Chloride Ion Diffusion and Durability Characteristics of Rural-Road Concrete Pavement of South Korea Using Air-Cooled Slag Aggregates

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Abstract: In the construction industry, the lack of supply and demand for high-quality natural aggregates is a problem. In the case of South Korea, according to data from the Ministry of Environment, it is predicted that the depletion of aggregate resources will occur in 20 years, considering the amount of aggregate used in construction every year and the amount of natural aggregate. Therefore, it is necessary to develop recycled aggregates that can replace natural aggregates for construction. The purpose of this study is to evaluate the applicability of recyclable air-cooled slag (ACS) aggregates as a substitute material for natural aggregates applied to rural-road pavement concrete. That is, the applicability of rural-road pavement concrete is evaluated by evaluating the strength and durability of rural-road pavement concrete to which an ACS aggregate is applied. Durability was assessed in terms of the chloride ion diffusion, repeated wetting-drying, abrasion resistance, impact resistance, and repeated freezing-thawing tests. The test result showed that the diffusion coefficient of the mixture to which the ACS aggregate was applied was slightly larger. In addition, the diffusion coefficient was slightly larger in the case of applying the air-cooled slag coarse aggregate (GG) than in the case of applying the air-cooled slag fine aggregate (GS). The results of abrasion and impact resistance tests of ACS-aggregate-incorporated rural-road concrete indicated that abrasion and impact resistance decreased as the aggregate content increased. The ACS retained some of the properties of the blast furnace slag. Thus, in repetitive wetting-drying tests, which can cause changes in chemical properties, the ACS aggregate increased the concrete’s long-term residual strength. In addition, the results showed that the relative dynamic elastic modulus targeting repeated freezing-thawing resistance satisfied the 80% target. The freeze-thaw resistance improved as the ACS aggregate content increased. In conclusion, the results of this study showed that the durability of rural-road pavement concrete can be improved experimentally by applying both GG and GS at the same time. Therefore, it is shown that ACS aggregates can be applied to rural-road pavement concrete as a substitute for natural aggregates.

Keywords: air-cooled slag (ACS) aggregate; concrete aggregates; durability; rural-road concrete pavement; steel manufacturing by-product

1. Introduction

In the construction industry, there is a growing shortage of high-quality natural aggregates [1–5]. To preserve the environment, substitute alternative concrete aggregates must be identified to promote more environmentally sound practices [6–8]. Recently, numerous studies have explored the use of blast furnace slag as a potential concrete aggregate [5–7]. Slag, which is generated as a steel manufacturing by-product, crystallizes during the high-temperature discharge process, followed by cooling [8,9]. Slag is non-toxic to the environment because it is physically and chemically stable [5,6]. Additionally, slag generated in the blast furnace has similar specific gravity to natural aggregates, making
it highly suitable as an alternative to concrete aggregates [5–10]. Research into the use of blast furnace slag as a concrete aggregate began in the 1980s [1–3]. In recent years, research efforts have focused on using waste slag (water-granulated quench blast furnace slag) as an admixture of cement and concrete [1–3]. In contrast, the use of air-cooled slag (ACS) has progressed more slowly, only recently being applied to non-structural concrete secondary products in which 90% of the ACS is recycled as a filler and landfill-type aggregate [10–12]. Therefore, it is necessary to study the application of continuous-use ACS aggregates to replace natural aggregates for improved environmental and economic efficiency [13–20]. In a previous study that assessed the physical and mechanical properties of concrete, the air volume increased due to the pores in the aggregate, and the slump content decreased due to the increase in the absorption quantity of the mixing water [1,16–20]. In addition, the increase in the number of pores reduced the concrete’s strength and increased chloride ion penetration [1,2,21–23]. It is possible to fill the pores by applying fly ash (FA) and blast furnace slag (BFS) powder, effectively increasing the physical and mechanical properties of the concrete by increasing the fluidity via the ball-bearing phenomenon [1,2,21–23]. A rural road can be defined as a road that is directly used for the production activities of farmers in general connected to cultivated land. Therefore, it can be defined as a road on which agricultural machinery and the like mainly move, unlike general roads such as automobile-only roads. In a study on the physical and mechanical properties of rural-road pavement to which the existing ACS aggregate was applied, it was confirmed that an air-cooled slag aggregate has physical, mechanical, and environmental properties applicable to rural-road pavement [24]. However, the durability of concrete with ACS aggregate incorporation has yet to be evaluated. Compared with natural aggregates, the ACS aggregate has a large number of pores therein [24], which may affect the abrasion, freeze-thaw, and impact resistance of the concrete.

Thus, in this study, we investigated the strength properties and durability performance of concrete containing an ACS aggregate in an attempt to optimize the concrete’s durability. The purpose of this study was to evaluate the possibility of using the ACS aggregate as an aggregate for concrete through the durability evaluation of rural-road pavement concrete to which the industrial by-product, the ACS aggregate, is applied. To achieve this purpose, the target performance of rural-road pavement concrete was investigated. In addition, when there was no target performance standard, the performance was compared and evaluated with concrete that did not use the ACS aggregate. The target performance of the pavement concrete for rural roads with ACS aggregate application was \( \geq 4.5 \) MPa flexural strength and \( \geq 80\% \) freeze-thaw resistance using the existing Agricultural Production Infrastructure Maintenance Business Plan’s Design Criteria [25] and the Korea Expressway Corporation’s Highway Specialized Specification [26]. The effect of the addition of the ACS aggregate on concrete durability was also examined in terms of the chloride ion penetration depth, chloride diffusion coefficient, repeated wetting and drying cycles, repeated freezing and thawing cycles, abrasion resistance, and impact resistance.

2. Materials and Methods

2.1. Materials

ASTM Type I cement (Ssangyong Cement Co., Ltd., Seoul, South Korea) was used in this study. The physical properties and chemical composition of the cement are provided in Table 1. The fly ash (FA) used in this study was collected and refined by an electrostatic precipitator after burning bituminous coal at the Dangjin Thermal Power Plant, which meets the properties specified by KS L 5405 [27]. The physical and chemical properties of the FA are listed in Table 2. Blast furnace slag (BFS) fine powder was used to improve concrete performance as a latent hydraulic material. BFS products manufactured in Hyundai Steel (Dangjin, South Korea) were used. The physical properties and chemical composition of the studied BFS are given in Table 3. Washed sea sand was used as a fine aggregate with a specific gravity of 2.62. Some parts of the fine aggregate were replaced with a crushed fine aggregate (CS, Table 4). As a coarse aggregate, a crushed coarse aggregate (G) with
a maximum size of 25 mm and a specific gravity of 2.58 was used (Table 5). The ACS aggregate for concrete was manufactured by Kyungsung Development Co. Ltd. (Dangjin, South Korea) using raw materials produced by Hyundai Steel Co. Ltd. (Dangjin, South Korea) [24]. The properties of the air-cooled slag fine aggregate (GS) and the air-cooled slag coarse aggregate (GG) are listed in Table 6. In addition, the manufacturing process of the ACS aggregate is shown in Figure 1. When raw slag, an industrial by-product, is discharged from the blast furnace, GG and GS are produced through a manufacturing process for use as aggregates for concrete [24]. Additionally, a polycarboxylic-acid-based high-range water-reducing agent (HRWA) was applied; the characteristics are provided in Table 7.

### Table 1. Properties of cement.

| Type of Cement | Fineness (cm²/g) | Specific Gravity | Stability (%) | Setting Time (min) Initial | 3 Days | 7 Days | 28 Days | Compressive Strength (MPa) 3 Days | 7 Days | 28 Days |
|----------------|-----------------|------------------|---------------|--------------------------|--------|--------|--------|-----------------------------------|--------|--------|
| Type I         | 3200            | 3.15             | 0.02          | 220                      | 400    | 20.3   | 30.2   | 38.7                              |        |        |

### Table 2. Physical and chemical properties of fly ash.

| Density (g/mm³) | Fineness (cm²/g) | Absorption (%) | LOI * (%) |
|-----------------|-----------------|---------------|-----------|
| 2.14            | 3400            | 0.13          | 3.28      |

**Chemical Composition (%)**

| SiO₂  | Al₂O₃ | Fe₂O₃ | CaO | MgO | Na₂O | K₂O | TiO₂ |
|-------|-------|-------|-----|-----|------|-----|------|
| 58.12 | 23.56 | 7.69  | 2.59| 1.12| 0.31 | 1.42| 1.05 |

* LOI: loss on ignition.

### Table 3. Physical and chemical properties of blast furnace slag powder.

| Density (g/mm³) | Fineness (cm²/g) | LOI (%) |
|-----------------|-----------------|--------|
| 2.8             | 4000–6000       | 3.0    |

**Chemical Composition (%)**

| SiO₂  | Al₂O₃ | Fe₂O₃ | CaO | MgO | MnO | TiO | S   |
|-------|-------|-------|-----|-----|-----|-----|-----|
| 33.1  | 13.9  | 0.29  | 42.4| 6.1 | 0.4 | 0.96| 0.66|

### Table 4. Physical properties of the crushed fine aggregate.

| Fineness Modulus | Density (g/mm³) | Water Absorption Ratio (%) | 0.08 nm Pass Efficiency |
|------------------|-----------------|-----------------------------|-------------------------|
| 2.72             | 2.58            | 1.58                        | 6.9                     |

### Table 5. Physical properties of the coarse aggregate.

| Type of Aggregate | Density (g/mm³) | Absorption (%) | F.M |
|-------------------|-----------------|----------------|-----|
|                   | Bulk | Bulk (SSD) | Apparent |         |
| Crushed coarse aggregate | 2.80 | 2.65 | 2.83 | 0.35 | 6.92 |
Table 6. Properties of air-cooled slag aggregates.

| Type of Aggregate | Absolute Dry Density | Water Absorption Ratio | Unit Volume Weight |
|-------------------|----------------------|------------------------|--------------------|
| Fine aggregate    | 2.77                 | 1.57                   | 1.70               |
| Coarse aggregate  | 2.49                 | 4.28                   | 1.41               |

**Chemical Composition (%)**

| CaO    | S | SO₃ | FeO |
|--------|---|-----|-----|
| 40.81  | 0.00 | 0.39 | 1.19 |

Table 7. Properties of the polycarboxylic-acid-based high-performance water-reducing agent.

| Type    | Color      | Solids (%) | Density (g/mm³) | pH   |
|---------|------------|------------|-----------------|------|
| Liquid  | Light brown| ≥40        | 1.10 ~ 1.20     | 4.0 ~ 7.5 |

Figure 1. Manufacturing of the ACS aggregate.

2.2. Mix Proportions

To analyze the durability performance of rural-road pavement concrete using the ACS aggregate, the natural aggregate (CS, CC, and CS) was replaced with the ACS aggregate as a mixing variable. The details of the studied mix proportions are listed in Table 8. A mix proportion of concrete named GS 50%/GG 100% was the optimal result determined from the physical and mechanical properties of rural-road pavement concrete using the existing ACS aggregate in a previous study [24]. A durability test was conducted by adding the optimal mix proportion. To compare the results, a plain mix without the ACS aggregate and a mix proportion with GG 100% were studied in parallel. The mixing method for producing concrete to which the ACS aggregate was applied is given below. The aggregates and cement were put in a forced-action pan mixer and mixed for 1 min 30 s in a dry state before adding water. After that, water and the HRWA were added to the mixture and mixed for 2 min additionally.
Table 8. Mix proportion of rural-road pavement concrete.

| Type of Mix          | W/B (%) | S [%] | Unit Weight (kg/m³) |
|----------------------|---------|-------|---------------------|
|                      |         |       | W                  | C    | BFS | FA | CS | SS | GS | G  | GG | HRWA |
| Plain                | 55.5    | 49.6  | 161                | 173  | 73  | 44 | 458| 452| -  | 926| -   | 2.03 |
| GG 100%             |         |       | 161                | 173  | 73  | 44 | 458| 452| -  | -  | 926 | 2.03 |
| GS 50%/GG 100%      |         |       | 161                | 173  | 73  | 44 | 229| 226| 455| -  | 926 | 2.03 |

1 Binder (C + BFS + FA); 2 fine aggregate (CS + SS + GS); 3 aggregate (CS + SS + CS + G + GG); 4 water; 5 cement; 6 blast furnace slag powder; 7 fly ash; 8 crushed sand; 9 sea sand; 10 air-cooled slag fine aggregate; 11 crushed coarse aggregate; 12 air-cooled slag coarse aggregate; 13 polycarboxylic-acid-based high-performance water-reducing agent.

2.3. Test Methods

2.3.1. Flexural Strength

The flexural strength test was performed in accordance with ASTM C78/C78M, “Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)” [28]. A sized 100 × 100 × 400 mm³ prismatic specimen was manufactured and initially cured at a constant temperature of 23 ± 2 °C and 58% relative humidity (RH) for 24 h. After the initial curing, the form was removed and water curing was performed at a constant temperature of 23 ± 2 °C for 27 days. For evaluating the flexural strength, three specimens were manufactured at once and the process was repeated twice. Therefore, a total of six specimens were tested for accuracy.

2.3.2. Chloride Ion Diffusion

Chloride ions can affect the durability of concrete due to the penetration of sulfate ions. In particular, it is necessary to evaluate the chloride ion diffusion characteristics according to the application of the ACS aggregate because the de-icing agent can affect the rural-road pavement concrete in winter. The diffusion evaluation of chloride ions by rapid electrophoresis was performed according to the NT Build 492 test standard [29]. The chloride diffusion test setup is shown in Figure 2. A 100 × 200 mm² cylindrical specimen was manufactured. A 50 mm section was cut from the center of the specimen and pretreated for the test as a sample. For the pretreatment, the cut specimen was maintained in a vacuum desiccator at a pressure of 1 to 5 kPa for 3 h at first, followed by a second vacuum enclosure for 3 h. Ca(OH)₂ was then added to all of the specimens to be immersed; the specimens were placed under vacuum for 1 h. The desiccator lid was opened to allow air exposure for 18 ± 2 h; the specimen surface was then drained. After this pretreatment, specimens were installed in the test apparatus. For the installation method, first, the specimen was placed in a rubber tube and fixed with two stainless-steel clamps, and the surrounding area was treated with silicone to prevent the solution from leaking into the area where the specimen and rubber tube intersect. After fixing the specimen, 300 mL of 0.3 M NaOH was added to the rubber tube along with a stainless-steel circular plate inserted for use as an anode. The test sample was then placed on a device with a plastic base, where it was soaked in a container carrying 12 L of 10% NaCl (mass concentration) solution. After sample preparation, an external power supply was connected to the sample, and voltage was applied. During the experimental process, the initial current running through each specimen was measured by applying a voltage of 30 V at the beginning of the experiment. From the measured initial current value, the voltage to be applied to the specimen was selected from Table 9 and the voltage was adjusted [30,31]. After determining the voltage to be applied from the initial measurements, the voltage was applied to the test specimen from which the associated current was recorded. The temperature of the internal solution was measured. After voltage was applied, the current on completion of the experiment and the temperature inside the rubber tube was measured and recorded. Finally, after the test was completed, the specimen was separated from the rubber tube and the surface was cleaned. Then, the depth of the discolored portion of the specimen was measured by spraying 0.1 M AgNO₃ on the refined surface. The depth of discoloration was measured by excluding approximately 10 mm from the end of both sides of the specimen; the mean
value was measured seven times from the remaining portion of the sample. The Tang and Nilsson model [30,31] was used to obtain the diffusion coefficient from the results of the rapid electrophoresis experiment. To obtain specimens for evaluating the chloride ion diffusing test, two test specimens were manufactured at once and the process was repeated twice.

![Figure 2. Chloride ion diffusion test setup.](image)

Table 9. Test voltage and duration for concrete specimen [30,31].

| Initial Current $I_{30V}$ (with 30 V) (mA) | Applied Voltage $U$ (After Adjustment) (V) | Possible New Initial Current $I_0$ (mA) | Test Duration $t$ (hours) |
|------------------------------------------|------------------------------------------|----------------------------------------|--------------------------|
| $I_0 < 5$                                | 60                                       | $I_0 < 5$                              | 96                       |
| $5 \leq I_0 < 10$                        | 60                                       | $10 \leq I_0 < 20$                     | 48                       |
| $10 \leq I_0 < 15$                       | 60                                       | $20 \leq I_0 < 30$                     | 24                       |
| $15 \leq I_0 < 20$                       | 50                                       | $25 \leq I_0 < 35$                     | 24                       |
| $25 \leq I_0 < 30$                       | 40                                       | $25 \leq I_0 < 40$                     | 24                       |
| $30 \leq I_0 < 40$                       | 35                                       | $35 \leq I_0 < 50$                     | 24                       |
| $40 \leq I_0 < 60$                       | 30                                       | $40 \leq I_0 < 60$                     | 24                       |
| $60 \leq I_0 < 90$                       | 25                                       | $50 \leq I_0 < 75$                     | 24                       |
| $90 \leq I_0 < 120$                      | 20                                       | $60 \leq I_0 < 80$                     | 24                       |
| $120 \leq I_0 < 180$                     | 15                                       | $60 \leq I_0 < 90$                     | 24                       |
| $180 \leq I_0 < 360$                     | 10                                       | $60 \leq I_0 < 120$                    | 24                       |
| $360 \leq I_0$                           | 10                                       | $120 \leq I_0$                        | 6                        |

2.3.3. Repeated Wetting-Drying

Since rural-road pavement in summer has a climatic characteristic of repeated drying and wetness, a dry-wet repeated experiment was conducted to evaluate the effect on the strength of concrete due to the repeated dry-wetting phenomenon [32]. In this experiment, the specimens cured in water for 28 days were immersed in 23 $\pm$ 2 °C water for 24 h and then taken out and dried in an oven at 60 °C for 24 h, defined as one cycle. After the experiment was carried out for a total of 25 cycles for 50 days, a compressive strength test according to ASTMC C 39 [33] was performed. To obtain specimens for evaluating the repeated wetting and drying test, three test specimens were manufactured at once and the
process was repeated twice. Therefore, six specimens were tested for repeated wetting and drying cycles. The test results were expressed as residual compressive strength, and the residual compressive strength was calculated as in Equation (1).

\[
\text{Residual Compressive strength} = \frac{\text{Compressive strength after repeated wetting – drying exposure}}{\text{Compressive strength before repeated wetting – drying exposure}} \times 100(\%) \quad (1)
\]

2.3.4. Abrasion Resistance

For the concrete abrasion test using the ACS aggregate, a cylindrical specimen of 150 × 50 mm² was prepared and cured in the same condition as the flexural strength specimens [34]. To obtain specimens for evaluating the abrasion test, three test specimens were manufactured at once and the process was repeated twice for accuracy.

2.3.5. Impact Resistance

The impact resistance test was performed using the method outlined in the ACI Committee 544 (1995) guidelines [35]. The test involved dropping a 4.54 kg steel body onto a specimen of 150 × 50 mm² at a height of 450 mm. The number of hits before being destroyed was measured, along with initial crack formation after 28 days of curing. The specimens were cured in the same condition as the flexural strength specimens. To obtain specimens for evaluating the impact test, three specimens were manufactured at once and the process was repeated twice. Therefore, a total of six specimens were tested for impact resistance.

2.3.6. Repeated Freezing and Thawing Resistance

Cyclical freeze-thaw tests were conducted according to ASTM C 666 standard [36] using two 100 × 100 × 400 mm³ test specimens for each case. One 4 h cycle consisted of freezing the test specimen to lower the core temperature of a standard test piece from 4 to −18 °C; this was followed by a thawing process to raise the core temperature back to 4 °C. The tests consisted of 300 cycles, and the relative dynamic elastic modulus was measured every 30 cycles. To obtain test specimens for evaluating the repeated freezing and thawing cycles test, two test specimens were manufactured at once and the process was repeated twice. Therefore, a total of four specimens were tested for repeated freezing and thawing cycles.

3. Results

3.1. Flexural Strength

Flexural strength test results are shown in Figure 3. The flexural strength decreased as the amount of ACS aggregate increased; the flexural strength values were 5.69, 4.88, and 4.80 MPa for mixes of plain, GG 100% mix, and GS 50%/GG 100% mixes, respectively. However, the difference in flexural strength was small between the GG 100% mix using 100% GG and the GS 50%/GG 100% mix using GS 50% and GG 100%. In this study, the target flexural strength value of rural-road pavement concrete was selected to be 4.5 MPa, the quality standard of the Korea Expressway Corporation’s Highway Specialized Specification [26]. The designed flexural strength targeted for all mixes was satisfied.
the quality standard of the Korea Expressway Corporation’s Highway Specialized Specification [26]. The designed flexural strength targeted for all mixes was satisfied.

![Figure 3](image)

(a) Flexural strength

(b) Flexural strength ratio

Figure 3. Test results of flexural strength.

3.2. Chloride Ion Diffusion

The results of the chloride penetration depth test of pavement concrete using the ACS aggregate are shown in Figure 4. The chlorine ion penetration depths were 12.82, 19.37, and 15.15 mm for plain, GG 100%, and GS 50%/GG 100% mixes, respectively. The chloride ion penetration depth increased with the ACS aggregate’s substitution ratio, being 1.00, 1.51, and 1.18 for plain, GG 100%, and GS 50%/GG 100% mixes, respectively. The chloride ion diffusion coefficient test results are shown in Figure 5; the diffusion coefficient values depended on the substitution ratio of the ACS aggregate, being $5.13 \times 10^{-12}$, $5.45 \times 10^{-12}$, and $5.27 \times 10^{-12} \text{ m}^2/\text{s}$ for plain, GG 100%, and GS 50%/GG 100% mixes, respectively. The test result showed that the diffusion coefficient of the mixture to which the ACS aggregate was applied was slightly larger. In addition, the diffusion coefficient was slightly larger in the case of applying GG 100% than in the case of applying the GS. Therefore, the diffusion coefficient and penetration depth of the GS 50%/GG 100% mix with the GS and GG applied...
decreased compared to the GG 100% mix with only the GG applied. According to previous studies, coarse slag aggregates have relatively more voids compared to natural coarse aggregates [11–13]. Therefore, when the GG of rural-road pavement concrete is applied, the penetration depth of the concrete increases due to an increase in the volume of voids. In addition, the ACS aggregate is composed of components similar to the fine powder of blast furnace slag, so it expresses a similar pozzolanic reaction and makes the structure of the concrete dense in the long-term. In particular, it can be seen that this effect is more effective than the GG because of the smaller particle size of the GS.

Figure 4. Test results of chloride ion penetration depth.

(a) Chloride ion penetration depth

(b) Chloride ion penetration depth ratio
3.3. Repeated Wetting and Drying

The repeated wetting and drying resistance of pavement concrete for rural roads using air-cooled slag aggregates was evaluated. In general, the surface temperature of road pavement rises above 60 °C in summer, and the temperature drops rapidly when it rains [32]. As a result of this phenomenon, there is a possibility that a concrete road may be destroyed due to the difference in the moisture content inside the concrete, resulting in compressive stress on the surface and tensile stress on the inside. Therefore, in this study, the characteristics of concrete to which the ACS aggregate was applied were evaluated and analyzed for such a phenomenon. The test results are shown in Figure 6. The result of the test showed that the strength of the concrete to which the bulky slag aggregate was applied increased after repeated wetting-drying. The residual compressive strength test results of plain, GG 100%, and GS 50%/GG 100% mixes were 102.06%, 110.15%, and 112.44%, respectively. As the air-cooled slag aggregate content increased, the residual
compressive strength increased. Figure 6c shows the compressive strength ratio before and after repeated wetting-drying according to the replacement rate of the air-cooled slag aggregate. The compressive strength ratios before wetting-drying repetition were 1.00, 0.94, and 0.94 in plain, GG 100%, and GS 50%/GG 100% mixes, respectively. The compressive strength ratios after repeated wetting-drying were 1.00, 1.10, and 1.11, respectively. Before the wetting-drying repetition, the compressive strength ratio decreased according to the air-cooled slag replacement rate, and after the wetting-drying repetition, the compressive strength ratio showed a tendency to increase. In the GS 50%/GG 100% mix, the compressive strength decreased by about 6% before the wetting-drying cycle but increased by about 11% after the wetting-drying cycle. The repeated wetting-drying test is an accelerated aging test to obtain long-term results at an early stage [32]. The results of previous studies, conducted on concrete to which pozzolanic materials such as fly ash and potential hydraulic materials such as blast furnace slag fine powder were applied, showed an increase in strength when exposed to accelerated deterioration environments such as repeated drying and wetting conditions [32]. Since the accelerated exposure environment results in accelerating the delayed hydration reaction when the pozzolanic material and latent hydraulic material are included, the strength can be increased by promoting the hydration reaction [32]. In this study, the blast furnace slag fine powder, fly ash, and air-cooled slag aggregate also showed a pozzolanic reaction and latent hydraulic properties because blast furnace slag was the main component. Therefore, the strength increases with curing age.

![Figure 6](image-url)
3.4. Abrasion Resistance

Road pavement concrete may wear out due to continuous wheel load. In particular, the ACS aggregate has a larger number of pores than natural aggregates and thus can be affected by abrasion. The abrasion test results for rural-road pavement concrete are shown in Figure 7. The ACS aggregate had no significant effect on the abrasion resistance of the rural-road pavement concrete. The abrasion amount was 0.055, 0.055, and 0.053 g/cm² for plain, GG 100%, and GS 50%/GG 100% mixes, respectively, with associated abrasion ratios of 1.00, 1.00, and 0.96. Thus, the abrasion resistance increased for the GS 50%/GG 100% mix, showing a 4% reduction. This suggests that exposure of the aggregate to the surface for long periods may affect its abrasive action; thus, additional investigation may be necessary to resolve this effect. Overall, the application of the ACS aggregate did not present a significant issue in terms of abrasion resistance.
3.5. Impact Resistance

The impact test results of the pavement concrete using the ACS aggregate are shown in Figure 8. The impact resistance decreased with the increased application of the ACS aggregate. The decrease in resistance was larger when a coarse aggregate was used relative to when the GS was used. The GG has a relatively larger absorption rate due to a greater number of pores; this increases the likelihood of crack formation and degradation. Thus, the results showed that the impact resistance was reduced. The mean number of initial crack initiation hits per mix was 6.50, 5.50, and 5.25 times for plain, GG 100%, and GS 50%/GG 100% mixes, respectively, and the mean number of hits causing destruction and cracking was 10.0, 9.00, and 8.75, respectively. The mean number of initial crack initiation hits of the impact strength ratio according to the substitution ratio of the ACS was 1.00, 0.85, and 0.81 for plain, GG 100%, and GS 50%/GG 100% mixes, respectively, and the impact strength ratio at the time of destruction and crack formation was 1.00, 0.90, and...
0.88, respectively (Figure 6). The ACS aggregate has pores in the aggregate itself and is weaker than the natural aggregate. In particular, the mean number of initial crack initiation hits was influenced more than the mean number of destruction/crack hits. In the case of the GS 50%/GG 100% combination, which showed the lowest impact strength, the mean number of initial crack hits reduced by 19% compared to that of the plain mix, and the mean number of destruction/crack hits decreased by 12%.

![Graph showing impact strength ratio](image)

(a) No. of impact

![Graph showing first crack ratio](image)

(b) First crack ratio

Figure 8. Cont.
The study evaluated the freeze-thaw resistance of pavement concrete for rural roads with the ACS aggregate under repeated cycling of freezing and thawing. In Korea, the four seasons are distinct. The temperatures in the morning, day, and night can vary significantly and tend to have a cycle of 3 cold days followed by 4 warm days. The externally exposed concrete road pavement is exposed to humidity via moisture, rain, ice, and snow, as well as variable loads due to vehicle travel, such as in snow, during winter. Thus, freezing and thawing effects were expected to be significant. The damage caused to the concrete pavement by repeated freezing and thawing is attributable to the filling of concrete pores with water. When the pore water turns to ice, the ice cracks and grows inside the concrete, thereby ultimately destroying the concrete pavement. Therefore, in this study, we assessed the effect of freeze and thaw repetition to more closely model the weather patterns. The test results are shown in Figure 9. The test samples with the ACS aggregate did not appear to be affected by freezing and thawing. Our results showed that applying the ACS aggregate to the plain mix provided better freeze-thaw resistance. The relative elastic modulus ratios were 1.00, 1.00, and 1.05 after 300 repetitions for plain, GG 100%, and GS 50%/GG 100% mixes, respectively. The dynamic elastic modulus increased with the ACS aggregate’s substitution ratio in freeze-thaw repetitive testing over 90 days. Materials that undergo a similar pozzolanic reaction (blast furnace slag powder and ACS aggregate) exhibit long-term strength as opposed to higher initial strength. Here, the initial hydration reaction is delayed; thus, the initial strength tends to be lower. However, the long-term strength is excellent. The target relative dynamic elastic modular ratio of rural-road pavement concrete was set by referring to the relative dynamic elastic modulus presented in the Concrete Pavement Standards of the Korea Expressway Corporation. As a result of the test, the relative dynamic elastic modulus was shown to be 80% or greater. In this study, the air volume was designed to be 4.5% ± 1.5%, having the greatest effect on freezing and thawing. In all the mixes, this standard was satisfied. The pores in the ACS aggregate provide resistance against freezing and thawing effects. As the water absorption rate increases, the damage may become more extensive due to repetitive freezing and thawing. The ACS aggregate applied in this study achieved a 3% absorption rate, which is the standard for the blast furnace slag aggregate. The results of the repeated freezing and thawing tests indicated that the ACS aggregate applied to rural-road pavement concrete plays a major role in securing freezing and thawing resistance.
and thawing tests indicated that the ACS aggregate applied to rural-road pavement concrete plays a major role in securing freezing and thawing resistance.

![Figure 9. Test results of repeated freezing and thawing cycles.](image)

4. Conclusions

The purpose of this study was to replace natural aggregates, which are gradually being depleted as aggregates for concrete, with the ACS aggregate, which is an industrial by-product, and apply it to rural-road pavement concrete. To achieve this purpose, the performance of rural-road pavement concrete was evaluated through experiments when a natural aggregate was used instead of the ACS aggregate. The conclusions from the results of this study are as follows:

1. As the amount of ACS aggregate increased, the flexural strength decreased. This result is because the ACS aggregate has many voids compared to the natural aggregate. However, the flexural strengths tested satisfied all target strength values ($\geq 4.5$ MPa). The chloride ion penetration depth increased with the ACS aggregate’s substitution ratio. In addition, when the GS and GG were used at the same time, the diffusion depth and...
The diffusion coefficient decreased compared to the case where the GG was used. Therefore, it is effective to use the GG and GS at the same time.

2. The durability test results of pavement concrete with the ACS aggregate showed that the ACS aggregate had no significant effect on the abrasion resistance of rural-road pavement concrete. The impact resistance decreased with the increased application of the ACS aggregate. The decrease in the resistance was larger when the GG was used relative to when the GS was used. As a result of the repeated wetting-drying test, the residual compressive strength slightly increased when the ACS aggregate was applied. In addition, the results indicated that the freezing and thawing resistance satisfied 80% of the relative dynamic elastic modulus targeted.

3. Rural-road pavement shows an increase or decrease in durability items depending on the content of the ACS aggregate as a result of the durability test, but since the decrease is not large, it can be applied in terms of resource recycling.

4. As a result of this study, the industrial by-product, the ACS aggregate, can be used in rural-road pavement concrete as an alternative to natural aggregates, so it has an excellent environmental effect in terms of resource recycling. However, in this study, the evaluation of cracks and microstructural characteristics in the concrete according to the application of the ACS aggregate was not conducted. Therefore, for future research, it is necessary to study the crack characteristics and microstructure analysis according to the use of the ACS aggregate. In addition, studies such as CO$_2$ emission analysis and economic feasibility analysis are needed in consideration of the environmental aspects of ACS aggregates.

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