

# Quality of Recycled Fine Aggregate using Neutral Reaction with Sulfuric Acid and Low Speed Wet Abrader

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## Abstract

The use of recycled aggregate, even for low-performance concrete, has been very limited because recycled aggregate, which contains a large amount of old mortar, is very low in quality. To produce a high-quality recycled aggregate, removing the paste that adheres to the recycled aggregate is very important. We have conducted research on a complex abrasion method, which removes the component of cement paste from recycled fine aggregate by using both a low-speed wet abrasion crusher as a mechanical process and neutralization as chemical processes, and well as research on the optimal manufacturing condition of recycled fine aggregates. Subsequently, we evaluated the quality of recycled fine aggregate manufactured using these methods, and tested the specimen made by this aggregate. As a result, it was found that recycled fine aggregates produced by considering the aforementioned optimal abrasion condition with the use of sulfuric acid as reactant showed excellent quality, recording a dry density of 2.4 and an absorption ratio of 2.94. Furthermore, it was discovered that gypsum, which is a reaction product occurring in the process, did not significantly affect the quality of aggregates. Furthermore, the test of mortar using this aggregate, when gypsum was included as a reaction product, showed no obvious retarding effect. However, the test sample containing gypsum recorded a long-term strength of 25.7MPa, whereas the test sample that did not contain gypsum posted a long-term strength of 29.4MPa. Thus, it is thought to be necessary to conduct additional research into the soundness and durability because it showed a clear reduction of strength.

Keywords : neutralization, recycled fine aggregate, low speed wet abrader, high quality, gypsum

## 1. Introduce

### 1.1 Research background and objective

As the demand for urban redevelopment has been on the rise, the SOC and housing built in the 1960s and 1970s is being dismantled. The industrial waste generated during this dismantling

is not environmentally hazardous, but the volume of waste is massive and should be handled with care. The annual industrial waste produced by dismantling has risen more than 5-fold, from 16 million tons in the 1990s to 64 million tons in 2008, and now accounts for more than 50% of the total waste generated in Korea[1,2,3]. In contrast with the trend for industrial waste of other types, for which the increase has slowed, dismantling-related waste continues to increase, and it is expected to amount to about 1 billion tons in 2020[4].

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enacted “Quality Criteria for Recycled Aggregate” in August 2005 based on Article 35 in the Act on the Promotion of Construction Waste Recycling, to promote the recycling of industrial waste and improve utilization of waste concrete.

The usage of recycled concrete is categorized into 13 grades, from high-quality concrete to low-quality concrete for burial. Of these various usages, recycled aggregate falls into a relatively low grade. It is natural that low-quality waste concrete should be used for purposes with low quality requirements. However, there are some regions in which the supply of concrete is not smooth, and some markets where demand for low-quality concrete is not particularly high; therefore, a technology to produce high-quality recycled aggregate must be developed. In developing the technology, the quality of recycled aggregate has a close relation with the amount of the old cement paste attached to the original coarse aggregate, and it is necessary to remove the old cement paste as much as possible.

On the other hand, potassium hydroxide ( $\text{Ca(OH)}_2$ ) and calcium silicate hydrate account for 20~25% of cement paste.  $\text{Ca(OH)}_2$  is one of the alkali hydrates, and when dissolved into water, the pH of the water reaches 12 or higher. Recycled aggregate contains some  $\text{Ca(OH)}_2$  generated in an initial reaction of carbonization, but a large amount of  $\text{Ca(OH)}_2$  is still contained within it. Therefore, when recycled aggregate is widely used as a burial material, it will inevitably become a pollutant that continues to pollute soil and water resources. With this in mind, the removal of the alkali material from recycled aggregate is a significant step in enabling recycled aggregate to be used stably. In line with this, in the 2011 environmental management criteria for recycled aggregate, it is recommended to use pre-processed

aggregate with a pH of 9.8 or lower of hydrogen ion concentration by usage[5].

This study aims to present a plan to simultaneously resolve the problem of removal of alkali source while improving the quality of recycled aggregate. Low-quality recycled aggregate with high content of old cement paste was stirred using a low-speed wet abrader to make it into high-quality recycled aggregate, and the characteristics of the mortar with the high-quality aggregate manufactured in this process was observed.

## 1.2 Literature review

Recycled aggregate is generally produced through more than 4 successive abrasion and cleansing processes. The water separation process is a technology to produce high-quality recycled sand by removing fine particles using cleansing water. The pre-processed coarse aggregate with abrasion or sieving is put into a tank with cleansing water inside or outside of an oil water separator. In the separator, air or high-pressure water is supplied to generate eddy and foam which causes the aggregate to sink to the bottom while suspended soils are buoyant on the top, and then the water with the suspended soils and fine particles is released out of the tank, leaving the aggregate in the tank. The wind separation process is a dry separation method. In this process, wind is blown to the crushed recycled aggregate and fine particles that are a hindrance to the production of high-quality sand from waste concrete lumps to remove the fine particles using weight difference. However, in both processes, the bond strength of the aggregate with cement paste was shown to be similar to the strength of aggregate. It is believed that despite the successful removal of cement paste from aggregate through several abrasion and

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cleansing processes, the aggregate was also cracked in the abrasion process, which causes a sharp decline in the strength of the aggregate produced. For this reason, it is controversial for the aggregate to be used as concrete aggregate. Therefore, there are realistic constraints to improving the quality of recycled aggregate using the conventional abrasion and grinding process only. Hence, a new method is needed to effectively separate concrete paste from aggregate. With this in mind, this study aims to separate concrete paste from aggregate by re-abrading the aggregate that has already passed through the conventional abrasion and grinding process. The abrasion mechanism largely consists of compression, impact, shear and friction. However, the abrasion mechanism is hardly used without repetition. Two or more forms of abrasion mechanism are used simultaneously. To improve the efficiency of the abrasion process, if diverse types of abrasion media are applied, the abrasion media deliver more energy to the material to be crushed, and the abrasion efficiency can be improved.

### 1.3 Old cement paste vulnerable to neutralization reaction

$\text{Ca(OH)}_2$ , which is known as the cause of alkali, dissolves in water, but is low in solubility while high in degree of ionization. These characteristics prevent  $\text{Ca(OH)}_2$  from being removed rapidly, but since  $\text{Ca(OH)}_2$  dissolved can be ionized, it can be turned into other material through the neutralization reaction.

This neutralization reaction can be effective when solid calcium hydroxide is dissolving in liquid solution. When the neutralization reaction is processed while the solid calcium hydroxide is dissolving and the neutralization reaction triggers, calcium carbonate is created. It is reported as a problem that the average size of the calcium

carbonate generated through the reaction is  $1\sim 3\mu\text{m}$ , which is relatively smaller than the natural size of calcium carbonate of  $3\sim 5\mu\text{m}$ , which sinks and adheres to the surface of the recycled aggregate and fills the pores from which  $\text{Ca(OH)}_2$  comes off[6]. To resolve the problem, acid water, usually used with an abrasion method rather than the conventional crushing and grinding method, was used in the neutralization reaction instead of process water. The neutralization reaction removes  $\text{Ca(OH)}_2$  with a small energy by making  $\text{Ca(OH)}_2$  a soluble, alkali material of components of cement paste, react with acidic material, and making the cement paste porous and vulnerable as a result[7]. This is based on the experiment result that cement paste, mortar or concrete reacted with the acidic or magnesium solution, and its compressive strength decreased by 2% at the removal of 1%  $\text{CaO}$ [8]. In addition, the alkali process water is neutralized and no waste water is generated, and aggregate cleansing efficiency is also expected[9]. On the other hand, the abrasion method applied along with neutralization reaction, as shown in Figure 1, effectively separates the porous cement paste after the reaction without any destruction in or damage to aggregate itself using kinetic energy, through friction between aggregates and free fall.

When the method above was applied to the production process of recycled aggregate, it was found that cement paste was effectively separated, and density increased and absorption rate decreased accordingly. However, the acid used in the neutralization reaction was sulfur, which reacted with  $\text{Ca(OH)}_2$  and turned into gypsum( $\text{CaSO}_4$ ). Gypsum was ionized in the cement paste matrix before  $\text{C}_3\text{A}$  was melted, delaying hydration and forming ettringite ( $3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 3\text{CaSO}_4 \cdot 31\text{H}_2\text{O}$ ) that turned into monosulfate ( $3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{CaSO}_4 \cdot 12\text{H}_2\text{O}$ ). It was

reported that if there was a lot of ettringite, monosulfate was formed rapidly, which brought about volume collapse and had adverse effects on the characteristics of strength[10].

For this reason, low-speed wet abrasion was used in this study along with neutralization of low-quality recycled aggregate to make high-quality recycled aggregate. The characteristics of the aggregate newly made were reviewed by testing density, absorption ratio, aggregate strength and aggregate soundness. The mortar was tested based on the results to analyze the influence and strength of gypsum.

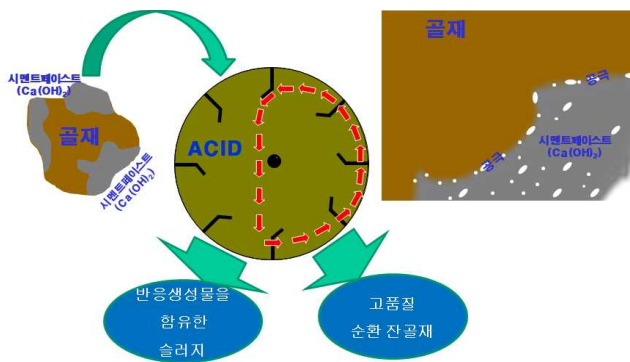


Figure 1. Principle of technique

## 2. Characteristics of recycled aggregate produced by neutralization reaction and low-speed wet abrasion

### 2.1 Outline

To review the physical characteristics of recycled aggregate produced by neutralization and low-speed wet abrasion, several tests were conducted. Through the tests, it was revealed that the important factors influencing aggregate quality were the amount of process water and abrasion time, and the amount of the material to be abraded[11]. Based on this, the optimal conditions were drawn from a preliminary study, and it was found that the smaller the amount

of cleansing water, the longer the abrasion time, and the more the material to be abraded, the more efficient the production process. In particular, when there was more material to be abraded, it took less time for abrasion[12]. The characteristics of recycled aggregate produced using the optimal conditions drawn in the preliminary study were reviewed.

### 2.2 Experiment plan and method

#### 2.2.1 Experimental plan

As indicated in Table 1, the experiment plan and levels were to perform a comparative analysis of density and absorption ratio of the low-quality aggregate and the processed high-quality aggregate with gypsum and that with no gypsum. In particular, a wet sieving was done for the processed aggregate to analyze changes in grading of the processed aggregate.

Table 1. Experimental factors and levels

| Factor Levels   | Test items                   |                      |             |
|---|------------------------------|----------------------|-------------|
|   | Before acid treatment        | After acid treatment |             |
|   | Physical                     | Physical             | Chemical    |
| A   | - Density                    | - Density            |             |
| B   | - Grade                      | - Grade              |             |
| Aggregate   | - Absorption ratio           | - Absorption ratio   | - XRD & XRF |
|   | - Percentage of solid volume | - Soundness          |             |
| C   |                              | - Crushing ratio     |             |
| D   | -                            | - Wet sieve analysis | -           |
| A - Low quality recycled fine aggregate                                   |                              |                      |             |
| B - High quality recycled fine aggregate 1                                |                              |                      |             |
| C - High quality recycled fine aggregate 2 (Washing after acid treatment) |                              |                      |             |
| D - High quality recycled fine aggregate 1 (Wet sieve analysis)           |                              |                      |             |

#### 2.2.2 Experimental method

Figure 2 indicates the experimental method using friction between aggregates and head with a tilting mixer. The low-quality recycled aggregate and coarse aggregate were placed and the cleansing water was added. Sulfuric acid was added three times at an

interval of 3 minutes, and the abrasion time was set at 10 minutes.

After abrasion and acidic process, the aggregate was dried at two different temperatures:  $100^{\circ}\text{C}\pm 5$  and  $45^{\circ}\text{C}\pm 5$ . Figure 3 illustrates the low-speed wet abrader.

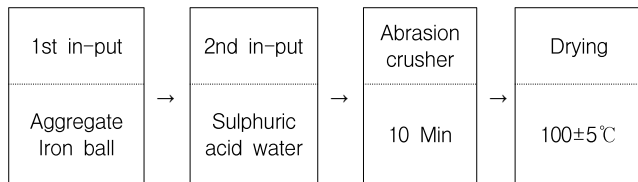


Figure 2. Experimental method



Figure 3. Low Speed Wet Abrader

### 2.2.3 Materials and measurement method

#### 1) Materials

The recycled aggregate used in the test was produced by D company located in Cheonan-si, Chungcheongnam-do, and the physical properties of the aggregate are indicated in Table 2. In addition, the cleansing water used in the test was tap water used in a general recycled aggregate manufacturer, and the sulfuric acid, odorless and pale yellow, with 98% of purity, produced by L Company, was used in a weight ratio of 1,84.

Table 2. The physical properties of recycled fine aggregate

| Density (g/cm <sup>3</sup> ) | absorption ratio (%) | F.M. | Solid content in aggregate(%) | Unit weight (kg/m <sup>3</sup> ) |
|------------------------------|----------------------|------|-------------------------------|----------------------------------|
| 2.27                         | 6.56                 | 3.40 | 59.6                          | 1443                             |

#### 2) Measurement method

The quality test for the recycled aggregate was based on the items stipulated in the quality criteria for recycled aggregate (limited only to recycled aggregate for concrete), and the items not stipulated in the quality criteria were tested based on the general test criteria for aggregate. In addition, chemical characteristics and the characteristics of hydrate were reviewed by XRD and XRF.

### 2.3 Test results

Table 3 shows the physical characteristics of aggregate before and after neutralization and abrasion process and before and after removal of gypsum. The aggregate quality was shown to be improved after the neutralization and abrasion, and the aggregate quality was also shown to be improved after the gypsum removal compared to the quality before the removal.

Table 3. Test results

| ID | Density (g/cm <sup>3</sup> ) | Absorption ratio(%) | Soundness (%) | Crushing ratio(%) |
|----|------------------------------|---------------------|---------------|-------------------|
| A  | 2.27                         | 6.56                | 5.2           | 4.20              |
| B  | 2.41                         | 4.21                | 6.7           | 2.72              |
| C  | 2.47                         | 2.98                | 5.1           | 2.26              |

A - Low quality recycled fine aggregate  
 B - High quality recycled fine aggregate 1  
 C - High quality recycled fine aggregate 2  
 (Washing after acid treatment)

#### 2.3.1 Density and absorption ratio

Figure 4 illustrates density and absorption ratio of the recycled aggregate by level. The density of the aggregate under the neutralization and abrasion process (B) was shown to be improved compared to the original aggregate (A), at 2.41(g/cm<sup>3</sup>) versus 2.27(g/cm<sup>3</sup>), but the highest density in the aggregate was measured at 2.47 under the cleansing process after the neutralization and

abrasion process(C). Inversely to the density, the absorption ratio was gradually decreasing from 6.56% to 4.21% after the neutralization and abrasion and to 2.98% under the cleansing.

In the neutralization and abrasion process, the sulfuric acid( $H_2SO_4$ ) reacted with calcium hydroxide( $Ca(OH)_2$ ) in the cement paste, and the hydrate was released, resulting in many pores on the cement paste surface, which led to a deterioration in bond strength between aggregate and cement paste. The improvement of the abrasion environment caused the coarse aggregate to turn into fine aggregate, which is believed to have improved density and decreased absorption ratio.

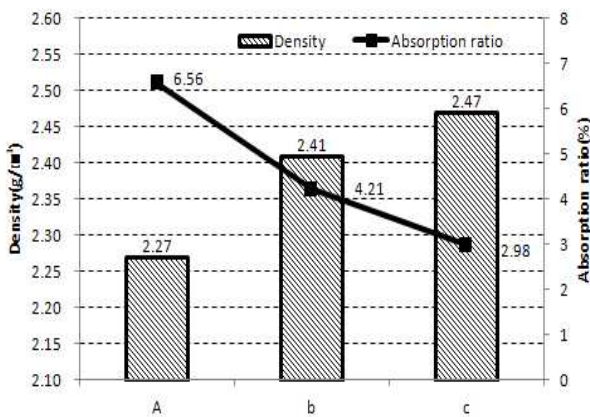


Figure 4. Density and absorption ratio

### 2.3.2 Grading

Figure 5 shows the grading of each test material, and an overall decrease in the size of the aggregate produced under the neutralization and abrasion was found compared to the low-quality recycled aggregate before the process. In addition, D, the specimen identical to B, was sieved under a wet condition. Despite having identical properties to B before the test, the F.M (fineness modulus) of D was shown to be lower. It is believed that the aggregate was lumped in the drying process after abrasion, and that the fine particles and gypsum adhering to

the aggregate were released by the cleansing water. In C aggregate, less fine particles were found because C was in the process of cleansing before drying after the acid process, and in the process fine particles and gypsum were released.

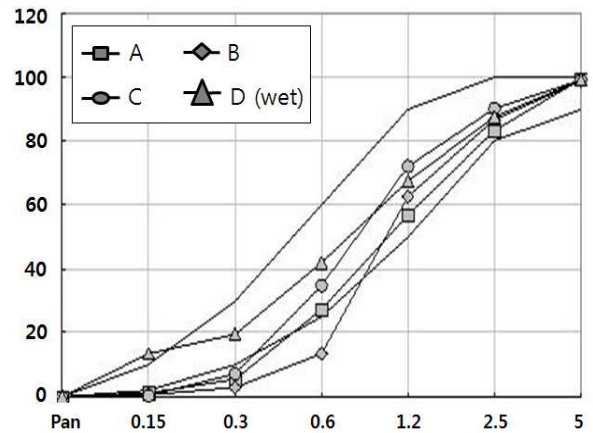


Figure 5. A grading curve

### 2.3.3 Soundness

Figure 6 illustrates the soundness results of the recycled fine aggregate produced from low-quality recycled aggregate through the acid process. The soundness of original aggregate (A) was shown to be 5.2%, of the coarse aggregate after the neutralization and abrasion (B) was shown to be 6.7%, and of the aggregate under the cleansing after the process (C) was shown to be 5.1%, all of which satisfied less than 10% soundness set in the Quality Criteria for Recycled Aggregate. In particular, C showed a higher soundness value than B, based on which it is believed that there were gypsum and fine particles in the aggregate itself and the fine particles were removed in the cleansing process after the soundness test.

### 2.3.4 Characteristics of aggregate strength

The abrasion ratio of aggregate strength by 100KN is shown in Figure 7. The original aggregate (A) stood at 4.2%, which was the highest in terms

of the abrasion ratio, followed by 2.72% of the aggregate after neutralization and abrasion process (B) and 2.26% of the aggregate under the cleansing after the process (C). In the course of the entire process, the calcium hydroxide ( $\text{Ca}(\text{OH})_2$ ) in the cement paste was separated in the form of gypsum ( $\text{CaSO}_4$ ), which created a vulnerable contact surface between aggregate and cement paste, and the cement paste was actively separated from the aggregate, accordingly. The aggregate that only went through neutralization and abrasion (B) was under the sieving process, and in the process the gypsum and fine particles were removed, and the abrasion ratio was improved compared to the aggregate under the cleansing process(C).

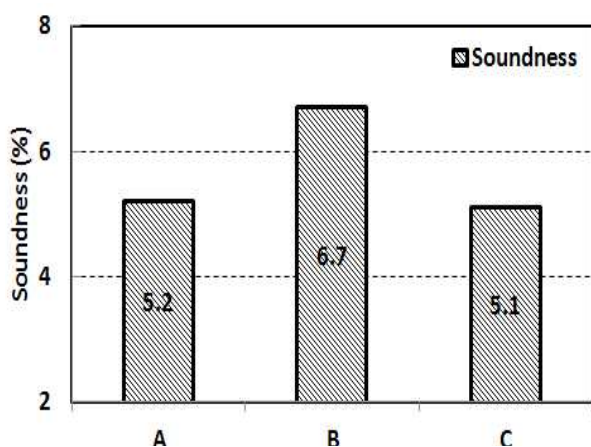


Figure 6. A variation of soundness

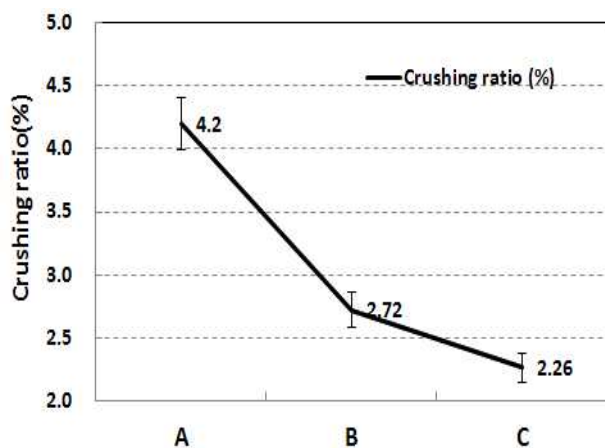


Figure 7. A variation of crushing ratio

Table 4. The chemical composition of ID B

| Type                           | C       |         |         |         |          |
|--------------------------------|---------|---------|---------|---------|----------|
|                                | average | 1.2-2.5 | 0.6-1.2 | 0.3-0.6 | 0.15-0.3 |
| Na <sub>2</sub> O              | 0.04    | 0.05    | 0.08    | 0.03    | 0.00     |
| MgO                            | 0.94    | 1.09    | 0.96    | 0.78    | 0.94     |
| Al <sub>2</sub> O <sub>3</sub> | 8.73    | 9.54    | 8.63    | 8.26    | 8.49     |
| SiO <sub>2</sub>               | 59.47   | 58.87   | 59.22   | 60.80   | 58.97    |
| SO <sub>3</sub>                | 3.93    | 3.51    | 4.17    | 3.60    | 4.44     |
| K <sub>2</sub> O               | 6.00    | 6.19    | 5.87    | 5.82    | 6.11     |
| CaO                            | 13.20   | 12.62   | 13.18   | 14.12   | 12.89    |
| TiO <sub>2</sub>               | 0.76    | 0.79    | 0.82    | 0.68    | 0.74     |
| Cr <sub>2</sub> O <sub>3</sub> | 0.04    | 0.00    | 0.04    | 0.06    | 0.06     |
| MnO                            | 0.17    | 0.14    | 0.17    | 0.17    | 0.18     |
| Fe <sub>2</sub> O <sub>3</sub> | 6.62    | 7.07    | 6.77    | 5.60    | 7.05     |
| etc                            | 0.11    | 0.12    | 0.11    | 0.10    | 0.12     |

Table 5. The chemical composition of ID C

| Type                           | C       |         |         |         |          |
|--------------------------------|---------|---------|---------|---------|----------|
|                                | average | 1.2-2.5 | 0.6-1.2 | 0.3-0.6 | 0.15-0.3 |
| Na <sub>2</sub> O              | 0.04    | 0.05    | 0.08    | 0.03    | 0.00     |
| MgO                            | 0.94    | 1.09    | 0.96    | 0.78    | 0.94     |
| Al <sub>2</sub> O <sub>3</sub> | 8.73    | 9.54    | 8.63    | 8.26    | 8.49     |
| SiO <sub>2</sub>               | 59.47   | 58.87   | 59.22   | 60.80   | 58.97    |
| SO <sub>3</sub>                | 3.93    | 3.51    | 4.17    | 3.60    | 4.44     |
| K <sub>2</sub> O               | 6.00    | 6.19    | 5.87    | 5.82    | 6.11     |
| CaO                            | 13.20   | 12.62   | 13.18   | 14.12   | 12.89    |
| TiO <sub>2</sub>               | 0.76    | 0.79    | 0.82    | 0.68    | 0.74     |
| Cr <sub>2</sub> O <sub>3</sub> | 0.04    | 0.00    | 0.04    | 0.06    | 0.06     |
| MnO                            | 0.17    | 0.14    | 0.17    | 0.17    | 0.18     |
| Fe <sub>2</sub> O <sub>3</sub> | 6.62    | 7.07    | 6.77    | 5.60    | 7.05     |
| etc                            | 0.11    | 0.12    | 0.11    | 0.10    | 0.12     |

### 2.3.5 Analysis of chemical composite

#### 1) XRF Analysis

Table 5 and Figure 8 indicates the XRF test results. It was found that the aggregate after the neutralization and abrasion process (B) contained 20.18% SO<sub>3</sub> on average, of which 32.60% was found in fine particles with a size of 0.15 mm or smaller, the greatest proportion of all grades. This seems to be because sulfuric acid ( $\text{H}_2\text{SO}_4$ ) reacted with calcium hydroxide ( $\text{Ca}(\text{OH})_2$ ) in the cement paste, and released in the form of gypsum

(CaSO<sub>4</sub>). On the other hand, in the aggregate from which gypsum and the fine particles with a size of 150µm or smaller in the additional cleansing process after the process (C) only 3.93% of SO<sub>3</sub> was found. Based on the analysis, we believe gypsum, the hydrate, is easily removed by a simple washing and cleansing process.

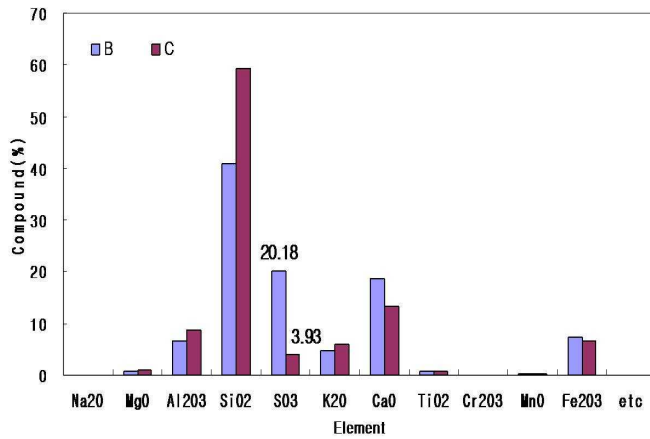


Figure 8. The chemical composite

2) XRD analysis

Figure 9 illustrates the XRD analysis results of the aggregate after the neutralization and abrasion process (B). The aggregate manufactured after the process was analyzed at two different temperatures: 100±5°C and under 45°C. Dried at 100±5°C, Basanite mineral was found, while when dried at under 45°C, gypsum was found. This seems to be because calcium hydroxide(Ca(OH)<sub>2</sub>), the main component of the cement paste, reacted with sulfuric acid(H<sub>2</sub>SO<sub>4</sub>) and generated white precipitate of β-hemihydrate gypsum(CaSO<sub>4</sub> · 2H<sub>2</sub>O). When dried at over 100°C, the white precipitate was turned into gypsum hemihydrate of Basanite. When dried at under 45°C, gypsum was found. Therefore, in the neutralization reaction with sulfuric acid, calcium hydroxide in the cement paste actively reacted with sulfuric acid,

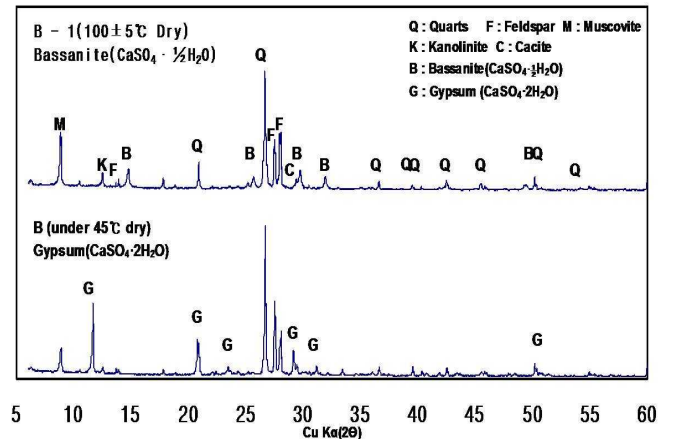


Figure 9. XRD of HRAI

3. Mortar test

3.1 Outline

The aggregate produced through neutralization and slow-speed wet abrasion was tested to determine whether it could be used as recycled aggregate for concrete. When calcium hydroxide is neutralized with sulfuric acid, gypsum is generated. In general, gypsum involves cement hydration and is used to control the rapid hydration of C3A, secure sufficient process time, and control the setting time. But if added excessively over a certain level, it generates excessive ettringite in the matrix and causes cracks, having an adverse impact on strength[13,14,15]. For this reason, through the mortar test, the impact of gypsum of the aggregate produced through neutralization and low-speed wet abrasion on the characteristics of strength in cement matrix was analyzed.

3.2 Experimental plan and method

3.2.1 Experimental plan

Table 7 illustrates the experimental plan of mortar to analyze the impact of the high-quality aggregate produced from low-quality recycled aggregate through a series of neutralization, low-speed wet



abrasion and drying at  $100\pm 5^{\circ}\text{C}$ . The aggregate was classified into three experimental factors: RS, LRA, HRAII and RIAI. RS is river sand, LRA is recycled fine aggregate, HRAII is the aggregate with fine particles with the size of 0,15mm or smaller removed from the high-quality aggregate produced through neutralization and low-speed wet abrasion, and HRAI is the aggregate before the removal of fine particles. Table 6 illustrates the experimental mix.

### 3.2.2 Experiment method

To conduct the test, the mortar was mixed in compliance with the IS 679 Cement Strength Test Method, as shown in Figure 10. The flow test was performed first and then setting test was performed after molding the specimen. The specimen was placed at room temperature for the first 24 hours, and wet cured at  $20\pm 2^{\circ}\text{C}$  upon removal from the mold to analyze compressive strength, flexural strength and variation in length by age.

Table 6. Experimental mix

| W/C(%) | Mix ratio (wt./%)             |
|--------|-------------------------------|
| 50     | Cement : aggregate<br>= 1 : 3 |

Table 7. Experimental plan of mortar

| Factor     | Types of aggregate | Test items     |                                       |
|------------|--------------------|----------------|---------------------------------------|
|            |                    | Fresh state    | Hardened state                        |
| Aggre gate | - RS*              |                | - Compressive strength (3, 7, 28 day) |
|            | - LRA**            | - Flow         | - Flexural strength (3, 7, 28 day)    |
|            | - HRA I ***        | - Setting time | - Length change (1, 4 week)           |
|            | - HRA II ****      |                |                                       |

- \* River sand
- \*\* Low quality recycled fine aggregate
- \*\*\* High quality recycled fine aggregate I with  $150\mu\text{m}$  under size particles
- \*\*\*\* High quality recycled fine aggregate II without  $150\mu\text{m}$  under size particles

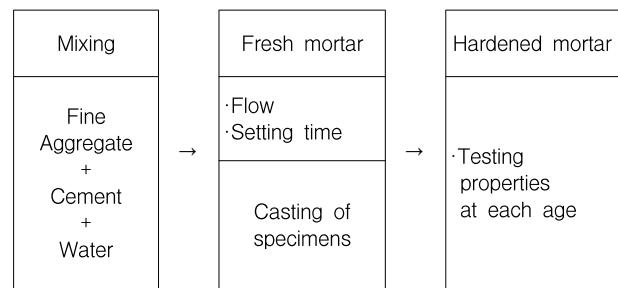


Figure 10. Experimental method

### 3.2.3 Materials

#### 1) Cement

The cement used in the test is OPC produced by S company, and meets the requirements of Class 1 in KS L 5201. The physical properties are shown in Table 8.

Table 8. Physical properties of cement

| Density (g/cm <sup>3</sup> ) | Blain (cm <sup>2</sup> /g) | Setting    |             | Stability(%) |
|------------------------------|----------------------------|------------|-------------|--------------|
|                              |                            | Start(min) | Finish(min) |              |
| 3.15                         | 3,240                      | 290        | 380         | 0.09         |

#### 2) Aggregate

The aggregate used in the test is the standard sand from Jumunjin with  $2,6(\text{g}/\text{cm}^3)$  density, 1,99 F.M and  $1,537\text{kg}/\text{m}^3$  unit volume weight. The aggregate before and after neutralization and abrasion was used, and the physical properties of the aggregate are shown in Table 9. Notably, the aggregate after the process was prepared in two types: one with fine particles and the other with fine particles removed.

Table 9. Physical properties of fine aggregate

| ID     | Density(g/cm <sup>3</sup> ) | Absorption ratio (%) | Percentage of solid volume (%) |
|--------|-----------------------------|----------------------|--------------------------------|
|        | Dry                         |                      |                                |
| RS     | 2.51                        | 1.32                 | 44.6                           |
| LRA    | 2.27                        | 6.56                 | 63.5                           |
| HRA I  | 2.41                        | 4.21                 | 64.0                           |
| HRA II | 2.47                        | 2.98                 | 63.1                           |

### 3.3 Test results

#### 3.3.1 Flow test

The flow of mortar by aggregate type is illustrated in Figure 11. At a certain water-to-cement ratio (W/B), RS, LRA, HRAI and HRAII were measured as 145, 115, 141, and 179mm, respectively. As the specific surface area of LRA was coarse and relatively large, the flow was shown to be low. Abrasion improved the grain form of HRAII and the removal of fine particles with the size of  $150\mu\text{m}$  or smaller caused the specific surface area to decrease, and the flow of HRAII was shown to be high. The abrasion improved the grain form of HRAI and the flow was shown to be similar to that of RS. From the test results, it was verified that recycled aggregate can be manufactured as aggregate to have a flow similar to that of natural aggregate.

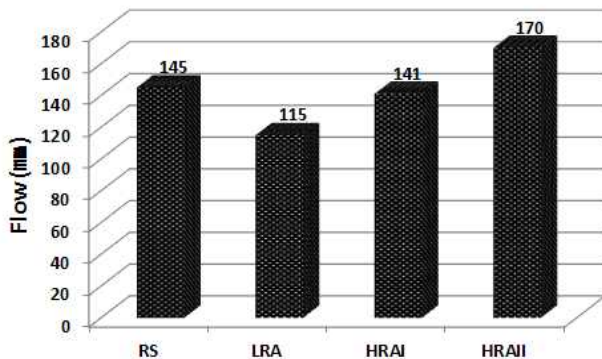


Figure 11. Variation of flow

#### 3.3.2 Setting test

Figure 12 illustrates the setting time of mortar by aggregate type. The initial setting time taken to reach the early-age strength was shortest in RS, followed by HRAII, LRA, and HRAI in that order. The mortars with RS, HRAII, and LRA were initially set between 2 and 3 hours. HRAI was initially set at 4 hours and 20 minutes and finally set at 7 hours and 10 minutes, showing the longest setting time. When gypsum is included, the

setting is usually delayed, as ettringite is generated on the particle surface of  $\text{C}_3\text{A}$ , which is reported to depend on the  $\text{SO}_4^{2-}$  ions in the matrix [16,17,18]. Therefore, for HRAI the gypsum adhering to the surface of aggregate was expected to generate ettringite on the surface of particle of  $\text{C}_3\text{A}$  and delay the setting. In the test results, the setting time was actually delayed in HRA I compared to the other specimens. The initial setting was delayed more than the final setting.

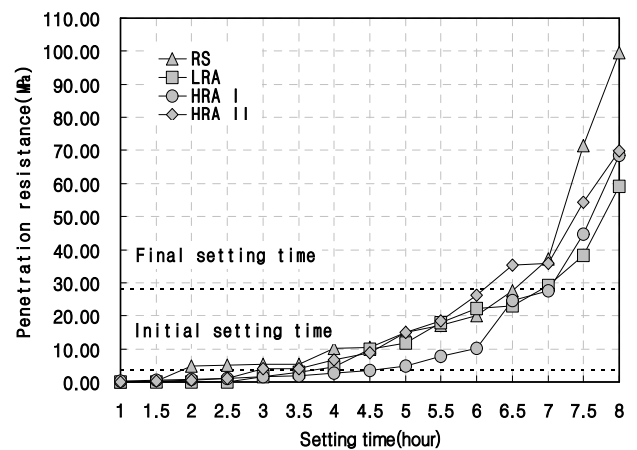


Figure 12. Variation of setting time

#### 3.3.3 Length change ratio

Figure 3 shows the length change ratio over curing time at 1 week and 4 weeks by aggregate type. The variation in length change ratio of RS was shown at 0.06 and 0.05% HRAI at 0.05 and 0.01%, and HRAII at 0.21%. HRAII showed a relatively higher variation in length change ratio but was smaller than HRAI. LRA showed the highest variation in length change ratio at 0.62 and 0.61%.

Through the results, it was revealed that sulfuric acid water and low-speed wet abrasion helped to improve the grain forms of HRAI and HRAII and to decrease the absorption ratio, and showed a dimensional stability similar to that of RS.

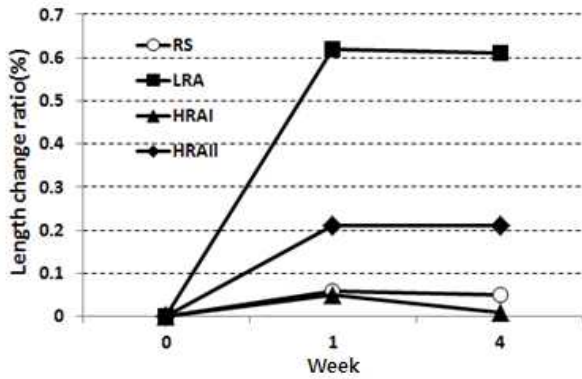


Figure 13. Variation of length change ratio

### 3.3.4 Variation of strength

Compressive strength of mortar by aggregate type is illustrated in Figure 14. In RS, the compressive strength was measured at 11.0, 19.6 and 29.1MPa at 3, 7 and 28 days, respectively. In LRA, the compressive strength was measured at 10.9, 18.7, and 32.1MPa, the highest of all. It is believed that coarse grain form and high absorption ratio improved the specific surface area, bringing about a decrease in W/C ratio and an increase in bond strength on the contact surface between aggregate and cement paste. As a result, the compressive strength was improved.

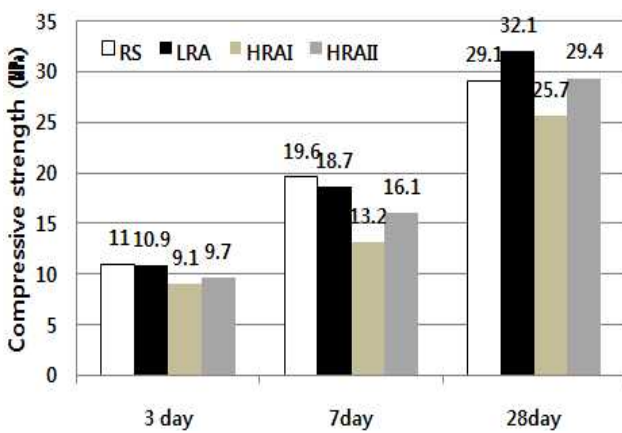
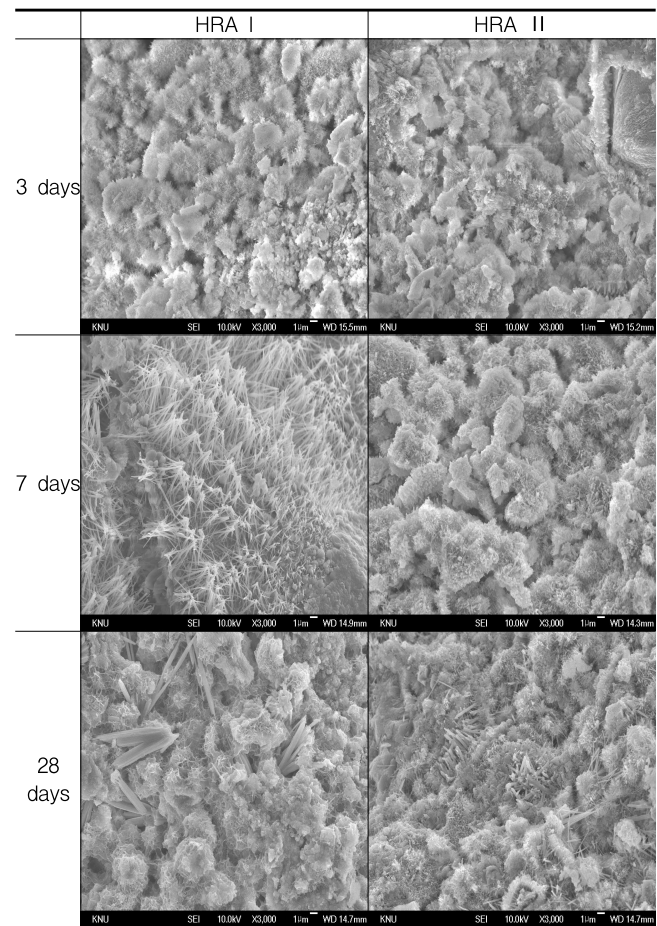


Figure 14. Variation of compressive strength

In HRAI, the lowest compressive strength was measured at 9.1, 13.2 and 25.7MPa, while in

HRAII, the compressive strength was measured at 9.7, 16.1 and 29.4MPa, respectively. HRAI contained fine particles with a size of  $150\mu\text{m}$  or smaller, resulting in a decrease in W/C ratio and an increase in  $\text{SO}_3$  content by gypsum ( $\text{CaSO}_4$ ), which in turn led to an increase in compressive strength, and the compressive strength of HRAI was shown to be higher than that of HRAII[19,20].

Figure 15. SEM photographs of HRA I and HRA II



In addition, SEM results of HRAI and HRAII by age are illustrated in Figure 15. HRAI with the aggregate before cleansing had more ettringite than HRAII with the aggregate after cleansing.

The variation of flexural strength of the mortar by aggregate type is shown in Figure 16. In RS, the flexural strength was measured at 4.3, 6.3 and

8.0MPa by age. In LRA, the highest flexural strength was measured at 5.8, 8.7 and 10.4MPa. In HRAI, 4.2, 5.3, and 6.3MPa were measured, and in HRAII the flexural strength was measured at 3.8, 5.9, and 7.9MPa, the smallest of all. As was the case with compressive strength, LRA showed the highest flexural strength. Through the test results, it was found that the high content of gypsum and grain form of aggregate affected grain form.

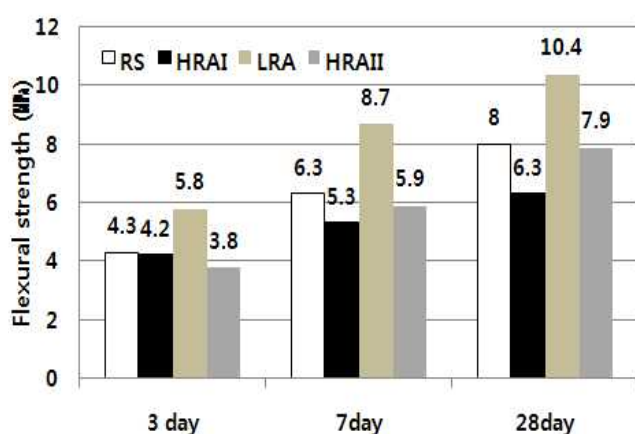


Figure 16. Variation of flexural strength

#### 4. Conclusion

Through an analysis of the quality characteristics of recycled fine aggregate and the characteristics of mortar by aggregate type in the application of neutralization and low-speed wet abrasion, the research findings were drawn as follows:

- 1) In the application of the neutralization and abrasion process, calcium hydroxide ( $\text{Ca}(\text{OH})_2$ ) on the surface of aggregate reacted with sulfuric acid ( $\text{H}_2\text{SO}_4$ ) and released gypsum ( $\text{CaSO}_4$ ), which caused the generation of pores on the contact surface, decreasing the bond strength between aggregate and cement paste. The cement paste was effectively removed with a comparatively small amount of energy and the quality of aggregate overall was

improved.

- 2) In the flow test of fresh mortar, the flow was highest in HRAII while it was lowest in HRA. The flow of HRAI was shown to be similar to that of RS.
- 3) In the test of recycled fine aggregate produced, when gypsum, a hydrate was included, no clear delay in setting time was shown. In terms of long-term strength, the specimen with gypsum was shown at 25.7MPa while the specimen with no gypsum was shown at 29.4MPa, indicating a clear decline in strength.
- 4) In the experimental test results, to produce high-quality recycled fine aggregate, the neutralization and low-speed wet abrasion are believed to be effective. To utilize the recycled fine aggregated produced through the sulfuric acid treatment, an additional process is required to remove the sulfuric composite on the surface of aggregate.

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