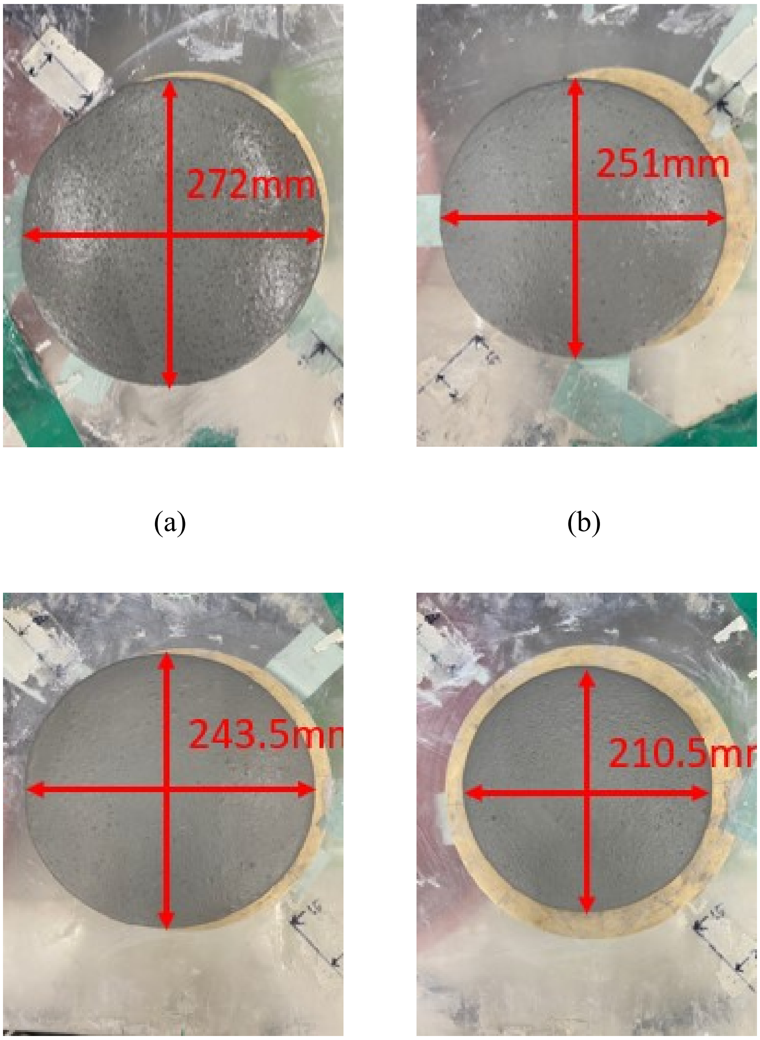
Flow test is conducted, as shown in Chapter 3. The flow test result is shown in Table 4-2 and Figure 4-2.

As the replacement rate of waste glass aggregate increases, the flow generally tends to decrease.

When the replacement rate is 10% or 20%, the results are suitable with 90% fluidity of the UHPC. However, when the replacement rate of waste glass aggregate is 50%, it can be known that the fluidity is significantly decreased compared to UHPC. It can be judged that this replacement rate has a bad effect on the performance. Therefore, it in not suitable when the replacement rate of waste glass aggregate is 50%.

Table 4-2 Flow test result UHPC depending on replacement raio

Group	Mean length (mm)	Standard deviation	Relative ratio
UHPC (Ref.)	272.00	3.56	1.00
UHPC-WGA (10%)	251.00	0.00	0.92
UHPC-WGA (20%)	243.50	2.12	0.90
UHPC-WGA (50%)	210.50	3.53	0.77



(a) (b)

(c) (d)

Figure 4-2 Flow test result and shape: (a) UHPC (Ref.), (b) UHPC-WGA (10%), (c) UHPC-WGA (20%), (d) UHPC-WGA (50%)

4.3.2 Compressive strength test

The compressive strength test is conducted, as shown in Chapter 3. The compressive strength test result is shown in Table 4-3 and Figure 4-3.

As the replacement rate of waste glass aggregate increases, the compressive strength generally tends to decrease.

If the replacement rate of waste glass aggregate is 10% or 20% at high-temperature steam curing, the compressive strength is smaller than the UHPC, but it is more than 150MPa, so it is suitable. Likewise, when the compressive strength of the 7th day and the 28th day is compared to the UHPC, it is suitable because all of them trigger more than 90% of the compressive strength of UHPC.

However, if the replacement rate of waste glass aggregate is 50%, it is 81% of the UHPC compressive strength and less than 150MPa at high- temperature steam curing. Therefore, it is not suitable. In addition, the compressive strength on the 7th and 28th days is also inappropriate.

Table 4-3 The compressive strength of UHPC with waste glass aggregate

	7d		28d		Steam curing	
	Compressive strength (MPa)	Relative ratio	Compressive strength (MPa)	Relative ratio	Compressive strength (MPa)	Relative ratio
UHPC (Ref.)	101.75	1.00	131.00	1.00	166.00	1.00
UHPC-WGA (10%)	95.00	0.93	124.50	0.95	161.75	0.97
UHPC-WGA (20%)	92.00	0.90	121.00	0.92	160.25	0.96
UHPC-WGA (50%)	70.50	0.69	83.75	0.64	134.00	0.81

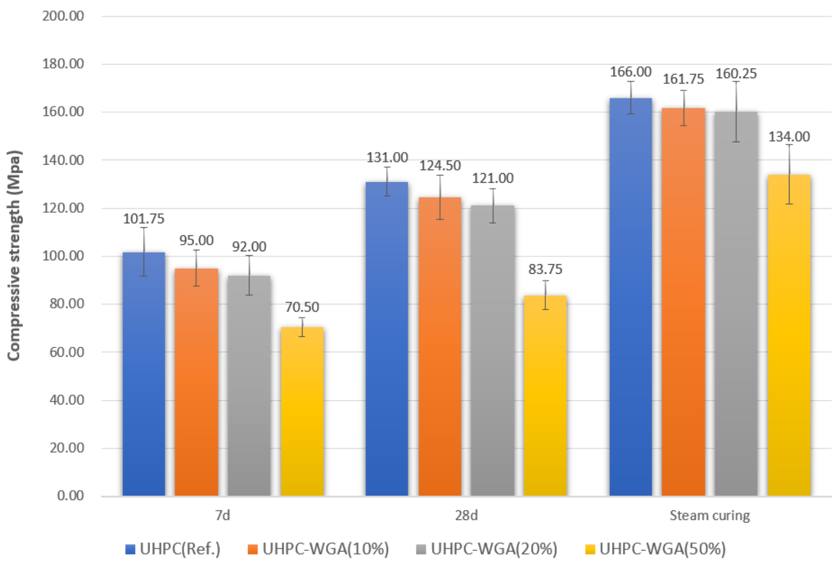


Figure 4-3 The compressive strength of UHPC with waste glass aggregate

4.3.3 Flexural strength test

The flexural strength test is conducted, as shown in Chapter 3. The Flexural strength test result is shown in Table 4-4 and Figure 4-4.

UHPC has a large compressive strength but has a small flexural strength. As a result, as the replacement rate of waste glass aggregate increases, the flexural strength of UHPC decreases. However, the gap is no significant. This is because the flexural strength of UHPC is so small.

When the replacement rate of waste glass aggregate is 50%, it has 98% performance compared to the UHPC at high-temperature steam curing. And the flexural strength of the 7th day and 28th day is more than 90% compared to the UHPC.

Table 4-4 The flexural strength of UHPC with waste glass aggregate

	7d		28d		Steam curing	
	Flexural strength (MPa)	Relative ratio	Flexural strength (MPa)	Relative ratio	Flexural strength (MPa)	Relative ratio
UHPC (Ref.)	22.55	1.00	23.77	1.00	24.84	1.00
UHPC-WGA (10%)	22.13	0.98	23.44	0.98	24.66	0.99
UHPC-WGA (20%)	21.42	0.95	22.95	0.96	24.54	0.98
UHPC-WGA (50%)	20.83	0.92	21.70	0.91	24.42	0.98

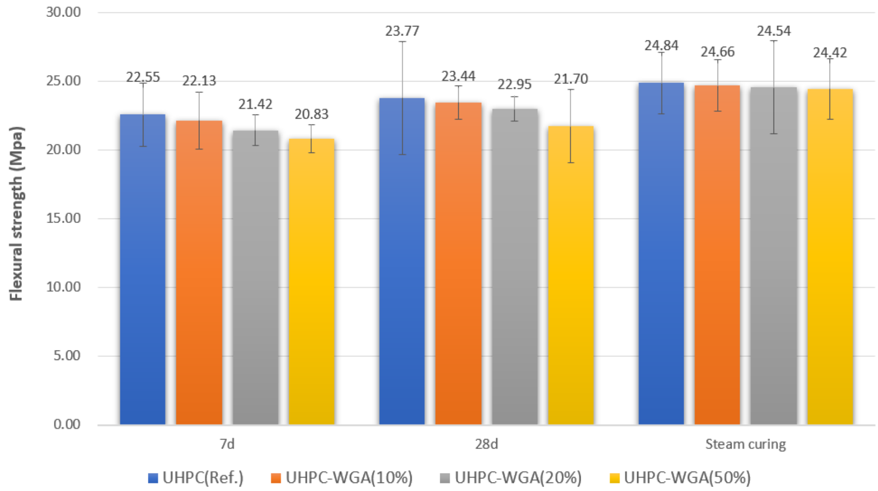


Figure 4-4 The flexural strength of UHPC with waste glass aggregate

4.4 Discussion

In this chapter 4, we confirmed the performance of UHPC according to the replacement rate (0, 10, 20, 50%) of waste glass aggregate.

To summarize 3 things,

1. As the replacement rate of waste glass aggregate increases, the fluidity decreases. If the replacement rate of waste glass aggregate is 10 or 20%, it is not a problem at all because it is more than 90% of the performance of UHPC. However, if the replacement rate is higher than that, the degradation of fluidity adversely affects the workability.

2. As the replacement rate of waste glass aggregate increases, the compressive strength decreases. The reduction rate decreases with longer curing time. If the replacement rate of waste glass aggregate is 10 or 20% (at high - temperature steam curing), it is judged suitable because it is 97, 96% of the UHPC compressive strength, which is more than 150MPa, which is the standard of UHPC compressive strength. However, if the replacement rate is 50%, it is only 71% performance, which is not suitable for the performance and standard of the UHPC.

3. The UHPC has low flexural strength compared to compressive strength. Although the flexural strength decreases as the replacement rate of waste glass aggregate increases, the reduction

rate is so small. So, it is not considered a big problem.

The reason for the degradation of the performance of UHPC with waste glass aggregate is that the surface of the waste glass aggregate is smooth as shown in Figs. 2-1 and 2-2. It causes a slip phenomenon, which reduces the adhesion between materials. Therefore, the durability is weakened, and both of compressive and flexural strength are degraded.

Based on the above, the most optimal replacement rate of waste glass aggregate is 10% when eco-friendliness, economy, and performance are all considered.

Chapter 5. Waste Glass Aggregate for UHPC with Steel Fiber

5.1 Introduction

In the Chapter 4, the most optimal waste glass aggregate replacement rate is determined to be 10% and the performance degradation is also checked.

In this Chapter 5, when steel fiber, which is one of the development method of performance degradation, is added, the new development concrete compare with UHPC and UHPC-WGA (10%).

Identify the performance change through the mechanical peoperties test and determine whether it is suitable material through durability test.

5.2 Specimen study

The parameter is only presence and absence of steel fiber. The steel fiber content is set at 2%, which is the optimal content of UHPC, as shown in Table 5-1. Steel fiber is calculated by volume to cement, not by weight. The steel fiber is smooth type with a length of 13 mm.

The speicmens are mixed and cured in the same way as described in Chapter 3,4.

Table 5-1 Material proportion of UHPC, UHPC-WGA (10%) with steel fiber

	Cement	Silica fume	Quartz	Silica sand	Waste glass aggregate (WGA)	Water	SP	Steel fiber
UHPC (Ref.)	1	0.25	0.35	1.1	0	0.24	0.04	0
UHPFRC (Ref.)	1	0.25	0.35	1.1	0	0.24	0.04	0.02
UHPC-WGA (10%)	1	0.25	0.35	0.99	0.11	0.24	0.04	0
UHPFRC-WGA (10%)	1	0.25	0.35	0.99	0.11	0.24	0.04	0.02

5.3 Mechnical properties test

5.3.1 Flow test

As shown in Table 5-2 and Figure 5-1, the fluidity decreases when steel fiber is added. As discussed in Chapter 4.3.1, the fluidity decreases when silica sand is replaced with waste glass aggregate. Since the steel fiber is added, the fluidity is further reduced.

However, in the worst case (replacing waste glass aggregate instead of silica sand and adding steel fiber), it can be considered suitable because it is 91% of UHPC fluidity performance. It is considered that there is no problem in workabilitry.

Table 5-2 Flow test result of UHPC, UHPC-WGA (10%) depending on steel fiber

Group	Mean length (mm)	Standard deviation	Relative ratio
UHPC (Ref.)	272.00	3.56	1.00
UHPFRC (Ref.)	256.25	3.50	0.94
UHPC-WGA (10%)	251.00	0.00	0.92
UHPFRC-WGA (10%)	246.50	3.53	0.91

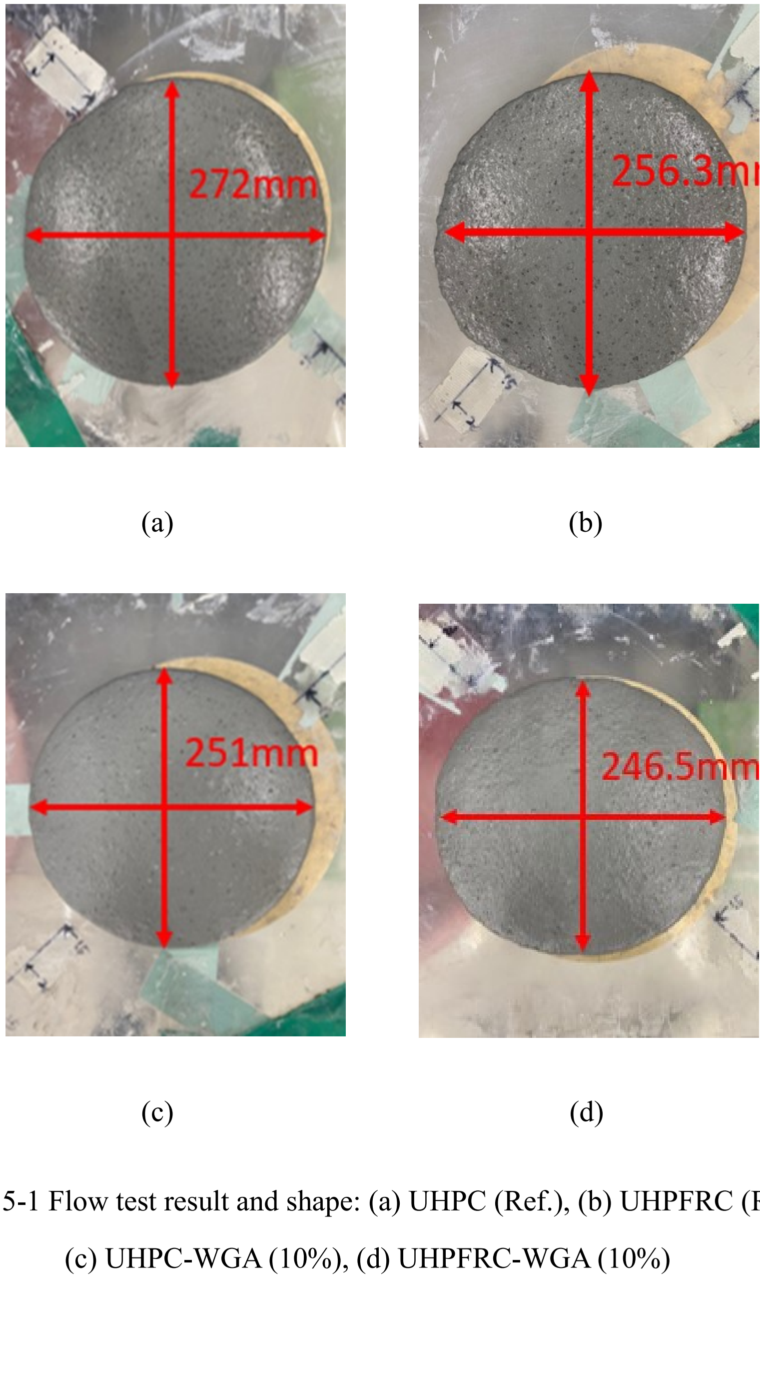


Figure 5-1 Flow test result and shape: (a) UHPC (Ref.), (b) UHPFRC (Ref.), (c) UHPC-WGA (10%), (d) UHPFRC-WGA (10%)

5.3.2 Compressive strength test

As shown in Table 5-3 and Figure 5-2, when the steel fiber is mixed in the UHPC, the compressive strength slightly increases. In addition, when 10% of the waste glass aggregate is replaced, the compressive strength increases when the steel fiber is added.

The important point is that the compressive strength of UHPFRC-WGA (10%) is higher than the compressive of the UHPC. Therefore, adding steel fiber is an effective method for alleviate the performance degradation due to replacement of waste glass aggregate instead of silica sand.

Table 5-3 The compressive strength of UHPC, UHPC-WGA (10%) depending on steel fiber

	7d		**28d**		**Steam curing**	
	Compressive strength (MPa)	**Relative ratio**	**Compressive strength (MPa)**	**Relative ratio**	**Compressive strength (MPa)**	**Relative ratio**
UHPC (Ref.)	101.75	1.00	131.00	1.00	166.00	1.00
UHPFRC (Ref.)	115.60	1.14	145.25	1.11	174.00	1.05
UHPC-WGA (10%)	95.00	0.93	124.50	0.95	161.75	0.97
UHPFRC-WGA (10%)	111.00	1.10	135.67	1.04	171.50	1.03

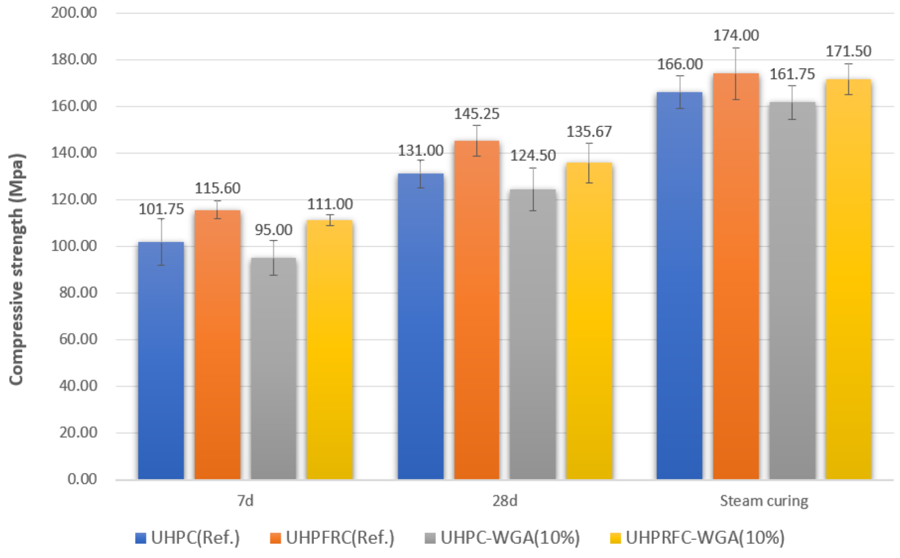


Figure 5-2 The compressive strength of UHPC, UHPC-WGA (10%) depending on steel fiber

5.3.3 Flexural strength test

The flexural strength of UHPC is small compared to the compressive strength and has a brittle fracture form. However, by adding steel fiber, this brittle fracture form can be alleviated. Because the steel fiber holds the concrete cracks, so it takes the form of ductile fraction.

As shown in Table 5-4 and Figure 5-3, the flexural strengths of UHPC and UHPC-WGA (10%) are small. However, when the steel fiber is added, The flexural strength of UHPFRC increases to 42.33MPa (at high-temperature steam curing) and the flexural strength of UHPFRC-WGA (10%) increases to 44.63MPa (at high-temperature steam curing). Therefore, the adding steel fiber shows good effect in terms of the flexural strength.

Table 5-4 The flexural strength of UHPC, UHPC-WGA (10%) depending on steel fiber

	7d		**28d**		**Steam curing**	
	Flexural strength (MPa)	**Relative ratio**	**Flexural strength (MPa)**	**Relative ratio**	**Flexural strength (MPa)**	**Relative ratio**
UHPC (Ref.)	22.55	1.00	23.77	1.00	24.84	1.00
UHPFRC (Ref.)	30.80	1.37	33.70	1.42	42.33	1.70
UHPC-WGA (10%)	22.13	0.98	23.44	0.98	24.66	0.99
UHPFRC-WGA (10%)	30.81	1.37	37.17	1.56	44.63	1.80

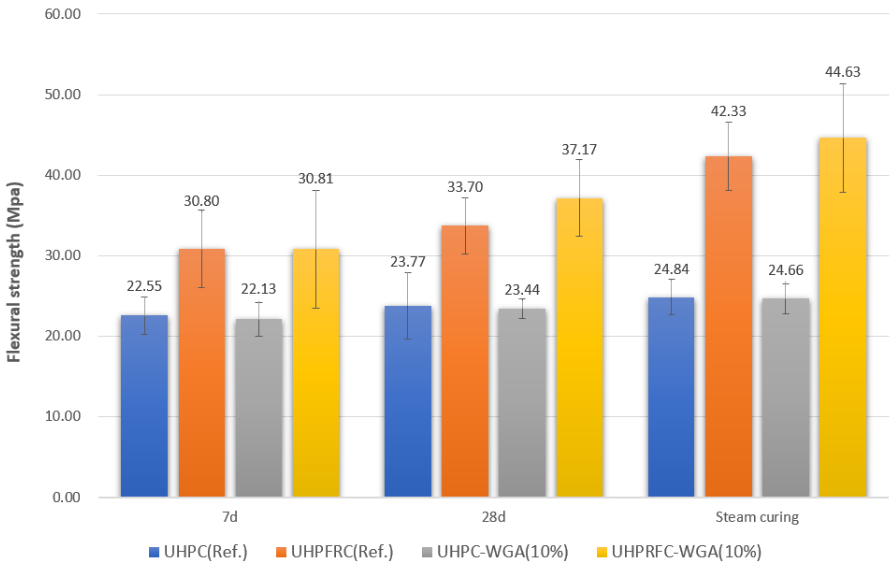


Figure 5-3 The flexural strength of UHPC, UHPC-WGA (10%) depending on steel fiber

5.4 Durability test

5.4.1 Alkali – Silica Reaction test (ASR)

As mentioned in Chapter 1, Alkali-Silica Reaction is a very important part to be considered in the waste glass aggregate UHPC. The standards for the adverse effect of expansion due to Alkali-Silica Reaction on concretre are as follows.

Expansion rate (ASTM C 1260)

- Expansions of less than 0.1% at 16th day after casting are indicative of innocuous behavior in most cases.
- Expansions between 0.1 and 0.2% at 16th day after casting include both aggregates that are known to be innocuous and deleterious in field performance.
- Expansions of more than 0.2% at 16th day after casting are indicative of potentially deleterious expansion.

The ASR determines the expansion rate based on 16th day. As shown in Figure 5-4, the expansion rate of the UHPC is 0.093% at 16th day, less than 0.1%, so there is no adverse effect of ASR. The expansion rate of UHPC-WGA (10%) is 0.151%, which is between 0.1% and 0.2%, which is suitable for the standards. The expansion rate of UHPC-WGA (20%) is 0.215%, which is more than 0.2%, which is not suitable for the standards, so it has an adverse effect of ASR. UHPFRC-WGA (10%) added with steel fiber in UHPC-WGA (10%) is suitable for the standards as 0.145%, and it is slightly less than 0.151%, which is the expansion rate of UHPC-WGA(10%), showing good result. The steel fibers create some voids, which reduce the detrimental expansion of the ASR.

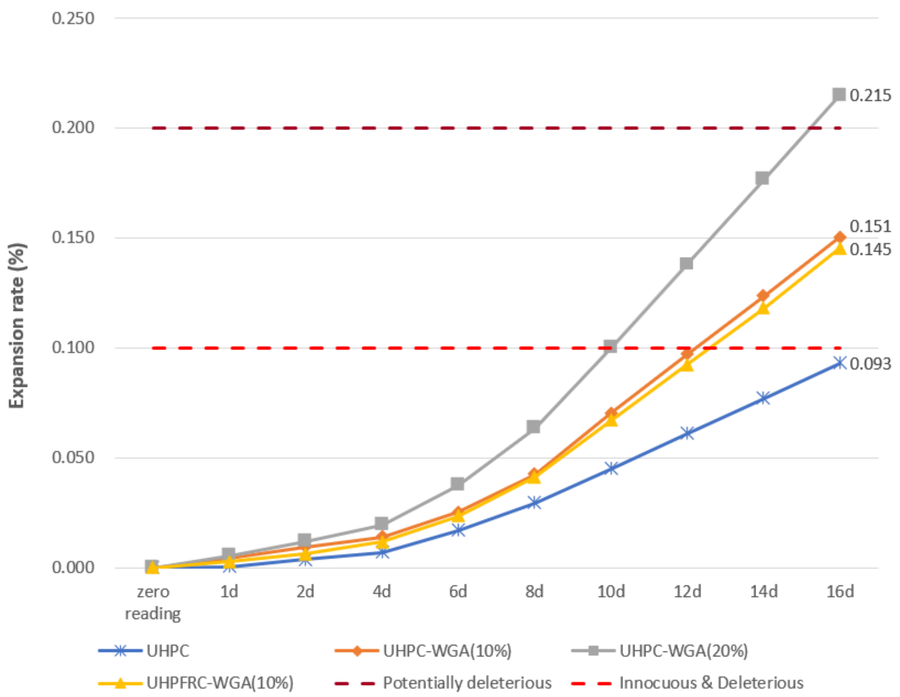


Figure 5-4 The expansion rate of UHPC, UHPC-WGA (10%) depending on steel fiber

5.4.2 Absorption rate test

The absorption rate test is conducted as described in Chapter 3. The smaller the absorption rate, the denser the internal matrix structure. The absorption rate is lower in the case of high-temperature steam curing than on the 28th day. In case of high - temperature stema curing, the matrix is denser than that of 28th day and hydration proceeds more.

Regardless of the presence or absence of steel fiber, UHPC-WGA (10%) and UHPFRC-WGA (10%) had lower absorption rate than UHPC and UHPFRC, as shown in Table 5-5. It means that when the waste glass aggregate is replaced with silica sand, the inner matrix beomces denser.

In terms of steel fiber, the absorption rate without steel fiber is lower than that of steel fiber adding. As shown in Figure 5-6, it is because voids around the steel fibers occur.

Table 5-5 The absorption rate of UHPC, UHPC-WGA (10%) depending on steel fiber

	28d		**Steam curing**	
	Absorption rate (%)	**Relative ratio**	**Absorption rate (%)**	**Relative ratio**
UHPC (Ref.)	5.19	1.00	2.47	1.00
UHPFRC (Ref.)	5.43	1.05	2.66	1.08
UHPC-WGA (10%)	2.68	0.52	0.98	0.40
UHPFRC-WGA (10%)	2.76	0.53	1.07	0.43

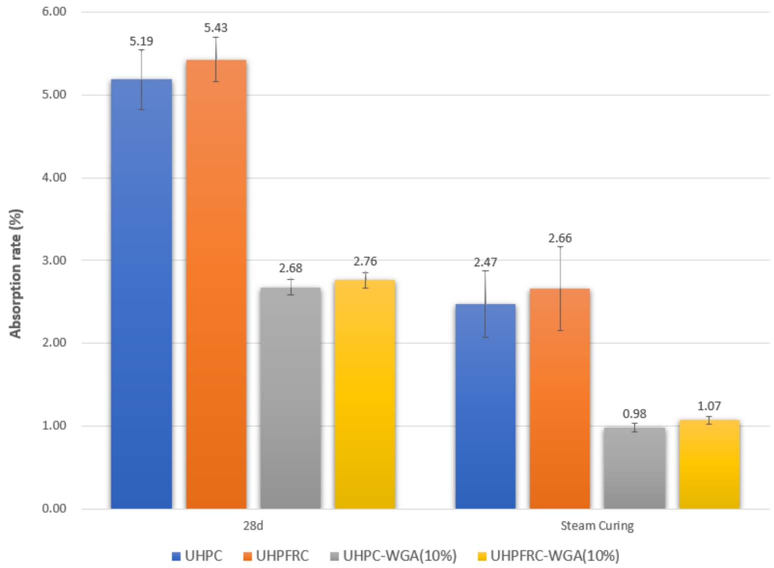


Figure 5-5 The absorption rate of UHPC, UHPC-WGA (10%) depending on steel fiber

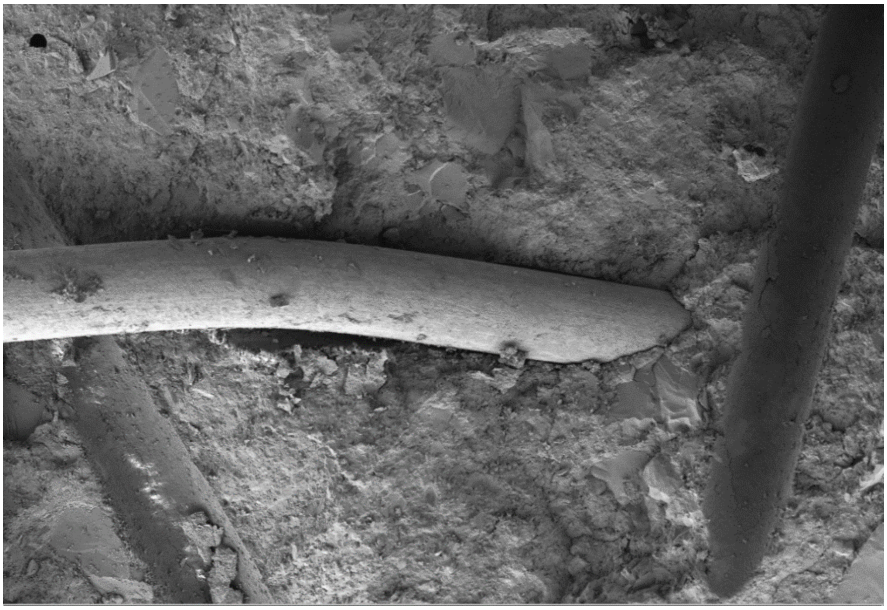


Figure 5-6 Effect of steel fiber on UHPC by SEM

5.4.3 Acid resistance test

The acid resistance test is conducted as described in Chapter 3.

1. pH 1

   As shown in Table 5-6 and Figure 5-7, when immersed in pH 1 solution, the specimens replaced with 10% of waste glass aggregate are more acidified than UHPC by more than 60% at 28th day. In addition, when the steel fibers are added and the pH is high, the weight gain rates increase due to corrosion of the steel fibers rather than the voids caused by the steel fibers.

2. pH 3

   As shown in Table 5-7 and Figure 5-8, when immersed in pH 3 solution, the specimens replaced with 10% of the waste glass aggregate are less acidified than UHPC by more than 60% at 28th day. In addition, when the steel fibers are added and the pH is low, the voids caused by the steel fibers affect larger than corrosion of the steel fibers, resulting in lower acidification.

3. pH 5

   As shown in Table 5-8 and Figure 5-9, when immersed in pH 5 solution, the specimens replaced with 10% of the waste glass aggregate are also less acidified than UHPC by more than 60% at 28th day. Similar with pH 3, when steel fibers are added, the pH is low and similar results are obtained.

Therefore, as mentioned in Chapter 3, the range of domestic acid rain is pH

4.3 to 6.0. At low pH, acidification proceeds more, but in the acid rain range, it shows a good effect when waste glass aggregate is substituted for silica sand, also demonstrats a better effect when steel fiber was added.

Table 5-6 The acid resistance rate of UHPC, UHPC-WGA (10%) depending on steel fiber of pH 1

	pH 1			
	14d		28d	
	Weight gain rate (%)	Relative ratio	Weight gain rate (%)	Relative ratio
UHPC(Ref.)	0.0373	1.00	0.3573	1.00
UHPFRC(Ref.)	0.0100	0.27	0.2913	0.82
UHPC-WGA (10%)	0.2433	6.52	0.5836	1.63
UHPFRC-WGA (10%)	0.2651	7.11	0.6919	1.94

Table 5-7 The acid resistance rate of UHPC, UHPC-WGA (10%) depending on steel fiber of pH 3

	pH 3			
	14d		28d	
	Weight gain rate (%)	Relative ratio	Weight gain rate (%)	Relative ratio
UHPC(Ref.)	0.0174	1.00	0.0958	1.00
UHPFRC(Ref.)	0.0151	0.87	0.0943	0.98
UHPC-WGA (10%)	0.0191	1.10	0.0383	0.40
UHPFRC-WGA (10%)	0.0118	0.68	0.0301	0.31

Table 5-8 The acid resistance rate of UHPC, UHPC-WGA (10%) depending on steel fiber of pH 5

	pH 5			
	14d		28d	
	Weight gain rate (%)	Relative ratio	Weight gain rate (%)	Relative ratio
UHPC(Ref.)	0.0166	1.00	0.0910	1.00
UHPFRC(Ref.)	0.0137	0.83	0.0900	0.99
UHPC-WGA (10%)	0.0143	0.86	0.0363	0.40
UHPFRC-WGA (10%)	0.0086	0.52	0.0246	0.27

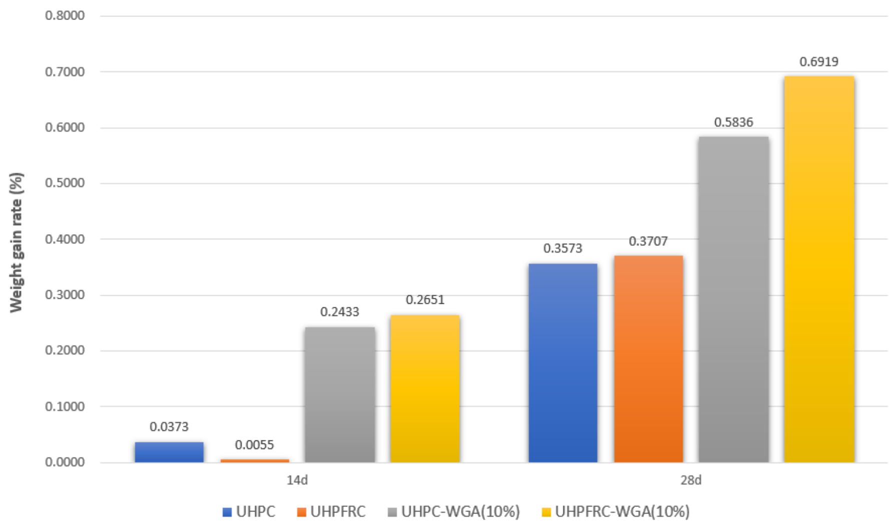


Figure 5-7 The acid resistance rate of UHPC, UHPC-WGA (10%) depending on steel fiber of pH 1

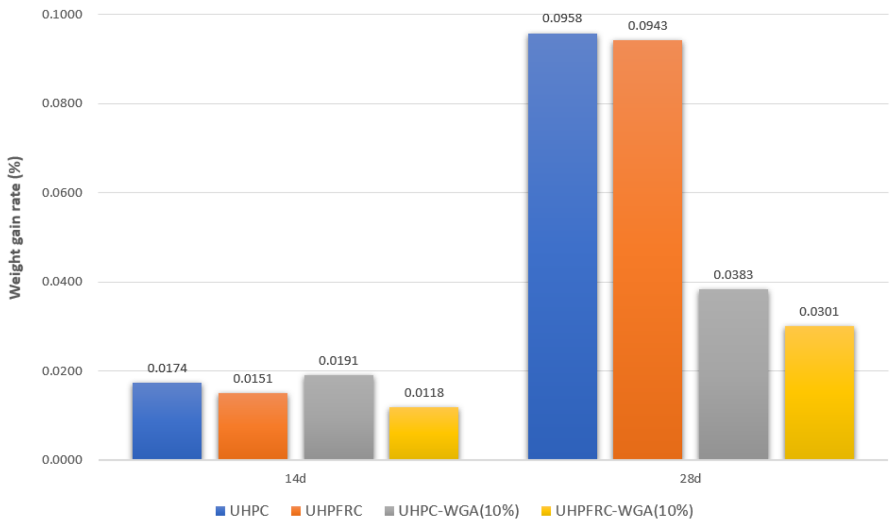


Figure 5-8 The acid resistance rate of UHPC, UHPC-WGA (10%) depending on steel fiber of pH 3

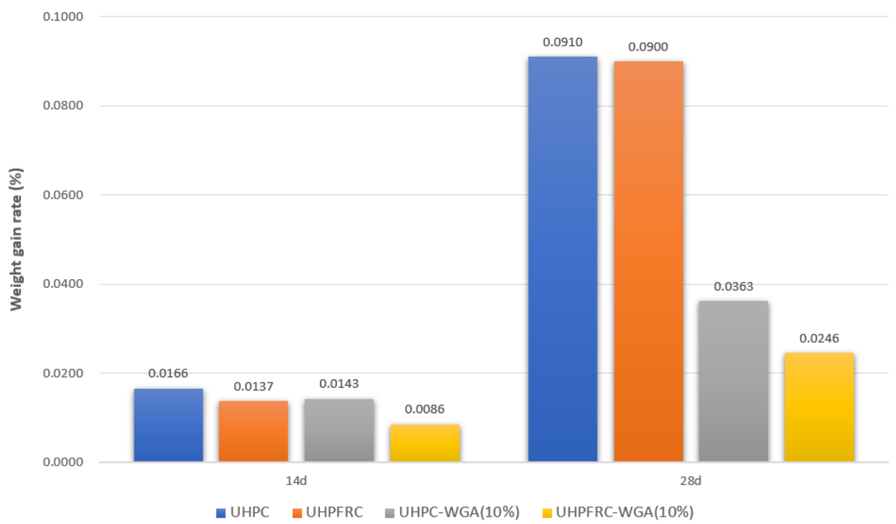
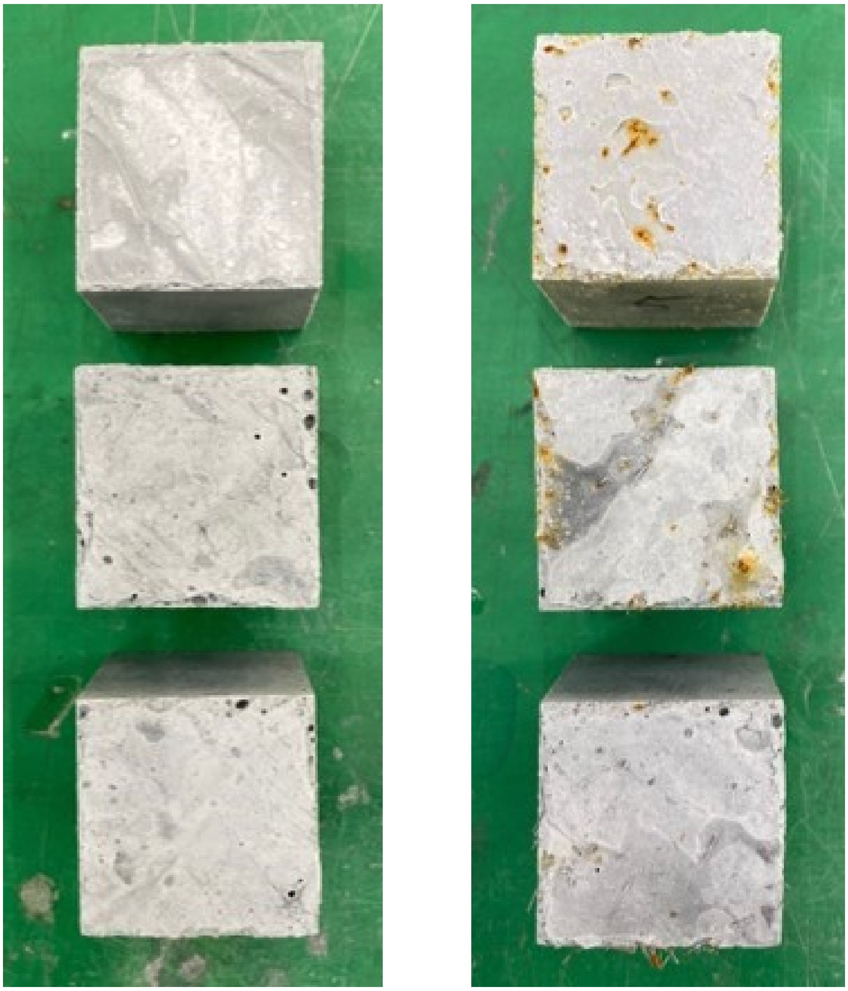
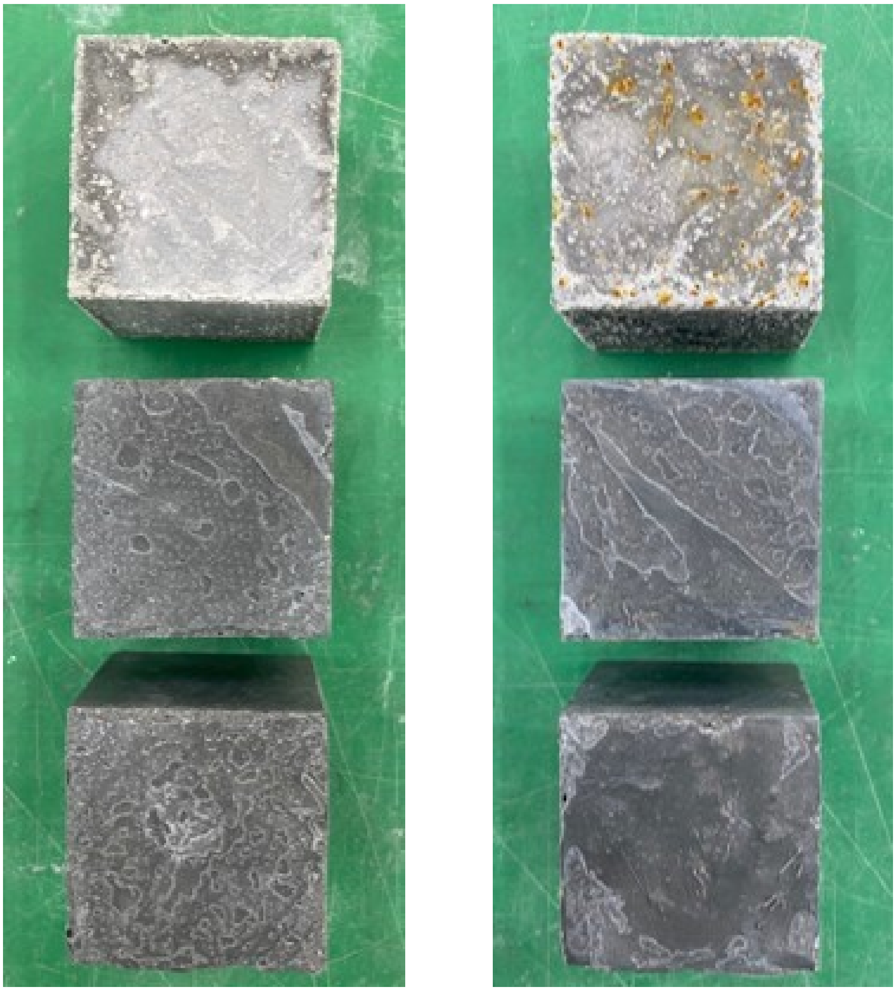


Figure 5-9 The acid resistance rate of UHPC, UHPC-WGA (10%) depending on steel fiber of pH 5



(a) (b)

Figure 5-10 The acid resistance test after 28 days: (a) UHPC, (b) UHPFRC



(a) (b)

Figure 5-11 The acid resistance test after 28 days: (a) UHPC-WGA(10%), (b) UHPFRC-WGA(10%)

5.5 Discussion

In this Chapter 5, the first method was applied to compensate for the reduced mechanical properties performance when 10% of the waste glass aggregate was replaced. By adding steel fiber with waste glass aggregate UHPC, the mechanical properties and durabilities tests results were confirmed by comparing with UHPC.

To summarize 2 things,

1. Mechanical properties tests result

   When the steel fiber is added into the waste glass aggregate UHPC, the fluidity decreases. It is decreased because the steel fiber holds the inner matrix of UHPC. However, UHPFRC-WGA (10%) showed more than 90% of UHPC performance, so it is suitable.

   The compressive strength was increased when steel fiber was added with UHPC and UHPC-WGA (10%). It slightly increased because the steel fiber holds the inner matrix. Although the compressive strength of UHPFRC-WGA (10%) was slightly lower than that of UHPFRC, it was improved compared to UHPC and UHPC-WGA (10%), showing a good effect.

   In terms of flexural strength, when steel fiber was added with UHPC and UHPC-WGA (10%), they all increased as well. It was confirmed that the brittle fracture form is changed to ductility fracture form because steel fiber holds inner matrix. In addition, it was confirmed that the flexural strength of UHPFRC-WGA (10%) was larger than that of UHPC, UHPFRC and UHPC-WGA (10%), showing a good effect.

2. Durability tests result

The Replacement rate of waste glass aggregate for UHPC increased the expansion rate. At 10% replacement, it met the standard, but at 20% replacement, it exceeded the standard and had a bad effect. Therefore, a reasonable basis for the optimal waste glass aggregate replacement rate in Chapter 4 was provided. When steel fiber was added into UHPC-WGA (10%), the expansion rate of UHPC-WGA (10%) was slightly decreased and it was confirmed that the standard was met, but it was not significant effect.

In the absorption rate test, when the waste glass aggregate was substituted, the absorption rate was lower than that of UHPC. It is because the inner matrix expands and becomes denser due to the small ASR. When the steel fiber was added, the absorption rate was slightly increased. It was confirmed to be due to the formation of voids by steel fiber.

In the acid resistance test, if the waste glass aggregate was substituted when the acidity was very low, acidification preceeded a lot. However, when the acidity was rather low, the acidification was rather decreased. It was confirmed that the waste glass aggregate had a good effect because the important pH concentration is rather low, like to the acid rain concentration. Acidification decreased when the acidity was rather low when the steel fiber was added. Therefore, it was confirmed that it had a good effect.

Based on these results, it can be proposed that adding steel fiber for UHPC-WGA (10%) is further implemented to enhance various properties such as mechanical and durability performance.

Chapter 6. Surface Modification of Waste Glass Aggregate for UHPC

6.1 Introduction

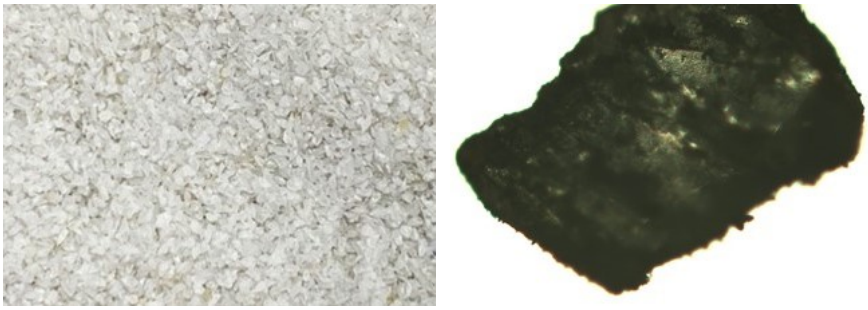
In this chapter, as mentioned in Chapter 3, the second development method is applied. The second development method of performance degradation of UHPC is the surface modification of the waste glass aggregate, and the tests for juding the suitability of UHPC are conducted at the same with in Chapter 5.

It aims to prevent slip phenomenon caused by waste glass aggregate by modifying the surface of waste glass aggregate. And then, it is determined whether it is suitable UHPC through durability test or not.

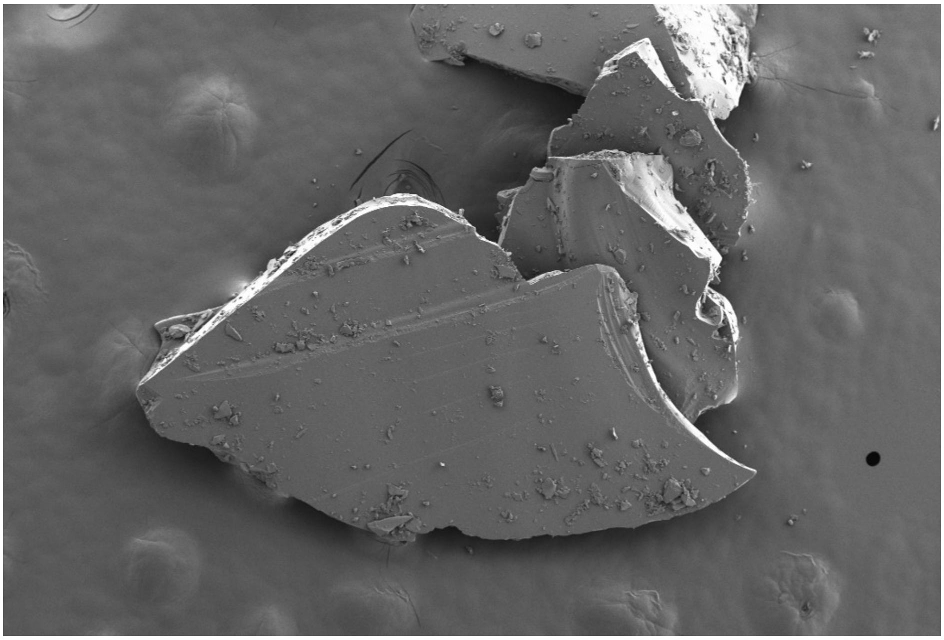
6.2 Specimen study

The surface of the waste glass aggregate is modified. The waste glass aggregate is immersed in a solution of supersaturated CaO in NaOH aqueous solution as shown in Figure 6-2. Then, C-S-H crystals are formed around the surface of waste glass aggregate.

It makes not only the surface of the waste glass aggregate rough, as shown in Figure 6-1, but also develops strength because of C-S-H crystals.



(a) (b)



(c)

Figure 6-1 Surface of MWGA: (a) MWGA, (b) by microscope, (c) by SEM

Table 6-1 Material proportion of UHPC and surface modification waste glass aggregate

	Cement	Silica fume	Quartz	Silica sand	Modification waste glass aggregate (MWGA)	Water	SP
UHPC (Ref.)	1	0.25	0.35	1.1	0	0.24	0.04
UHPC-WGA (10%)	1	0.25	0.35	0.99	0.11	0.24	0.04
UHPC-MWGA (10%)	1	0.25	0.35	0.99	0.11	0.24	0.04

(a) (b) (c)

Figure 6-2 Process of producing MWGA: (a) mixing NaOH(aq) and CaO, (b) WGA, (C) immersing WGA in the solution

6.3 Mechanical properties test

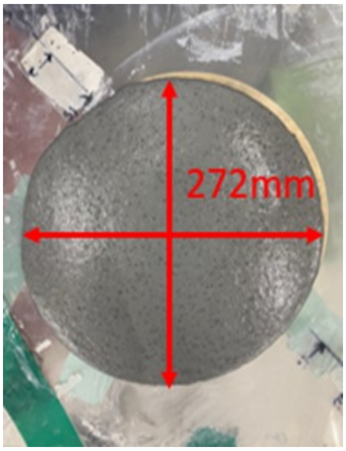
6.3.1 Flow test

As shown in Table 6-2 and Figure 6-3, the surface modification of the waste glass aggregate decreases the fluidity because modifying the surface of waste glass aggregate makes the surface rough.

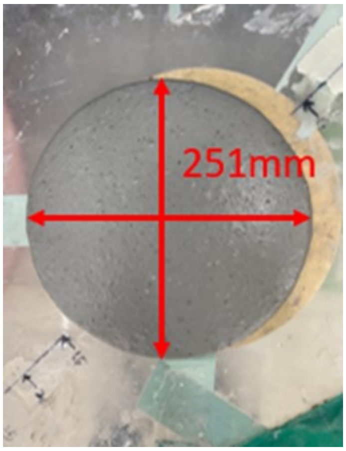
However, since the fluidity of UHPC-MWGA (10%) is 90% performance of that of the UHPC, there is no problem in workability at all. Therefore, it can be considered suitable.

Table 6-2 Flow test result of UHPC, UHPC-WGA (10%), UHPC-MWGA (10%)

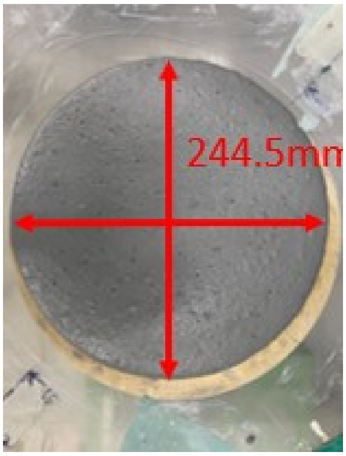
Group	Mean length (mm)	Standard deviation	Relative ratio
UHPC (Ref.)	272.00	3.56	1.00
UHPC-WGA (10%)	251.00	0.00	0.92
UHPC-MWGA (10%)	244.50	4.79	0.90



(a)



(b)



(c)

Figure 6-3 Flow test result and shape: (a) UHPC (Ref.), (b) UHPC-WGA (10%), (c) UHPC-MWGA (10%)

6.3.2 Compressive strength test

As shown in Table 6-3 and Figure 6-4, the UHPC substituted for modifying the surface of the waste glass aggregate has increased the compressive strength than the waste glass aggregate UHPC. The compressive strength of UHPC-MWGA (10%) is slightly smaller than UHPC, but it is effective because it is slightly increased than UHPC-WGA (10%).

It proved that C-S-H crystals formed on the surface of the waste glass aggregate during surface modification help to increase the compressive strength of UHPC-MWGA (10%) because it helps to generate strength.

Table 6-3 The compressive strength of UHPC, UHPC-WGA (10%) and UHPC-MWGA (10%)

	7d		**28d**		**Steam curing**	
	Compressive strength (MPa)	**Relative ratio**	**Compressive strength (MPa)**	**Relative ratio**	**Compressive strength (MPa)**	**Relative ratio**
UHPC (Ref.)	101.75	1.00	131.00	1.00	166.00	1.00
UHPC-WGA (10%)	95.00	0.93	124.50	0.95	161.75	0.97
UHPC-MWGA (10%)	99.83	0.98	130.83	0.99	163.50	0.98

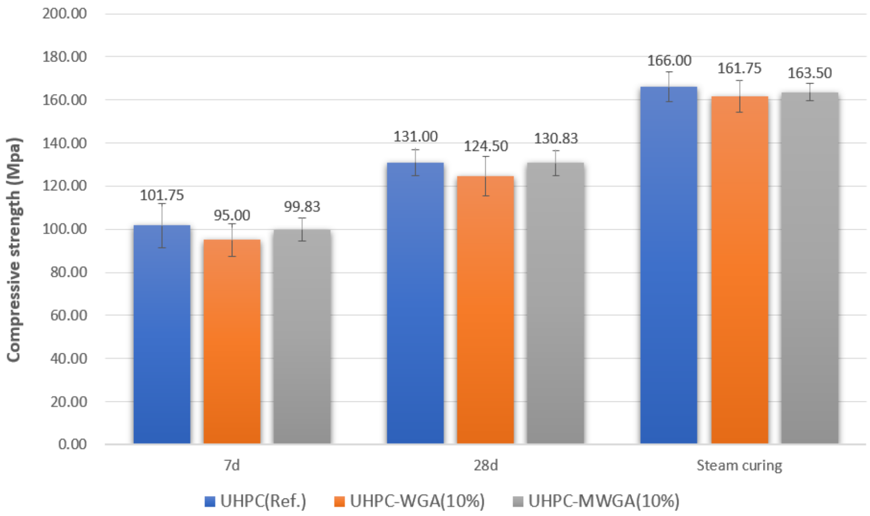


Figure 6-4 The compressive strength of UHPC, UHPC-WGA (10%) and UHPC-MWGA (10%)

6.3.3 Flexural strength test

As mentioned in Chapter 4 and 5, the flexural strength of UHPC is small compared to the compressive strength.

As shown in Table 6-4 and Figure 6-5, the flexural strength of UHPC is small, it is not greatly affected by the surface modification of the waste glass aggregate. It shows that there is a slightly good effect, but there is no effect.

Table 6-4 The flexural strength of UHPC, UHPC-WGA (10%) and UHPC-MWGA (10%)

	7d		**28d**		**Steam curing**	
	Flexural strength (MPa)	**Relative ratio**	**Flexural strength (MPa)**	**Relative ratio**	**Flexural strength (MPa)**	**Relative ratio**
UHPC (Ref.)	22.55	1.00	23.77	1.00	24.84	1.00
UHPC-WGA (10%)	22.13	0.98	23.44	0.98	24.66	0.99
UHPC-MWGA (10%)	22.16	0.98	23.72	0.99	25.26	1.02

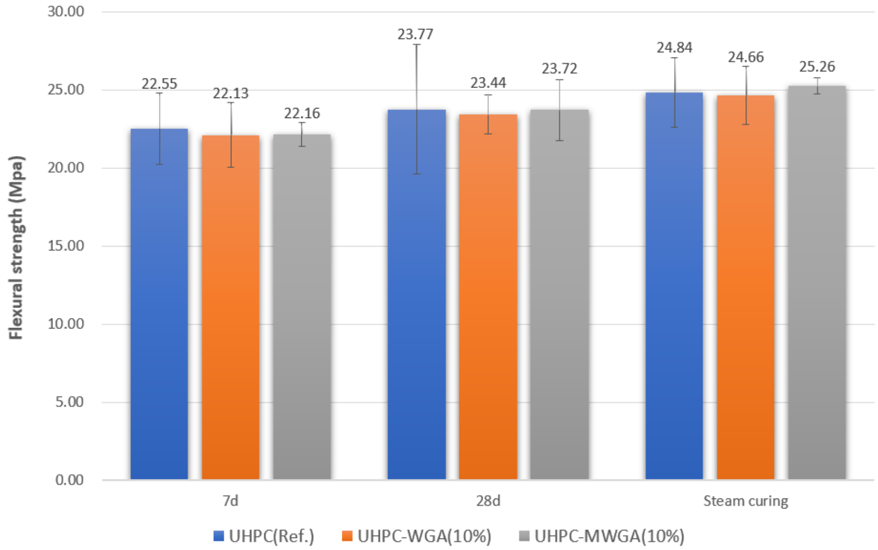


Figure 6-5 The flexural strength of UHPC, UHPC-WGA (10%) and UHPC-MWGA (10%)

6.4 Durability test

6.4.1 Alkali -Silica Reaction (ASR)

The standard for Alkali – Silica Reaction is mentioned in Chapter 5.4.1. As shown in Figure 6-6, the expansion rate of UHPC-MWGA (10%) which is substituted for 10% of modifying surface of waste glass aggregate in UHPC is 0.143%, which is suitable for the standard and is less than 0.151%, which is the expansion rate of UHPC-WGA (10%).

ASR causes the formation of swelling gel C-S-H, which causes detrimental reactions. In addition, the principle of surface modification is also to make small C-S-H crystals on the surface of the waste glass aggregate to make it rough.

Therefore, C-S-H crystals are previously formed on the surface of the waste glass aggregate, thereby reducing the ASR. So, the expansion rate of UHPC-MWGA (10%) is less than UHPC-WGA (10%), showing good result.

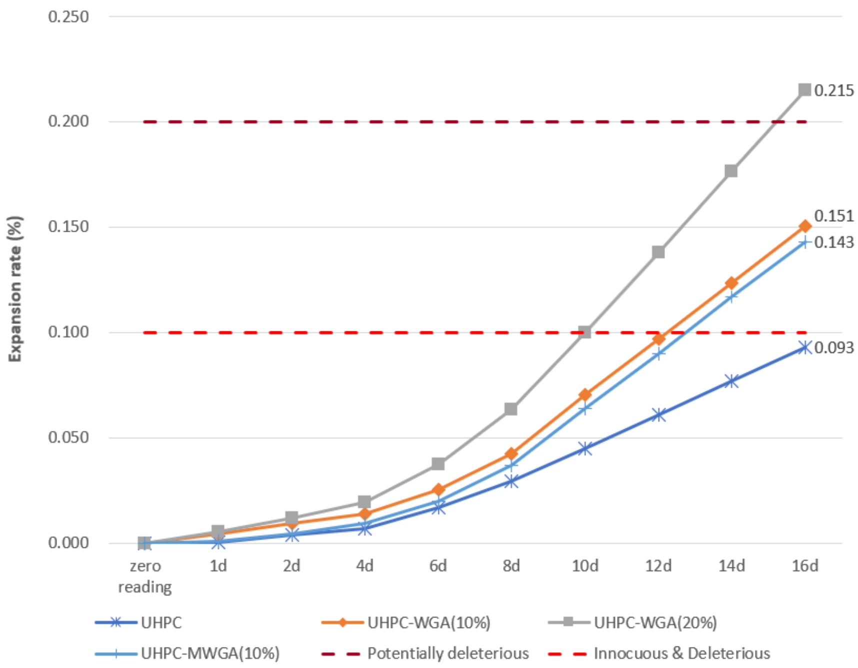


Figure 6-6 The expansion rate of UHPC, UHPC-WGA (10%), UHPC-MWGA (10%)

6.4.2 Absorption rate test

As shown in Table 6-5 and Figure 6-7, the absorption rate of UHPC manufactured by surface modification of waste glass aggregate is lower than UHPC by 50% at 28th day and 40% at high temperature steam curing. However, it has the same value with UHPC-WGA (10%). Therefore, it is considered that there is no effect of surface modification of the waste glass aggregate.

Table 6-5 The absorption rate of UHPC, UHPC-WGA (10%), UHPC-MWGA (10%)

	28d		**Steam curing**	
	Absorption rate (%)	**Relative ratio**	**Absorption rate (%)**	**Relative ratio**
UHPC (Ref.)	5.19	1.00	2.47	1.00
UHPC-WGA (10%)	2.68	0.52	0.98	0.40
UHPC-MWGA (10%)	2.70	0.52	0.98	0.40

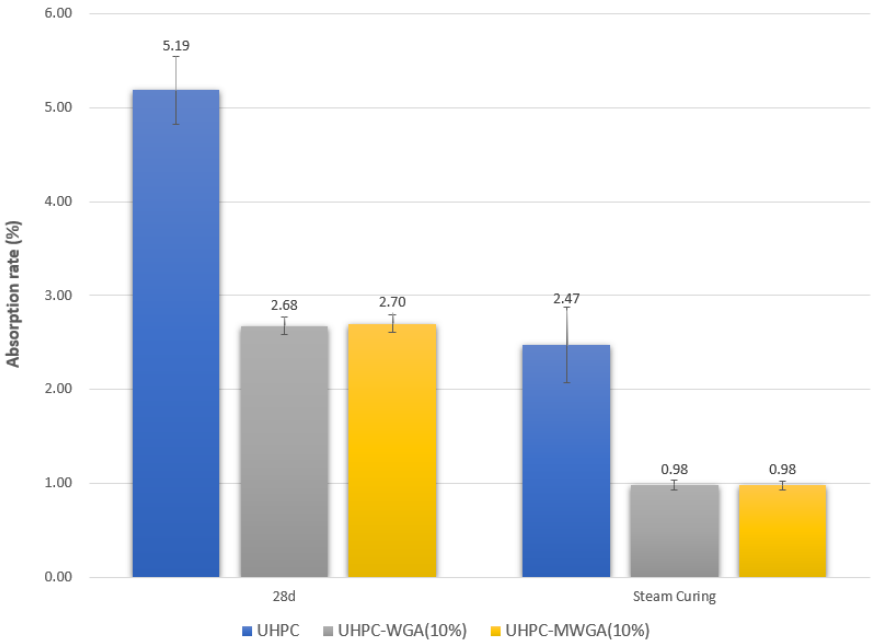


Figure 6-7 The absorption rate of UHPC, UHPC-WGA (10%), UHPC-MWGA (10%)

6.4.3 Acid resistance test

The acid resistance test is conducted as described in Chapter 3.

1. pH 1

   As shown in Table 6-6 and Figure 6-8, when immersed in pH 1 solution, the specimens replaced with 10% of the surface modification waste glass aggregate are more acidified than UHPC by more than 40%. In addition, UHPC-MWGA (10%) is less acidification than UHPC-WGA (10%) by 20%.

2. pH 3

   As shown in Table 6-7 and Figure 6-9, when immersed in pH 3 solution, the specimens replaced with 10% of the surface modification waste glass aggregate are less acidified than UHPC by more than 60%. Likewise, 2% less acidification is performed compared to the UHPC-WGA (10%).

3. pH 5

   As shown in Table 6-8 and Figure 6-10, when immersed in pH 5 solution, the specimens replaced with 10% of the surface modification waste glass aggregate are less acidified than UHPC by more than 65%. Likewise, 6% less acidification is performed compared to the UHPC-WGA (10%).

Therefore, as mentioned in Chapter 3, the range of domestic acid rain is pH 4.3 to 6.0. At low pH, acidification proceeds more than UHPC, but in the acid rain range, it shows a good effect rather than UHPC and UHPC-WGA (10%).

Table 6-6 The acid resistance rate of UHPC, UHPC-WGA (10%), UHPC-MWGA (10%) of pH 1

	pH 1			
	14d		28d	
	Weight gain rate (%)	Relative ratio	Weight gain rate (%)	Relative ratio
UHPC(Ref.)	0.0373	1	0.3573	1
UHPC-WGA(10%)	0.2433	6.52	0.5836	1.63
UHPFRC-MWGA(10%)	0.2120	5.68	0.5111	1.43

Table 6-7 The acid resistance rate of UHPC, UHPC-WGA (10%), UHPC-MWGA (10%) of pH 3

	pH 3			
	14d		28d	
	Weight gain rate (%)	Relative ratio	Weight gain rate (%)	Relative ratio
UHPC(Ref.)	0.0174	1	0.0958	1
UHPC-WGA(10%)	0.0191	1.10	0.0383	0.40
UHPFRC-MWGA(10%)	0.0177	1.02	0.0363	0.38

Table 6-8 Th acid resistance rate of UHPC, UHPC-WGA (10%), UHPC-MWGA (10%) of pH 5

	pH 5			
	14d		28d	
	Weight gain rate (%)	Relative ratio	Weight gain rate (%)	Relative ratio
UHPC(Ref.)	0.0166	1.00	0.0910	1.00
UHPC-WGA(10%)	0.0143	0.86	0.0363	0.40
UHPFRC-MWGA(10%)	0.0144	0.86	0.0310	0.34

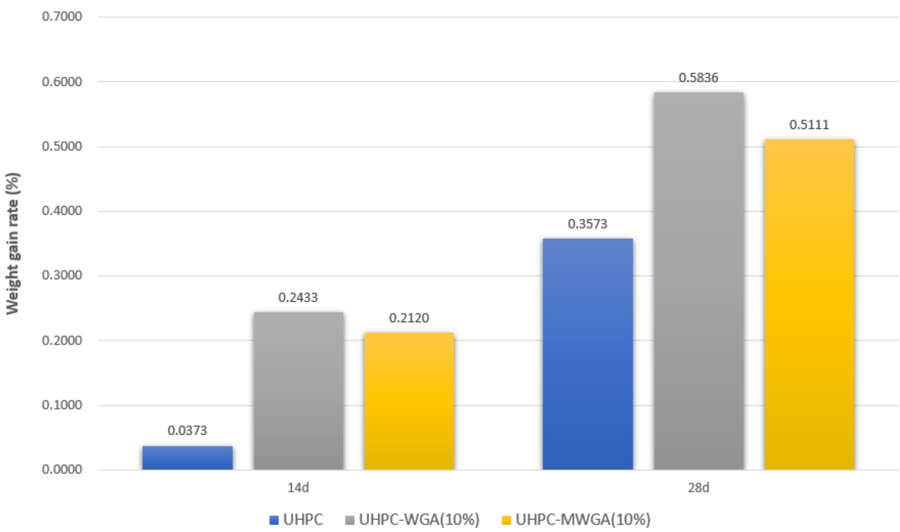


Figure 6-8 The acid resistance rate of UHPC, UHPC-WGA (10%), UHPC-MWGA (10%) of pH 1

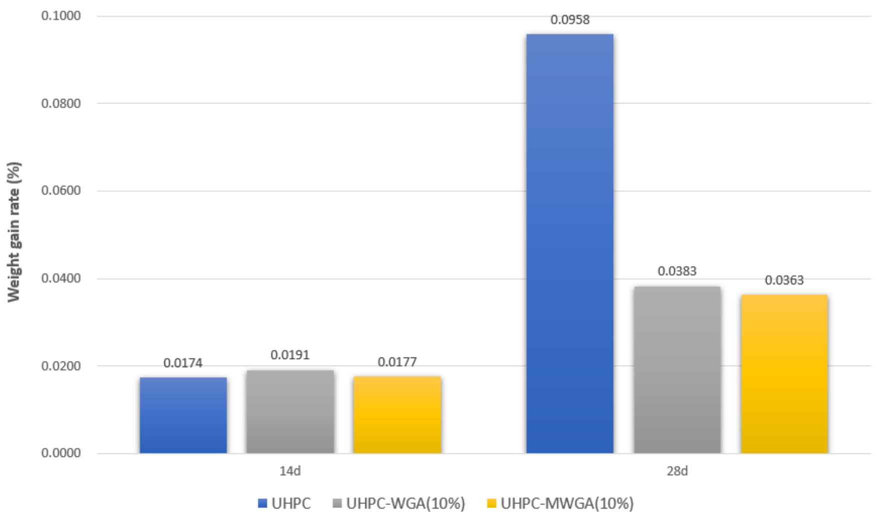


Figure 6-9 The acid resistance rate of UHPC, UHPC-WGA (10%), UHPC-MWGA (10%) of pH 3

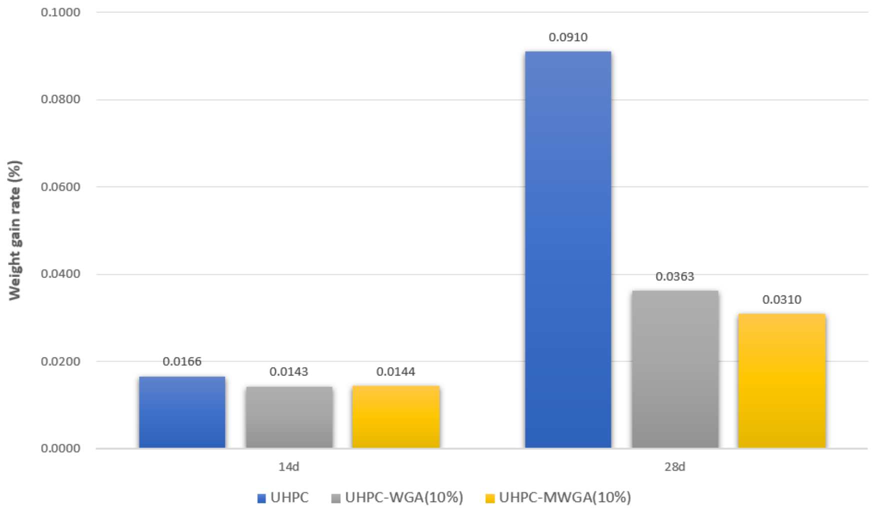


Figure 6-10 The acid resistance rate of UHPC, UHPC-WGA (10%), UHPC-MWGA (10%) of pH 5

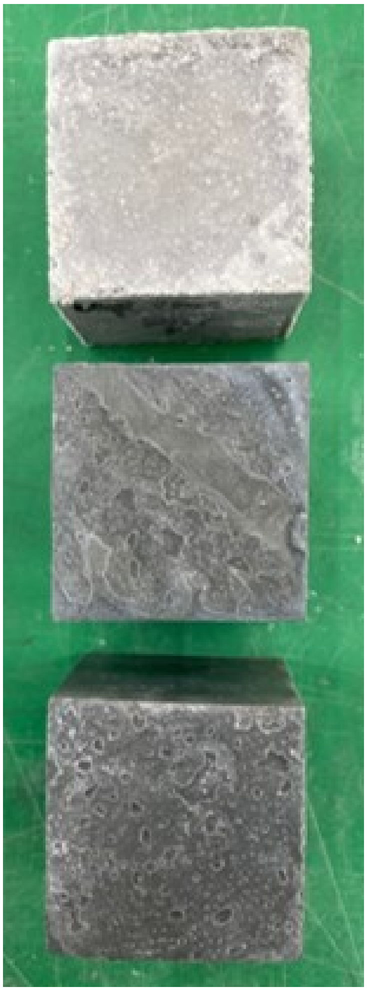


Figure 6-11 The acid resistance test after 16 days for UHPC-MWGA (10%)

6.5 Discussion

In this Chapter 6, the second method was applied to compensate for the reduced mechanical properties performance when 10% of the waste glass aggregate was replaced. The mechanical properties and durability tests results were confirmed by comparing the surface modification of the waste glass aggregate with UHPC.

To summarize 2 things,

1. Mechnical properties tests result

   The fluidity of surface modification waste glass aggregate for UHPC decreased. It decreased because the surface of the waste glass aggregate, which is the purpose of surface modification, became rough. However, UHPC-MWGA (10%) showed 90% performance of UHPC, so it is suitable.

   In terms of the compressive strength, the compressive strength slightly increased when the surface of the waste glass aggregate was modified. Although it didn’t increase compared to UHPC, it is confirmed that there is no significant effect in the three cases with similar values.

   The flexural strength increased slightly when the surface of the waste glass aggregate was modified, but it is also not considered to have a significant effect.

2. Durability testes result

   It was confirmed that the expansion rate of UHPC-MWGA (10%) was slightly reduced when moditying the surface of the waste glass aggregate and the standard was met, but it was confirmed that there was no significant effect on UHPC-WGA (10%).

   In the absorption rate test, it was confirmed that there was no significant effect when the surface of the waste glass aggregate was modified, showing the same values as the UHPC-WGA 10%).

   In the acid resistance test, if the surface of the waste glass aggregate was modified when the acidity was very low, the acidification was reduced than that of UHPC-WGA (10%), but the acidification proceeded more than that of UHPC, so it is not suitable. However, when the acidity was somewhat low, the acidification was also decreased compared to that of UHPC-WGA (10%) and decreased compared to that of UHPC. Since the pH concentration, which is important in acidification, is low, like to the acid rain concentration, it was confirmed that the surface modification of the waste glass aggregate has a good effect.

Based on theses results, it can be proposed that modifying the surface of waste glass aggregate for UHPC-WG A(10%) is further implemented to enhance only acid resistance. There are no significant effects in other tests.

Chapter 7. Conclusions

Waste glass is representing as an environmental problem all over the world and the recycling rate is very low. This thesis aims to develop a new Ultra High-Performance Concrete by crushing waste glass into fine aggregate size and replacing silican sand, which is the fine aggregate of Ultra High-Performance Concrete.

Glass is an amorphous silica mineral with smooth surface. The resulting reaction with concrete has negatice effects. Because the surface of glass is smooth, the boding strength with the inside of the concrete is weak, reducing the performance. In addition, when glass, which is an amorphous silica mineral, is used as an aggregate, it forms an expansional gel when it encounters cement, causing negative swelling (ASR).

Therefore, when replacing waste glass aggregate with Ultra High-Performance Concrete, the optimal replacement rate was selected by considering all performance, economic efficiency, and eco-friendliness. In addition, two methods (adding steel fiber and modifying surface of waste glass aggregate) were applied to compensate for the performance degradation due to waste glass aggregate and mechanical properties and durability tests were conducted to confirm suitability. Based on experimental results and analyses, the following conclusions can be drawn.

In Chapter 4, by substituting waste glass aggregate instead of silica sand of UHPC, specimens were made with the replacement rate as a parameter and mechanical properties tests were conducted. Since the surface of the waste glass aggregate is smooth, the performance of Ultra High-Performance Concrete gradually decreased as the replacement rate of waste glass aggregate increased. In the flow test, as the replacement rate of waste glass aggregate increased, the fluidity decreased. However, up to the replacement rate of 20%, it was suitable by expressing more than 90% of the performance of UHPC. In terms of compressive strength test, if the replacement rate is 10% or 20%, it is 97, 96% of performance of UHPC and these are suitable because these are more than 150 MPa. The flexural strength was similarly degraded but had no significant effect. Based on these results, the replacement rate of waste glass aggregate was set at 10% in consideration of performance, economical and eco-friendly factors.

In Chapter 5, by adding steel fiber with UHPC-WGA (10%), mechanical properties and durability tests were conducted to confirm suitability. First, if the durability test of UHPC-WGA (10%) was confirmed, the ASR of UHPC-WGA (10%) was suitable for the standard. In addition, when the replacement rate was 20%, it didn’t satisfy the standard, which provided an additional basis for the replacement rate of 10%. In the absorption rate test, it was decreased when the waste glass aggregate was replaced. It showed a good effect because the inner matrix became dense due to the small ASR caused by the waste glass aggregate. In the acid resistance test, it showed a good effect at a rather low pH concentration like to acid rain concentration. If steel fiber was added, the fluidity decreased, but it was suitable, and both compressive and flexural strengths increased compared to UHPC-WGA (10%). In the durability test, UHPC-MWGA (10%) showed a good effect because the ASR expansion rate of UHPC-WGA (10%) was small, and the absorption rate was slightly increased. In addition, it showed a better effect than UHPC-WGA (10%) at a rather lower pH concentration like to acid rain concentration. Based on these results, it was confirmed that the adding of steel fiber in UHPC-WGA (10%) compensate for the performance degradation caused by waste glass aggregates.

In Chapter 6, by modifying surface of waste glass aggregate for UHPC-WGA (10%), mechanical properties and durability tests were conducted, and suitability was confirmed. In case of surface modification of waste glass aggregate, the surface becomes rough, so fluidity is reduced, but it is suitable for 90% of UHPC performance. Compressive strength due to the roughened surface of waste glass aggregate, the inner bonding strength was stronger, and the compressive strength increased compared to UHPC-WGA (10%), but the performance was not as high as that of UHPC. There was no significant change in flexural strength. In the durability test, the ASR expansion rate not only satisfied the standard, but was also reduced compared to UHPC-WGA (10%), showing a good effect. This result was because the contact surface of the waste glass aggregate with the cement was reduced because of surface modification. No significant change was observed in the absorption rate test. In the acid resistance test, it showed a better effect than UHPC-WGA (10%) at a slightly lower pH concentration like to acid rain concentration. Based on these results, it was confirmed that if the surface of the waste glass aggregate was modified and then replaced with silica sand, it was suitable to compensate for the performance degradation caused by the waste glass aggregate, but it did not show a significant effect.

In conclusion, considering performance, economy, and eco-friendliness, a 10% replacement rate for waste glass aggregate is the most suitable rate, and the durability test showed good results. In addition, when steel fiber was added, the performance reduction of UHPC-WGA (10%) was sufficiently compensated and a better effect was shown, but the modifying surface of waste glass aggregate did not have a significant effect.

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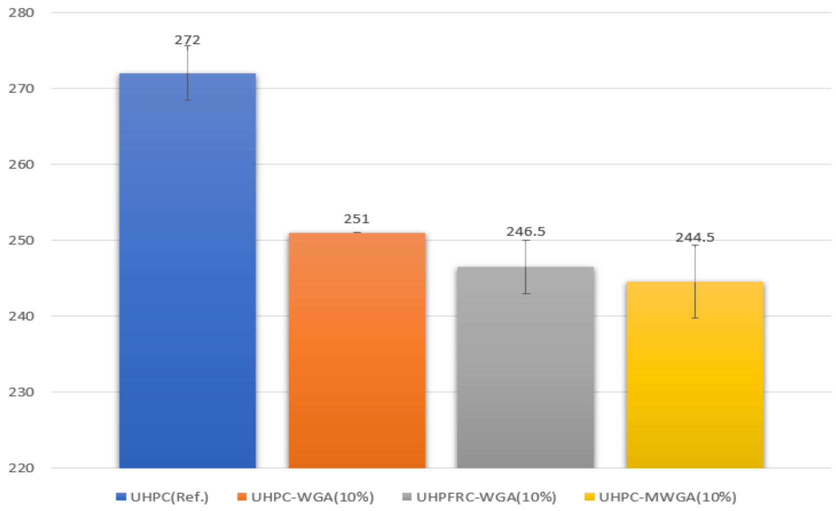
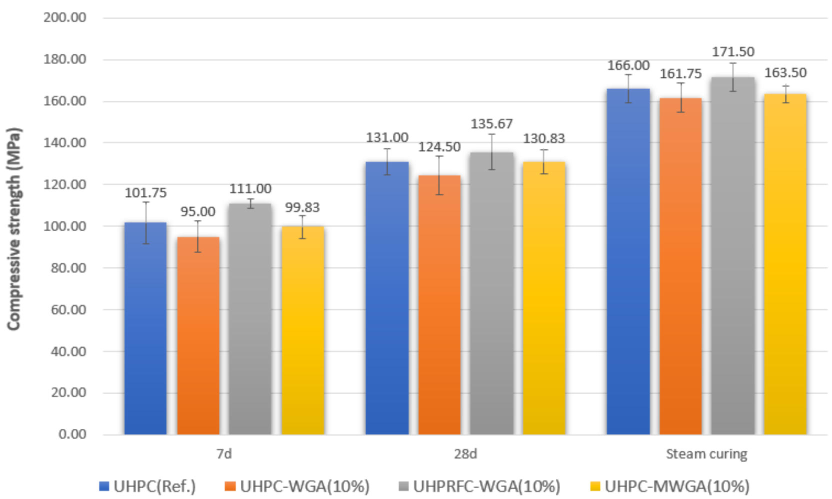
Appendix

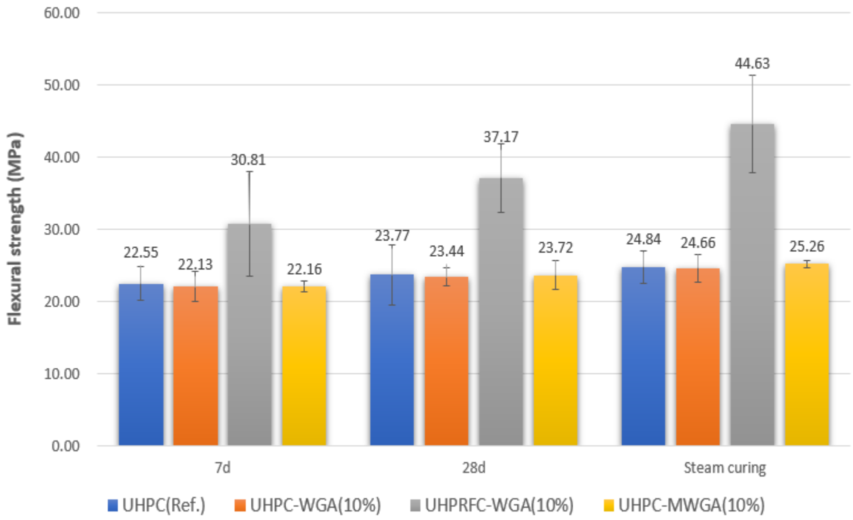
Appendix. A-1 Comparing all the specimens of the flow test



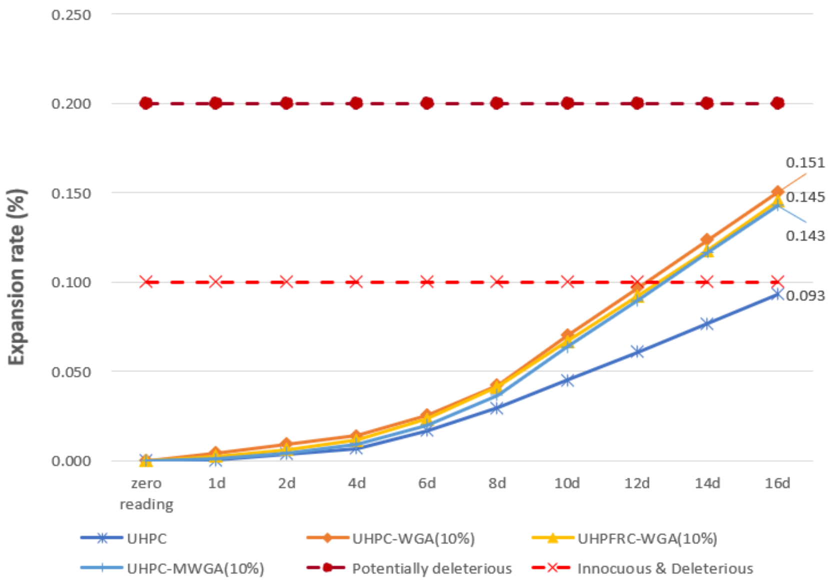
Appendix. A-2 Comparing all the specimens of the compressive test



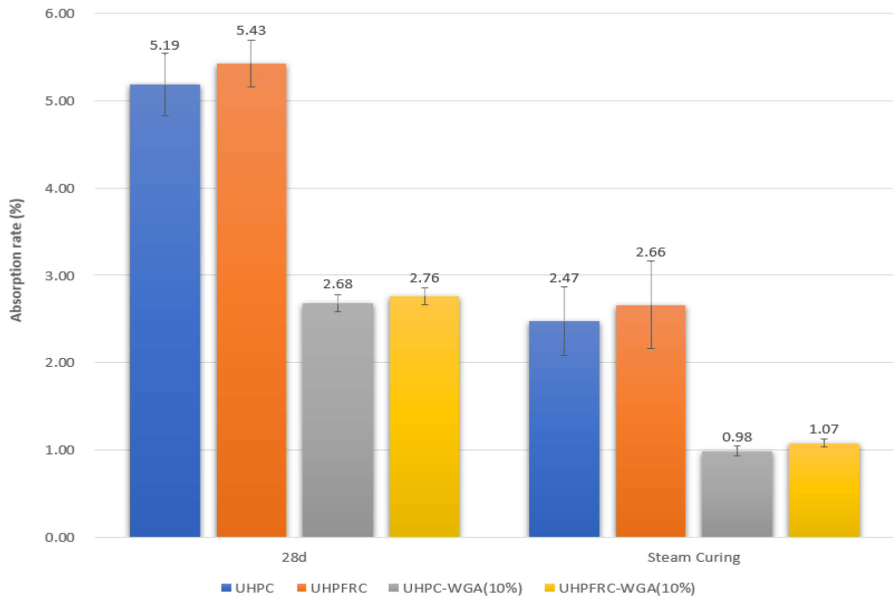
Appendix. A-3 Comparing all the specimens of the flexural test



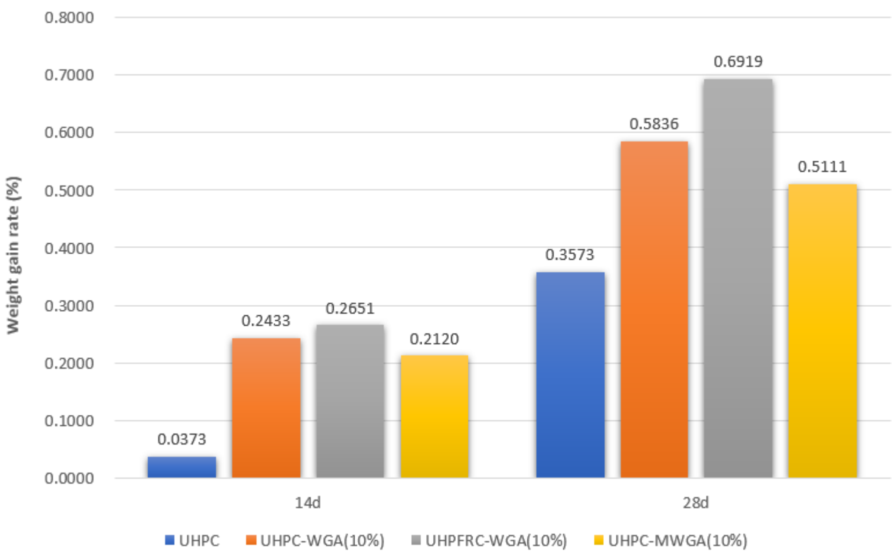
Appendix. A-4 Comparing all the specimens of the ASR test



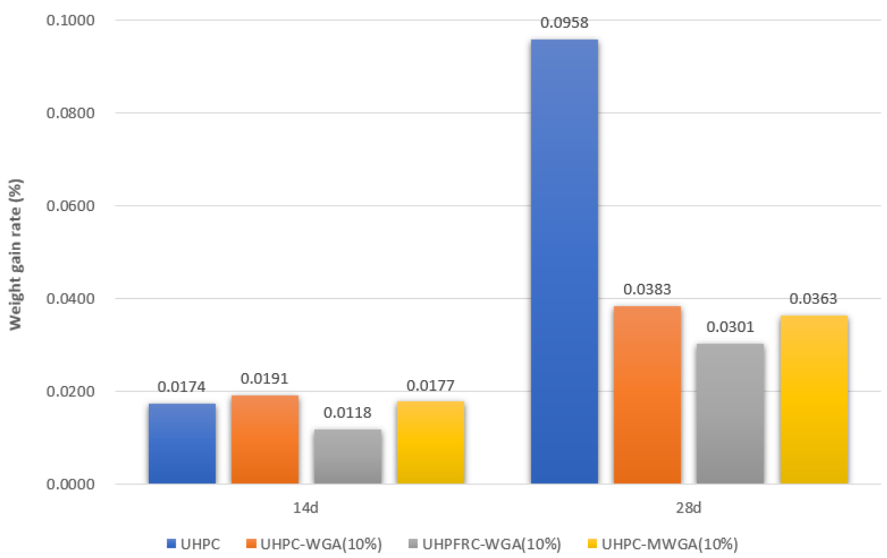
Appendix. A-5 Comparing all specimens of the absorption test



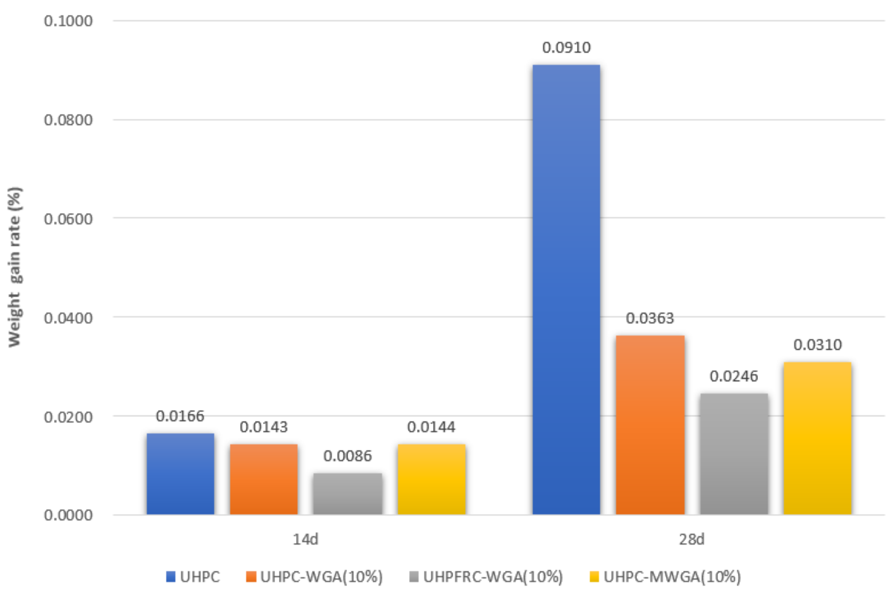
Appendix. A-6 Comparing all specimens of the acid resistance test (pH 1)



Appendix. A-7 Comparing all specimens of the acid resistance test (pH 3)



Appendix. A-8 Comparing all specimens of the acid resistance test (pH 5)



초 록

초고성능 콘크리트의 폐유리 골재 적용 효과 및 분석

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전 세계적으로 폐유리는 환경적인 문제로 부상하고 있다. 많은 폐유리가 매립지에 그대로 묻히기 때문에 환경적인 오염을 유발시키고 또한 폐유리의 재활용율도 재활용 의무량 기준에 도달하지 못하고 있다. 따라서 폐유리의 재활용에 관한 관심이 증가하는 가운데 최근 폐유리의 건축적 활용에 대한 연구들이 활발히 진행되고 있다. 대표적으로 폐유리를 파우더 크기로 분쇄하여 콘크리트의 시멘트와 대체하거나 골재 크기로 파쇄하여 콘크리트 속 골재를 대체하는 연구로 나뉜다. 하지만 기존 논문들에서는 폐유리의 대체율에 따른 성능 변화가 일정하지 않았다. 그리고 폐유리로 인한 부정적 영향인 ASR 반응도 일정하지 않았다. 일반 콘크리트에 폐유리 혼입에 관한 연구는 진행중인 반면, 초고성능 콘크리트에 폐유리 혼입에 관한 연구는 거의 이루어지지 않았다.

따라서 본 연구에서는 초고성능 콘크리트의 잔골재를 폐유리골재로 대체하는 것에 초점을 두었다. 초고성능 콘크리트의 잔골재인 실리카 퓸과 폐유리 골재를 비교하면서 성능 확인이 필요하다. 폐유리 골재가 실리카 퓸에 비해 표면이 매끄럽기 때문에 slip 현상이 발생할 것으로 예상, 성능적 저하가 우려된다. 따라서 성능에 영향을 미칠 것으로 예상되는 폐유리 골재 대체율을 변수로 두고 실험하였다. 또한 성능저하에 두 가지 방안을 적용하여 실험하였다. 결론적으로, 폐유리 골재 대체율이 증가함에 따라 초고성능 콘크리트의 성능이 저하되었다. 하지만 친환경성, 경제성을 고려할 경우 대체율이 10%가 최적의 배합비로 나타났다 (기존 초고성능 콘크리트 성능의 95%이상의 성능). 또한 폐유리 골재 대체(10%)에 따른 성능저하에 대한 방안 두 가지를 적용한 초고성능 콘크리트의 성능이 물리성, 내구성 실험을 통하여 향상 된 것을 확인했다.

본 연구는 환경적으로 큰 문제가 되고 있는 폐유리를 골재 크기로 파쇄하여 초고성능 콘크리트에 적용함으로써 물리성, 내구성 실험을 평가하고 친환경적, 경제적이며 성능에서 우수한 새로운 초고성능 콘크리트의 개발 근거를 제공할 수 있을 것으로 기대된다.

주요어 : 초고성능 콘크리트, 폐유리 골재, 슬립, 알칼리-실리카 반응, 표면개질

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