Effect of Carbonation Curing on Physical and Durability Properties of Cementitious Materials Containing AOD Slag

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Received: 21 August 2020; Accepted: 22 September 2020; Published: 23 September 2020

Abstract: In this study, the physical and durability properties of cementitious materials containing stainless steel argon-oxygen decarburization (AOD) slag were investigated by CO2 curing. Three contents (0, 30, 60%) of ordinary Portland cement (OPC) were replaced with AOD slag. Specimens were cured at four CO2 concentrations and three temperatures. The chloride diffusion coefficient, drying shrinkage, compressive strength, and porosity were measured. The drying shrinkage reduction was proportional to CO2 uptake. The chloride diffusion coefficient increased as contents of the AOD slag increased. At 15% CO2 concentration, the diffusion coefficient was similar to that of the OPC regardless of the AOD slag substitution rate. The durability of cementitious materials mixed with AOD slag can be improved by CO2 curing and can be used in construction.

Keywords: stainless steel AOD slag; γ-dicalcium silicate; CO2 curing; cementitious materials; drying shrinkage; diffusion coefficient

1. Introduction

Concrete continues to be challenged relating to sustainability in relation to energy consumption, and greenhouse gas emissions [1]. In modern concrete structures, sustainability and high durability are essential in terms of minimal maintenance, economics, and extended service life [2].

A large quantity of industrial by-products is generated worldwide, and their safe disposal and recycling has become a serious problem [3–5]. One way to solve this problem is by using industrial by-products as supplementary cementing materials in concrete production, which can help reduce the carbon footprint of the cement production process. Therefore, ecofriendly or green concrete that uses industrial by-products, such as ground granulated blast-furnace slag, fly ash and silica fume, have been widely used since the 2000s to reduce CO2 emissions [6–13].

Stainless steel slag is an industrial by-product produced during the production of stainless steel. It generally has a different chemical composition according to the stainless steel production process and is classified as electric arc furnace slag or argon-oxygen decarburization (AOD) slag [14–17]. The main component of AOD slag is 2CaO·SiO2 (C2S) [18]. AOD slag is produced by naturally cooling high-temperature melting slag to room temperature [15,19]. In this cooling process, the C2S phase is transferred from β-C2S to γ-C2S, and AOD slag is naturally powdered during this transition [18,20,21]. Since γ-C2S does not have hydraulic properties, unlike β-C2S, AOD slag does not react with water [19,22]. However, when CO2 is present, γ-C2S reacts with water, as expressed in Equation (1). The products of this reaction are silica gel and CaCO3 [23].
\[ 2(2\text{CaO})\cdot\text{SiO}_2 + \text{CO}_2 + 3\text{H}_2\text{O} \rightarrow 3\text{CaO}\cdot2\text{SiO}_2\cdot3\text{H}_2\text{O} + \text{CaCO}_3 \] (1)

Using the reaction of $\gamma$-C$_3$S with CO$_2$, as shown in Equation (1), studies have been conducted using AOD slag as a supplementary cementitious material [18,21,23–25]. Guan et al. [23] studied the hardening behavior via accelerated carbonation of $\gamma$-C$_3$S synthesized at 1300 °C. The compressive strength of the mortar specimen cured at 99.9% CO$_2$ for 24 h exceeded 60 MPa. However, the compressive strength of the specimen without CO$_2$ curing was only 0.19 MPa. They reported that this strength increase was owing to the increase in the amount of calcite produced by carbonation reaction. This was confirmed by thermogravimetry differential thermal analysis (TG/DTA). Kriskova et al. [18] studied the hydration of AOD slag activated using a mechanical method. From the results of their experiments, it was confirmed that C-S-H and CH were generated as hydrated products of the activated AOD slag. Salman et al. [24] investigated the mechanical properties of AOD slag under CO$_2$ curing and analyzed the chemical compositions of the products. They found that a compressive strength of 30 MPa or higher could be obtained in three weeks using CO$_2$ curing and examined the compressive strength according to the curing temperature. They also confirmed that the strength increase due to CO$_2$ curing was caused by the calcite and amorphous reactants produced by the carbonation of AOD slag. Moon and Choi [21,25] studied the effect of CO$_2$ curing on strength for AOD slag cement pastes. They reported that the strength was increased due to densification of the micropores by the calcite and silica gel produced by CO$_2$ curing.

A number of studies that utilize AOD slag as a cement substitute material have been conducted. Most of them focused on the characterization of hydration and compressive strength by carbonation curing of the AOD slag cement, but only a few have studied the durability and shrinkage characteristics. To use AOD slag for concrete, its durability and shrinkage characteristics must be investigated.

The main objective of this study is to investigate the effects of CO$_2$ curing concentrations and temperatures on the mechanical and durability characteristics of cementitious materials containing different replacement levels of AOD slag. The physical properties were evaluated by compressive strength and durability characteristics, mainly assessed by the drying shrinkage and chloride diffusion coefficients for each CO$_2$ curing condition. Furthermore, thermogravimetric (TG/DTG) analysis and mercury intrusion porosimetry (MIP) revealed that the CO$_2$ uptakes and pore structure change due to the CO$_2$ curing process.

2. Materials and Methods

2.1. Materials and Mixture Proportions

In this study, cement and AOD slag were used to fabricate various mixtures of cement mortar and paste. The cement and AOD slag used in this test have been described previously [21]. Table 1 shows chemical composition of the ordinary Portland cement (OPC) and AOD slag. Density and Blaine fineness of OPC were 3.14 g/cm$^3$ and 332 m$^2$/kg, respectively. The AOD slag was produced by Korean steel company POSCO, with a density and fineness of 2910 kg/m$^3$ and 359 m$^2$/kg, respectively.

| Chemical Compositions (wt. %) | CaO | SiO$_2$ | Al$_2$O$_3$ | Fe$_2$O$_3$ | MgO | Cr$_2$O$_3$ | K$_2$O | Na$_2$O | SO$_3$ |
|-------------------------------|-----|---------|-------------|-------------|-----|-------------|-------|--------|-------|
| OPC                           | 62.4| 20.8    | 4.9         | 3.5         | 1.6 | -           | 0.9   | 0.3    | 2.2   |
| AOD slag                      | 54.3| 17.7    | 6.4         | 3.0         | 9.2 | 2.8         | 0.2   | 0.1    | 0.4   |

The AOD slag was slowly cured in the air, which generated a large quantity of $\gamma$-C$_3$S in the slag. The average particle size of the AOD slag and OPC were 25.5 μm and 15.5 μm, respectively. The mineral composition of the AOD slag was calculated using Rietveld refinement analysis based on an X-ray diffraction (XRD) pattern, as shown in Figure 1. $\gamma$-C$_3$S accounted for approximately 38.1% of AOD slag, the highest proportion. Other mineral compositions of AOD slag included gehlenite.
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of the AOD slag. The mixture proportions of paste specimens are summarized in Table 2. The water to binder ratio was set at 0.5 with varying amounts of the AOD slag. The replacement levels of the AOD slag were varied as 0, 30, and 60% of the OPC by weight, respectively. For the mixture proportions of the mortar specimens, the mass proportions of water, binder, and fine aggregate were 0.6:2:3. Standard sand shown in ISO 679 was used as the fine aggregate in the production of the mortar [26].

Table 2. Mixture proportions of the paste specimens.

| Water (g) | OPC (g) | AOD Slag (g) |
|-----------|---------|--------------|
| STP0      | 50      | 100          |
| STP30     | 50      | 70           | 30 |
| STP60     | 50      | 40           | 60 |

AOD slag has non-hydraulic properties but generates silica gel and calcite through CO₂ curing [21,23]. Consequently, cementitious materials containing AOD slag show different mechanical properties and microstructure depending on the CO₂ curing condition [27]. In this study, two kinds of experiments were conducted, based on CO₂ curing conditions, using a CO₂ curing chamber with adjustable temperature and CO₂ concentrations, as shown in Figure 2 [21]. First, CO₂ curing concentrations of 0, 5, 10, and 15%, respectively, were used, and the specimens were cured under constant temperature and humidity (23 °C; RH = 60%). Second, curing was performed under various temperatures (23, 40, and 50 °C; RH = 60%), under CO₂ concentrations of 0 and 5%, respectively.
2.2. Test Methods

The compressive strength of the specimen was measured at 14 days under CO₂ curing. For each mixture, three mortar specimens (40 × 40 × 160 mm) were prepared. After splitting the mortar specimen into two, a compressive strength test on each specimen was performed according to ISO 679:2009. The average compressive strength value was used [26].

The chloride diffusion coefficients of the paste specimens were measured through the NT Build 492 test after 14 days under CO₂ curing [28]. The NT Build 492 test is a rapid method of estimating the chloride ion permeability of the specimens using an electrical charge to accelerate ion transport. The size of specimen was Φ 100 × 50 mm. After curing, the NT Build 492 test was performed on three specimens for each curing condition, and their average values were used as the results.

Drying shrinkage measurements were performed on paste specimens (40 × 40 × 160 mm). To measure the length change of the mortar specimens under different CO₂ curing conditions, a PMFL-series embedded strain gauge was placed longitudinally in the middle of the specimen. Further, the strain was periodically and automatically recorded. Glass rods supported both ends of the specimen to ensure that the carbonation curing would be uniform on all surfaces of the specimens.

To analyze the microstructure of the paste specimens owing to the CO₂ curing process, the porosity was measured using MIP (AutoPore IV9500, Micromeritics, GA, USA). Pore size distribution analysis was performed with samples (5-mm-sized particles) obtained from the surface layer of specimens at 14 days. Before the MIP test, the samples were dried at 60 ± 5 °C for 24 h.

The CO₂ uptake of the paste specimens was quantitatively evaluated by thermogravimetric analysis. Thermogravimetric analysis was performed through TG/DTG analysis (Thermo plus EVO II, Rigaku, Japan), for which the entire paste sample (40 × 40 × 160 mm) of the central section was crushed. After crushing, the sample was sieved to 150 μm or less and any over-sized samples were crushed again. Consequently, the calcite content and CO₂ uptake measured in this study was the average of each sample depth. The temperature was increased in the range of 20–1000 °C at a rate of 10 °C/min. TG/DTG analysis was performed in a nitrogen atmosphere (300 mL/min).

3. Experimental Results and Discussion

3.1. Compression Strength

Figure 3 shows the compressive strengths of the specimens at 14 days according to the CO₂ concentration. The variation in compressive strength was found to be within 8%. The compressive strength of normal cured specimens significantly decreased as the replacement level of the AOD slag increased. For STP60, in particular, the compressive strength was lower than 10 MPa. This was because γ-C₂S contained in the AOD slag did not react owing to the absence of CO₂ in the curing process, and only the OPC facilitated the hydration reaction. In the case of CO₂-cured specimens, specimens with the AOD slag showed improved compressive strength. As the CO₂ concentration increased, the compressive strength showed a tendency to increase. For STP0, which used 100% OPC,
the compressive strength increased slightly after CO₂ curing, but its impact was not significant. For STP30 and STP60, the compressive strength increase rates were highest for the CO₂ concentration of 5% compared to the specimens without CO₂ curing. When the CO₂ concentration was increased to 15%, the increase rates decreased compared to those at 5%. Compressive strength of STP30 was similar to that of STP0 when the CO₂ concentration was 15%. Its compressive strength was expected to be higher than that of STP0 if the CO₂ concentration exceeded 15%. STP60 exhibited higher compressive strength increase rates than STP30, but the difference was not in proportion to the mixed amount of AOD slag.

Figure 3. Compressive strength of specimens according to CO₂ concentration.

Figure 4 shows the compressive strengths of the specimens according to the curing temperature. In general, a high curing temperature promotes the initial hydration of cement. Therefore, the compressive strength of specimens should increase with high curing temperature. However, compressive strength tends to decrease when specimens were cured at high temperature [29,30]. The specimen size of this study was relatively small, and the compressive strength STP0 decreased with temperature.

Figure 4. Compressive strength of specimens according to temperature.
The compressive strengths of STP30 and STP60 showed different results from that of STP0. In the cases of STP30 and STP60, the compressive strength increased as the curing temperature increased, regardless of the CO₂ concentration.

The compressive strength of STP0 increased with CO₂ curing at all curing temperatures. As the curing temperature increased, the strength increase tended to increase slightly. Similar results were found by Xuan et al. [31]. For STP30 and STP60, the compressive strength significantly increased owing to CO₂ curing as the curing temperature increased. The compressive strength of STP0 exceeded that of STP0 when CO₂ curing was performed at 40 °C. This result confirms that the increase in the curing temperature accelerates the carbonation of the AOD slag. STP60 showed a similar trend to STP30, and its rate of increase in compressive strength owing to CO₂ curing was the largest.

3.2. Drying Shrinkage

Figures 5 and 6 show the drying shrinkages of the specimens according to the curing conditions. Table 3 summarizes the results of the 28-day drying shrinkage. Figure 5a shows drying shrinkage of the specimens cured in a normal curing environment (0% CO₂) at a curing temperature of 23 °C. The drying shrinkage decreased as the replacement level of the AOD slag increased. At 28 days, the value of the drying shrinkage was approximately −1300 × 10⁻⁶ m/m for STP0 and reduced to −1100 and −900 × 10⁻⁶ m/m for STP30 and STP60, respectively. As the AOD slag containing γ-C₂S has non-hydraulic properties in environments without CO₂, drying shrinkage reduced as the replacement level of the AOD slag increased.

![Graphs showing drying shrinkages](image)

**Figure 5.** Drying shrinkages according to CO₂ concentration: (a) 0% CO₂ (b) 5% CO₂ (c) 10% CO₂, and (d) 15% CO₂.
observed OPC the and approximately generated reduction approximately 10−6 × 0 concentration. CO2 CO2 under 1 to 10−6 5%. Figure 5c,d show the results of the drying shrinkage for specimens cured under 10% and 15% CO2 concentrations, respectively. The shrinkage reduction tended to be proportional to the CO2 concentration. Drying shrinkage decreased further under the CO2 concentration of 10% than it did under 5%, as shown in Figure 5c. For STP0, drying shrinkage at 28 days was approximately −1000 × 10−6 m/m, confirming that drying shrinkage was reduced by approximately 22% compared to non-CO2 curing. Drying shrinkage of STP60 at 28 days was approximately −640 × 10−6 m/m, a reduction of approximately 29% compared to non-CO2 curing.

Drying shrinkage was lowest when curing was performed under the CO2 concentration of 15% (see Figure 5d). The 28-day drying shrinkages of STP0, STP30, and STP60 were −975 × 10−6 m/m, −787 × 10−6 m/m, and −545 × 10−6, respectively. For STP0 and STP30, drying shrinkage was reduced by 24% and 28%, respectively, compared to non-CO2 curing. For STP60, drying shrinkage was reduced by approximately 40%. In particular, STP60 showed a tendency to expand until 10 days. This is because the effect of calcite generated by the reaction between γ-C2S and CO2 at an early age on shrinkage was greater than that caused by the drying shrinkage of cement.

The drying shrinkages of the specimens cured at high temperature reduced (Figure 6) compared to those cured at 23 °C (Figure 5b). The reduction of drying shrinkage with curing temperature was observed in STP0, STP30, and STP60. Typically, drying shrinkage of cementitious materials using OPC tends to increase with temperature [32]. In this study, however, the drying shrinkage of STP0

Figure 6. Drying shrinkages according to curing temperature: (a) 40 °C and (b) 50 °C.

Table 3. 28-day drying shrinkage according to the curing conditions.

| Variables | 28-Day Drying Shrinkage (× 10−6 m/m) | Drying Shrinkage Reduction (SH(0)−SH(x)/SH(0), %) |
|-----------|------------------------------------|-------------------------------------------------|
|           | STP0 | STP30 | STP60 | STP0 | STP30 | STP60 |
| T = 23 °C | CO2 = 0% | −1283 | −1097 | −900 | - | - |
|           | CO2 = 5% | −1169 | −903 | −737 | 8.9 | 17.7 | 18.1 |
|           | CO2 = 10% | −1003 | −853 | −640 | 21.8 | 22.2 | 28.9 |
|           | CO2 = 15% | −975 | −787 | −545 | 24.0 | 28.2 | 39.4 |
| T = 40 °C | CO2 = 5% | −993 | −844 | −682 | 22.6 | 23.1 | 24.2 |
|           | CO2 = 3% | −943 | −776 | −600 | 26.5 | 29.3 | 33.3 |

1 SH(0) is the 28-day drying shrinkage of STP0 non-CO2 cured at 23 °C. 2 SH(x) is the 28-day drying shrinkage.
reduced when the curing temperature increased from 20 °C to 40 °C. This is because the effect of carbonization was greater in drying shrinkage reduction than curing temperature. Drying shrinkage reduced when the curing temperature was 50 °C compared to when it was 40 °C. In addition, drying shrinkage tended to reduce as the AOD slag substitution rate increased. This can be attributed to the carbonation of the γ-C2S.

3.3. Chloride Diffusivity

The chloride diffusivity was measured by the NT Build 492 to evaluate the durability of the mortar specimens with AOD slag. The results are summarized in Table 4. The thicknesses of the specimens ranged from 49.85–50.25 mm, and the experiment was performed at 23 °C.

| Variables | Voltage (V) | Test Duration (h) | Temperature (K) | Thickness (mm) | Penetration Depth (mm) | Chloride Diffusivity (m²/s) |
|-----------|-------------|------------------|-----------------|----------------|------------------------|----------------------------|
| T = 23 °C | STP0 10     | 8                | 293             | 50.12          | 7.72                   | 26.80 × 10⁻¹²               |
| CO₂ = 0%  | STP30 10    | 8                | 293             | 50.05          | 10.54                  | 39.60 × 10⁻¹²               |
|           | STP60 10    | 8                | 293             | 49.85          | 21.78                  | 92.91 × 10⁻¹²               |
| T = 23 °C | STP0 10     | 8                | 293             | 50.24          | 6.54                   | 21.60 × 10⁻¹²               |
| CO₂ = 0%  | STP30 10    | 8                | 293             | 50.25          | 6.88                   | 23.10 × 10⁻¹²               |
|           | STP60 10    | 8                | 293             | 50.15          | 12.44                  | 48.52 × 10⁻¹²               |
| T = 23 °C | STP0 10     | 8                | 293             | 50.14          | 6.13                   | 19.78 × 10⁻¹²               |
| CO₂ = 10% | STP30 10    | 8                | 293             | 50.23          | 6.35                   | 20.76 × 10⁻¹²               |
|           | STP60 10    | 8                | 293             | 50.24          | 8.65                   | 31.04 × 10⁻¹²               |
| T = 23 °C | STP0 10     | 8                | 293             | 50.25          | 5.52                   | 17.16 × 10⁻¹²               |
| CO₂ = 15% | STP30 10    | 8                | 293             | 49.98          | 6.05                   | 19.39 × 10⁻¹²               |
|           | STP60 10    | 8                | 293             | 50.14          | 6.75                   | 22.49 × 10⁻¹²               |
| T = 40 °C | STP0 10     | 8                | 293             | 50.12          | 5.57                   | 17.35 × 10⁻¹²               |
| CO₂ = 5%  | STP30 10    | 8                | 293             | 50.20          | 6.88                   | 23.09 × 10⁻¹²               |
|           | STP60 10    | 8                | 293             | 50.22          | 8.44                   | 30.08 × 10⁻¹²               |
| T = 50 °C | STP0 10     | 8                | 293             | 50.12          | 5.42                   | 16.72 × 10⁻¹²               |
| CO₂ = 5%  | STP30 10    | 8                | 293             | 50.20          | 5.88                   | 18.68 × 10⁻¹²               |
|           | STP60 10    | 8                | 293             | 50.22          | 7.58                   | 26.05 × 10⁻¹²               |
Figure 7 shows the chloride diffusivity of the specimens according to the CO$_2$ concentration at 23 °C. As shown in the graph, the chloride diffusivity of STP0 decreased as the concentration increased, but the effect was not significant. An approximately 20% decrease was observed with the 5% CO$_2$ curing process compared to normal curing. For STP30, the decrease in the chloride diffusivity was clearly observed with 5% CO$_2$ curing compared to that of plain. For STP60, the chloride diffusivity significantly decreased as the CO$_2$ concentration increased. The chloride diffusivity of STP60 at 5% CO$_2$ curing was $49 \times 10^{-12}$ m$^2$/s, which was a decrease of more than 50% compared to the case of non-CO$_2$ curing ($93 \times 10^{-12}$ m$^2$/s). At 15% CO$_2$ curing, the chloride diffusivity was approximately $22 \times 10^{-12}$ m$^2$/s, which was approximately 130% of STP0.

![Figure 7. Chloride diffusivity according to CO$_2$ concentration.](image)

In the cases of STP30 and STP60 incorporating the AOD slag, the chloride diffusivity tended to converge to STP0 as the CO$_2$ curing concentration increased, as shown in Figure 7. This confirms that the reaction products of γ-C$_2$S with CO$_2$ filled the pores and decreased the chloride diffusivity. The porosity of the specimen containing AOD slag without carbonation curing increased as the replacement level of the AOD slag increased. However, the porosity is reduced by calcite and silica gel formed by carbonation curing [20,21]. Therefore, the specimens incorporating the AOD slag should increase their durability by pore structure densification through carbonation curing.

Figure 8 shows chloride diffusivity according to curing temperature at 5% CO$_2$ curing condition. For STP0, the chloride diffusivity decreased as the curing temperature increased. Similar tendencies occurred for STP30 and STP60 with the AOD slag. For STP30, chloride diffusivity was similar at curing temperatures of 23 and 40 °C, but it decreased at 50 °C. STP60 exhibited the largest change in chloride diffusivity as the curing temperature increased. Its diffusivity decreased by approximately 35% when temperature was increased from 23 °C to 40 °C. It was found that STP60 was significantly affected by the temperature. Salman et al. [24] reported that the strength of paste incorporating AOD slag increased with increasing temperature. Moreover, the acceleration of the reaction of γ-C$_2$S and the reaction products made the microstructure dense. The same tendency was observed in the compressive strength measurements.
3.4. **Mercury Intrusion Porosimetry (MIP)**

Figure 9 shows the cumulative intrusion for the specimens according to CO$_2$ concentration. For non-CO$_2$ curing, the cumulative intrusion increased as the replacement level of AOD slag increased. The cumulative intrusion was approximately 0.15, 0.27, and 0.3 mL/g for STP0, STP30, and STP60, respectively. This indicates that the cumulative intrusion was not proportional to the amount of AOD slag. For CO$_2$ curing, the cumulative intrusion decreased as the CO$_2$ concentration increased. These results were similar to the results of chloride diffusivity according to the CO$_2$ curing concentration (see Figure 7). This appears to be because γ-C$_2$S in the AOD slag generated silica gel and calcite through the CO$_2$ uptake, filling the large pores [20,21]. Mo et al. [33] examined the microstructure of a steel slag paste under CO$_2$ curing and reported that the pores were filled due to the generation of calcite.

For STP0, the cumulative intrusion decreased slightly until the CO$_2$ concentration reached 10%, after which it increased when the CO$_2$ concentration was 15%. This appeared to be because CO$_2$ was
excessively supplied in the curing process, and tricalcium silicate (C₃S) and C₂S in the OPC generated calcite instead of silicate gel through the hydration reaction, thereby increasing the volume of pores [34]. For STP30 and STP60, the cumulative intrusion decreased significantly as the CO₂ concentration increased. When the CO₂ concentration was 15%, STP0, STP30, and STP60 exhibited similar values. In particular, the reduction of porosity was largest when CO₂ concentration increased from 0 to 5%.

The pore volume fractions according to pore size were also analyzed. For STP0, no noticeable change was observed in the pore volume fraction according to the CO₂ concentration. For specimens with AOD slag, the fraction of pores smaller than 100 nm increased and that of the pores larger than 1000 nm decreased as the CO₂ concentration increased. Pores smaller than 100 nm correspond to the inter-layer or inter-granular pores in C-S-H gels, and their fractions were increased by the carbonation of the AOD slag [35,36].

Figure 10 shows the cumulative intrusion of specimens according to curing temperature. In the pore structure of STP0, no significant difference was observed according to the CO₂ curing concentration and temperature compared to the specimen incorporating the AOD slag. For STP30 and STP60, however, the cumulative intrusion decreased as the CO₂ curing temperature increased.

![Cumulative intrusion for specimens according to curing temperature.](image)

**Figure 10.** Cumulative intrusion for specimens according to curing temperature.

As the CO₂ curing temperature increased, the amount of silicate gel and calcite increased, filling the capillary pores. Similar results were also reported by other studies [35,36].

3.5. CO₂ Uptake

The CO₂ uptake was calculated from the TG/DTG measurements using Equation (2) [21].

\[
\text{CO}_2 \text{ uptake [wt. %]} = \Delta W / W_d
\]

where \( W_d \) is the weight of the specimen dried at 105 °C and \( \Delta W \) is the weight difference before and after carbonation curing (550–850 °C).

Figure 11 shows the CO₂ uptake for the specimens according to CO₂ concentration. The variation in CO₂ uptake was found to be within 7%. As shown in the graph, the CO₂ uptake increased as the CO₂ concentration increased for STP0. The CO₂ uptake of STP0 was not significant at 10% CO₂ concentration, but it almost doubled at 15% CO₂ concentration. For STP30 and STP60, the CO₂ uptake increased significantly by the carbonation of the AOD slag under CO₂ curing. The increase was most significant when the CO₂ concentration was 5%. The CO₂ uptake of STP60 increased compared to that of STP30, but it did not increase in proportion to the mixed amount of AOD slag. This can be attributed to the influences of solubility, diffusivity and reaction rate of CO₂.
Figure 11. CO₂ uptake for specimens according to CO₂ concentration.

The non-CO₂ cured specimens exhibited similar CO₂ uptake values (approximately 1.5%) regardless of the curing temperature, as shown in Figure 12. At CO₂ concentration of 5%, for STP0, the CO₂ uptake increased by approximately 1% due to the curing temperature change. This could also be confirmed via the compressive strength and MIP measurements. For STP30 and STP60, the CO₂ uptake significantly increased. However, the CO₂ uptake increased by approximately 1% only as the curing temperature increased for STP30 and STP60.

Figure 12. CO₂ uptake for specimens according to the curing temperature.
Figure 13 shows the comparison between the CO₂ uptake and the chloride diffusion coefficient. The chloride diffusivity decreased as the amount of CO₂ uptake increased in all variables, as shown in Figure 13a. The chloride diffusivity of STP0 decreased by up to 20%, depending on the CO₂ uptake. Evidently, the change in the chloride diffusivity of STP0 by CO₂ curing was greater than that of the compressive strength. For STP30, the chloride diffusion coefficient was approximately $4 \times 10^{-12} \text{ m}^2/\text{s}$ under non-CO₂ curing, but it decreased linearly to approximately $20 \times 10^{-12} \text{ m}^2/\text{s}$ as the CO₂ uptake increased. For STP60, the chloride diffusion coefficient decreased sharply in proportion to the CO₂ uptake compared to STP30. If the CO₂ uptake increases further, STP30 and STP60 are expected to exhibit smaller diffusion coefficients than STP0.

![Figure 13](image1.png)

**Figure 13.** Comparison between CO₂ uptake and chloride diffusivity: (a) CO₂ concentration and (b) curing temperature.

Figure 13b shows the comparison between the CO₂ uptake and chloride diffusivity according to curing temperature at a CO₂ curing concentration of 5%. The figure also shows that the chloride diffusivity decreases and the CO₂ uptake increases as the temperature increases. In the cases of STP0 and STP30, the chloride diffusion coefficient decreased slightly when the curing temperature increased from 23 to 40 °C. For STP60, the reduction in the chloride diffusion coefficient was significantly larger than that of STP0 and STP30. To secure the durability of high-volume AOD slag concrete, the curing temperature should be increased.

Figure 14a shows the comparison between the CO₂ uptake and drying shrinkage. The drying shrinkage reduced as the CO₂ uptake increased. For STP0, the drying shrinkage significantly reduced, even though the CO₂ uptake was less than 5%, which was much lower than that of STP30 or STP60. For STP30 and STP60, the drying shrinkage reduced in proportion to the increase in the CO₂ uptake. The overall reduction in drying shrinkage was similar for all variables.

![Figure 14](image2.png)

**Figure 14.** Comparison between CO₂ uptake and drying shrinkage: (a) CO₂ concentration and (b) curing temperature.
The CO₂ uptake increased, and the drying shrinkage was reduced as the temperature increased regardless of the AOD slag substitution rate, as shown in Figure 14b. The drying shrinkage of STP0 was significantly reduced as the curing temperature increased as shown in Figure 6, even though the CO₂ uptake was extremely low. For STP30 and STP60 with AOD slag, however, small changes were observed in the drying shrinkage, and the drying shrinkage decreased as the CO₂ uptake increased regardless of the replacement level of the AOD slag. It was found that the drying shrinkage of OPC is more affected by CO₂ curing temperature than AOD slag.

4. Conclusions

In this study, the physical and durability characteristics of mortar specimens with AOD slag under various CO₂ curing conditions were investigated.

The compressive strengths and porosities were analyzed according to CO₂ concentration. In addition, durability characteristics were evaluated by drying shrinkage and chloride diffusivity.

In STP30 and STP60, the compressive strength significantly decreased, while the porosity significantly increased by increasing the replacement level of the AOD slag under non-CO₂ curing. However, the compressive strength increased significantly, and the porosity decreased under CO₂ curing conditions. This was due to the calcite and silica gel formed by the reaction of γ-C₃S and CO₂.

The drying shrinkage decreased when CO₂ curing was performed. When the CO₂ concentration was 5%, the drying shrinkage significantly decreased for the specimens with AOD slag. When the CO₂ concentration reached 15%, STP0 and STP30 exhibited similar drying shrinkage reduction rates. Similar results were observed when the temperature increased. The drying shrinkage reductions of STP30 and STP60 according to the CO₂ uptake showed that the reduction remained unchanged for the same CO₂ uptake.

The chloride diffusion coefficient was significantly affected by the contents of AOD slag under CO₂ curing. When the CO₂ concentration was 15%, the diffusion coefficients of the specimens were similar regardless of the contents of the AOD slag. When the temperature increased, the diffusion coefficient decreased more significantly as the AOD slag substitution rate increased due to the acceleration of carbonation. A correlation between the CO₂ uptake and the diffusion coefficient showed that the diffusion coefficient reduction according to the CO₂ uptake increased as the contents of AOD slag increased. Thus, to improve the chloride diffusivity of concrete using a large quantity of AOD slag, the curing temperature should be increased.

Author Contributions: Conceptualization, methodology, validation Y.C.C.; formal analysis, investigation, resources, data curation, writing—original draft preparation, B.P.; writing—review and editing visualization; supervision; project administration; funding acquisition, Y.C.C. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIT) (2020R1A2C2008926). This work was also supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) and the Ministry of Trade, Industry & Energy (MOTIE) of the Republic of Korea (No. 20181110200070).

Conflicts of Interest: The authors declare no conflict of interest.

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