Improvement in Carbonation Resistance of Portland Cement Mortar Incorporating γ-Dicalcium Silicate

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In this study, γ-dicalcium silicate (γ-C2S) was incorporated into ordinary Portland cement (OPC) to sequester CO2 to enhance the carbonation resistance of cement-based composite materials. γ-C2S can react with CO2 rapidly to form vaterite and high dense SiO2 gel which could block the pores off and then inhibit further diffusion of CO2 into the system. Cement mortar specimens containing 0%, 5%, 10%, 20%, and 40% γ-C2S as cement replacement were prepared. After water curing for 28 days followed by curing in an environmental chamber for 28 days, the specimens were then exposed to an accelerated carbonation with 5% CO2 concentration for 28 days. He carbonation depth of the cement mortar with a low replacement rate (5% and 10%) was lower than that of the OPC mortar at all ages due to the sequestration of CO2 by γ-C2S. However, the cement mortar with a high replacement rate (20% and 40%) showed less carbonation resistance due to the dilution effect of γ-C2S replacement and increase in initial porosity caused by nonhydraulic characteristic of γ-C2S.

1. Introduction

Carbonation is an important factor affecting the service life of reinforced concrete structures. Carbonation of concrete occurs when CO2 in the air continuously traverses capillary pores, diffuses into concrete, dissolves in the pore solution, and forms carbonates that react with the hydration products to form calcium carbonates. The carbonation reaction reduces the pH value inside the concrete to a value low enough to break the protective film on the surface of steel reinforcement. Thus, the corrosion of steel bars is induced [1–4].

In order to extend the service life of reinforced concrete buildings which can be damaged by carbonation, several factors must be considered during the design stage, such as structural aspects, material selection, concrete mix design, proper compaction, and correct curing [5]. The application of coatings is also adopted in practical operations [6–9]. These methods aim to reduce the contact of CO2 with concrete by improving pore structure to reduce channels for the diffusion of CO2 or shielding the concrete surface. Unlike conventional methods, the approach proposed in this study attempts to inhibit the diffusion of CO2 by introducing a highly active CO2-capturable material, γ-C2S, into concrete to fix up CO2 present in the concrete, which could reduce CO2 diffusion rate. During the reaction between CO2 and γ-C2S, carbonation products with large molecular weights are formed [10, 11], which could block the capillary pores. Then, the permeability of cement-based composite materials can be reduced; thus, the available channels for the subsequent intrusion of CO2 are reduced, and the carbonation reactions can be further limited [12].

γ-C2S has an orthorhombic structure, which is called calcio-olivine. Olivine group minerals have become a popular subject of research for CO2 storage and capture (CSC) due to their high CO2 sequestration per unit mass capabilities [12, 13]. γ-C2S is considered as an insoluble substance, but it can rapidly react with CO2 [14, 15] to form calcium carbonates and highly polymerized silica gel.
CO₂ + H₂O → H₂CO₃
2CaO · SiO₂ + 2H₂CO₃ → 2CaCO₃ + SiO₂ gel-like

The carbonation reaction of γ-C₂S is as follows.

Although γ-C₂S does not react with water directly, it is the necessary reaction medium for the carbonation of γ-C₂S. Similarly, other olivine group minerals, γ-C₂S reacts with CO₂ after the formation of a thin water film on the surface of particles [16]. In Kerisi’s study, it was confirmed that γ-C₂S had the strongest water absorption capacity than the other four different types of olivine group minerals [17]. Additionally, different from the carbonation mechanism of other calcium silicates, such as C₃S and C₂S, which is close to that of control group without γ-C₂S. Guan et al. developed a γ-C₂S based mortar using CO₂ curing. By increasing the concentration of CO₂, the compressive strength of γ-C₂S mortar samples can reach up to 60 MPa in 5 hours.

However, the application of γ-C₂S has not been implemented on a large scale yet. The CO₂ emissions during the manufacturing of γ-C₂S using existing methods are lower than those of OPC [20]. From the perspective of mitigating the greenhouse effect, the application of γ-C₂S in the construction industry has a great research value. In this study, the beneficial effects of γ-C₂S on the carbonation resistance of cement-based composite materials are investigated. The macroscopic and microscopic properties, such as pore structure, carbonation depth, and calcium carbonate content, of cement mortar and cement paste containing γ-C₂S with and without carbonation were studied.

2. Materials and Methods

2.1. Materials

2.1.1. Synthesis of γ-C₂S. The γ-C₂S used in this study was prepared by using analytical grade Ca(OH)₂ and SiO₂ powders. Powders were mixed in a Ca/Si ratio of 2:1 and then placed in a muffle furnace for calcination. The heating rate was set at 10°C/min, and the temperature was maintained at 1450°C for 1.5 hours. After calcining, the samples were cooled down to room temperature with the cooling rate at 60°C/min, which is close to the natural cooling rate [20]. During the cooling process, the conversion from β-C₂S to γ-C₂S results in volume expansion, followed by pulverization of the materials, which is known as the "dusting phenomenon" [21]. X-ray diffraction (XRD) was performed for the phase identification and quantification of the synthetic γ-C₂S sample. RIGAKU D/MAX-2500 was used with CuKα radiation of 100 mA and 40 kV. XRD results for synthetic γ-C₂S after performing Rietveld refinement using the software Profex are shown in Figure 1. The purity of γ-C₂S is greater than 90%. The chemical composition of synthetic γ-C₂S was characterized by X-ray fluorescence (XRF), and the result is shown in Table 1. Synthetic γ-C₂S was sieved through a 150 μm sieve before use.

2.1.2. Sample Preparation and Curing Method. Type 1 ordinary Portland cement (OPC) was used in this study, and its chemical composition is listed in Table 2. Both cement mortar and cement paste specimens have a water-to-binder ratio of 0.5. As shown in Table 3, cement paste mixtures are designated as OPC-P, γ5-P, γ10-P, γ20-P, and γ40-P, which contain 0%, 5%, 10%, 20%, and 40% γ-C₂S replacement, respectively. The cement mortar specimens have a binder-to-sand ratio of 1:3. Cement mortar mixtures are designated as OPC-M, γ5-M, γ10-M, γ20-M, and γ40-M, which contain 0%, 5%, 10%, 20%, and 40% γ-C₂S replacement, respectively. Cement mortar specimens and cement paste specimens were prepared according to KS L 5109 and then cast into a 4 × 4 × 16 cm and 3.5 × 3.5 × 1 cm plastic mold, respectively.

Both cement paste and mortar specimens were demolded after 24 hours. After demolding, specimens were placed in tap water for 27 days and were then dried in a constant temperature chamber (relative humidity 60%, temperature 20°C) for 28 days. After that, cement mortar specimens and a portion of the specimens was moved into a CO₂ chamber (relative humidity 60%, CO₂ 5%, and temperature 20°C) for the accelerated carbonation curing over 28 days, and the remainder of the specimens was left in the environmental chamber. Curing process and characterizations used in this study are summarized in Table 4.

2.2. Test Methods

2.2.1. Hydration Product Analysis. To confirm the hydration products of the cement-based materials containing γ-C₂S subjected to or not subjected to accelerated carbonation, the cement paste specimens were ground into powder with a particle size less than 150 μm at 84 days, and the powders were analyzed by XRD and Fourier-transform infrared spectroscopy (FT-IR). FT-IR was performed using a PerkinElmer Spectrum Two FT-IR spectrometer (L160000A). Spectral analysis was performed over the range 4000–400 cm⁻¹ at a resolution of 4 cm⁻¹.

2.2.2. Quantification of Calcium Carbonate. Calcium carbonate content of carbonated cement paste was evaluated based on the results of thermogravimetry analysis (TGA). Each batch of cement paste specimens was ground to into
powder with a particle size less than 150 μm at 84 days. Powders were heated from room temperature to 1000°C at a heating rate of 10°C/min under a continuous flow of N2 gas.

### 2.2.3. Carbonation Depth Measurement.
Cement mortar specimens were sealed with epoxy resin except for two opposite rectangular faces at the age of 54 days. After drying for 2 days, the test specimens were placed in a CO2 chamber (relative humidity 60%, CO2 5%, and temperature 20°C) for the accelerated carbonation. The sealed specimens were cut perpendicular to the unsealed surfaces after 3, 7, 14, and 28 days of accelerated carbonation. The carbonation depth was measured by using a 1% phenolphthalein pH indicator. For each set, three specimens of each age were used for carbonation depth measurement. For each specimen, 12 carbonation depth data were obtained, and the average value was calculated as the carbonation depth.

### 2.2.4. Pore Structure Analysis.
Mercury intrusion porosimetry (MIP) was performed to study changes in pore structure of the cement mortar after accelerated carbonation. The pore structure of each test piece was measured and analyzed by Micromeritics AutoPore IV 9500 mercury intrusion porosimeter (MIP). The pore diameter measurement in this study is 0.003 to 370 μm.

### 3. Results and Discussion

#### 3.1. XRD Analysis.
Crystalline phases in the specimens with and without accelerated carbonation were analyzed by XRD, and the results are shown in Figures 2 and 3.

The diffraction peaks of the major hydration products, such as Ca(OH)2 and ettringite, can be observed in Figure 2.
At the same time, some diffraction peaks of quartz were also observed. The diffraction peaks of \( \gamma'-\text{C}_2\text{S} \) also appeared obviously at 20.5°, 22°, 32°, and 55° of 2\( \theta \) for \( \gamma'-\text{PC} \) and \( \gamma'-\text{OPC} \). In particular, it was found that the main diffraction peaks of Ca(OH)\(_2\) were reduced due to the decrease in the formation of Ca(OH)\(_2\) by the large replacement of cement for \( \gamma'-\text{PC} \); meanwhile, the diffraction peaks of \( \gamma'-\text{C}_2\text{S} \) became very conspicuous. In addition, since the analyzed powder samples were placed in the air and reacted with CO\(_2\), resulting in the formation of CaCO\(_3\), the diffraction peaks of calcite and vaterite were also detected.

The diffraction peaks of Ca(OH)\(_2\) were absent in all five batches of carbonated cement paste samples, and the diffraction peaks of three phases of CaCO\(_3\), calcite, aragonite, and vaterite, can be observed. Calcite was the main calcium carbonate phase formed in all specimens. Vaterite is considered to be the main carbonation product of \( \gamma'-\text{C}_2\text{S} \). Saito reported that the crystallinity of \( \gamma'-\text{C}_2\text{S} \) is associated with the crystallinity of the carbonation products [18]. \( \gamma'-\text{C}_2\text{S} \) and vaterite have a similar crystalline structure in which Ca\(^{2+}\) ions occupy a six-coordinate position of hexagonally close packed O\(^{2-}\), and their Ca-O bond lengths are also similar. Table 5 shows the coordination number and Ca-O bond length in \( \text{Ca}_2\text{S} \) and CaCO\(_3\) crystals [12, 22, 23]. Therefore, vaterite could be generated after the topotactic reaction of \( \gamma'-\text{C}_2\text{S} \) in the carbonation reaction process [24]. So, the diffraction peaks of calcite are reduced for the cement paste mixed with \( \gamma'-\text{C}_2\text{S} \). In addition, some previous studies reported that the main carbonation products of \( \gamma'-\text{C}_2\text{S} \) are calcite [15, 25]. This is because that calcite is more thermodynamically stable than the other two structures at room temperature and atmospheric pressure, aragonite is slightly less stable under similar conditions and is eventually transformed to calcite, and vaterite is thermodynamically the most unstable of the three crystal structures and can transform into the calcite at low temperature. Therefore, the different experimental environments and ways of preserving samples can cause a conversion of polymorphs in this study [26–30]. The diffraction peaks of quartz can be observed at approximately 26.5° in the XRD results of all cement pastes, especially in carbonated samples of OPC which was very sharp. The quartz in samples might come from the clinker of the cement and/or synthetic \( \gamma'-\text{C}_2\text{S} \) [31].

### Table 4: The curing process and characterizations of the samples.

<table>
<thead>
<tr>
<th>Accelerated carbonation experiment (curing process)</th>
<th>Characterizations</th>
<th>Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>X (28-day water curing + 56-day air curing)</td>
<td>XRD FT-IR</td>
<td>OPC-P</td>
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<tr>
<td></td>
<td></td>
<td>( \gamma^5)-P</td>
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<td></td>
<td></td>
<td>( \gamma^{10})-P</td>
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<td></td>
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<td>( \gamma^{40})-P</td>
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<tr>
<td></td>
<td></td>
<td>OPC-PC</td>
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<td>( \gamma^5)-PC</td>
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<td>( \gamma^{40})-PC</td>
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<tr>
<td>Cement paste</td>
<td></td>
<td></td>
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<tr>
<td>O (28-day water curing + 28-day air curing + 28-day accelerated carbonation)</td>
<td>XRD FT-IR DSC-TG</td>
<td>OPC-M</td>
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<td>( \gamma^{10})-M</td>
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<td></td>
<td></td>
<td>( \gamma^{40})-M</td>
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<tr>
<td></td>
<td></td>
<td>OPC-MC</td>
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<td>( \gamma^5)-MC</td>
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<td></td>
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<td>( \gamma^{10})-MC</td>
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<td>( \gamma^{20})-MC</td>
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<td></td>
<td>( \gamma^{40})-MC</td>
</tr>
<tr>
<td>Cement mortar</td>
<td>Mercury intrusion porosimetry (MIP)</td>
<td>OPC-M</td>
</tr>
<tr>
<td>O (28-day water curing + 28-day air curing + 28-day accelerated carbonation)</td>
<td>Carbonation depth</td>
<td>( \gamma^{10})-M</td>
</tr>
<tr>
<td></td>
<td>MIP</td>
<td>( \gamma^{40})-M</td>
</tr>
</tbody>
</table>

### 3.2. FT-IR Analysis.

The FT-IR spectra of noncarbonated and carbonated cement paste at 84 days are shown in Figure 4. The shapes of the FT-IR spectra of the non-carbonated specimens were substantially similar because the hydration products in the specimens were the same, which is consistent with the XRD results. The noncarbonated samples show weak peak at 3640 cm\(^{-1}\), which corresponds to \( \text{H-O} \) stretching vibrations of Ca(OH)\(_2\). The peak near 950 cm\(^{-1}\) corresponds to the \( Q^2 \) vibration of the \( v_2 \) Si-O bond in the hydrate produce—\( \text{C-S-H} \) [32, 33]. The calcium carbonate formed by the reaction of the powdered specimen with CO\(_2\) in air is also reflected in the FT-IR spectra. The peaks at approximately 1400 cm\(^{-1}\) correspond to the asymmetric stretching vibration of \( v_1 \) C-O from three polymorphs of calcium carbonate (calcite, vaterite, and aragonite). Also, the peaks at 870 cm\(^{-1}\) and 850 cm\(^{-1}\) were assigned to the out-of-plane bending vibration of \( v_1 \) C-O from calcite and vaterite, respectively. The peaks observed at 715 cm\(^{-1}\) were caused by the in-plane bending vibration of \( v_4 \) C-O from calcite and aragonite [27–29, 34, 35].

In the FT-IR spectra of the carbonated specimens, the effect of carbonation can be clearly observed. Due to carbonation of Ca(OH)\(_2\), peaks of O-H stretching vibrations were absent at 3640 cm\(^{-1}\). The peaks at approximately 1400 cm\(^{-1}\), 870 cm\(^{-1}\), 850 cm\(^{-1}\), and 715 cm\(^{-1}\) were sharper.
and more visible in comparison with noncarbonated samples. Lower crystallinity calcium carbonate formed during the accelerated carbonation, which was verified by the appearance of broad asymmetrical peaks at approximately 1410 cm$^{-1}$. Additionally, the appearance of new peaks was observed at 745 cm$^{-1}$, which is attributed to the formation of vaterite [24, 27, 28]. For carbonated OPC specimens, the vaterite peak can be also observed because the carbonation of...
C-S-H could form vaterite [2]. After the accelerated carbonation, the peaks of the Si-O-Si band that appeared in the FT-IR spectrum of the noncarbonated specimens at approximately 950 cm$^{-1}$ appeared at approximately 1070 cm$^{-1}$ in carbonated specimens. It indicates the formation of a silicate gel caused by the decalcification of C-S-H during the carbonation [36, 37].

3.3. TGA Analysis. To quantify the CaCO$_3$ content of carbonated cement paste specimens, the completely carbonated cement paste specimens (confirmed by 1% phenolphthalein solution) were ground into powder and measured by using TGA. The differential thermogravimetry (DTG) and TG behaviors of each sample are shown in Figure 5.

Figure 5(b) shows that all specimens show very similar results of TG-DTG, which indicate the reaction products were almost same. All samples showed a mass loss at approximately 100°C due to the decomposition of free water and/or physically adsorbed water from C-S-H and/or SiO$_2$ gel [38]. The humps in the region of 500°C–650°C and 650°C–750°C are due to the decomposition of poorly crystallized CaCO$_3$. Sharp peaks at the temperature between 750°C and 850°C were attribute to the decomposition of well crystallized CaCO$_3$ [35, 39]. In previous studies, researchers considered the mass loss at 750°C–850°C was from the decomposition of three polymorphs—calcite, vaterite, and aragonite. Based on these, we consider that the mass loss between 500°C and 850°C is mostly due to the decomposition of calcium carbonates of varying crystallinity [40]. Therefore, the mass loss in this range can be approximated as the amount of CO$_2$ fixation by the cement paste specimens during the accelerated carbonation. According to Figure 5(a), the mass loss between 500°C and 850°C was calculated and are shown in Table 6. The CaCO$_3$ content was calculated using formula (2) [41], and the results are shown in Table 7. It can be seen that the CaCO$_3$ content of the samples mixed with γ-C$_2$S is slightly higher than that of OPC-PC, and the CaCO$_3$ content increases with increases in the substitution ratio of γ-C$_2$S, which is attributed to the high carbonation activity of γ-C$_2$S.

$$\text{CaCO}_3 (\%) = \frac{\text{WL}_{\text{CaCO}_3} (\%)}{\text{MW}_{\text{CaCO}_3} / \text{MW}_{\text{CO}_2}} \times \frac{\text{MW}_{\text{CaCO}_3}}{\text{MW}_{\text{CO}_2}},$$  (2)

3.4. Pore Structure Analysis. The pore size distribution and total porosity of cement mortar specimens at 84 days are shown in Figures 6 and 7, respectively. In Figure 6(a), it can
be observed that the diameters of the pores in the non-carbonated sample of OPC-M, γ10-M, and γ40-M are mainly in the range of approximately 0.08–0.15 μm. Pores with diameters smaller than 0.1 μm are even more in γ10-M than in OPC-M, especially those smaller than 0.06 μm. The porosity above 0.1 μm is approximately the same as that of OPC-M. Therefore, it can be inferred that the addition of γ-C2S with low substitution leads to an increase in the formation of relatively fine pores (<0.08 μm). The pore structure of the γ40-M noncarbonated sample shows the lowest pore concentration in the range of 0.08–0.15 μm, and the quantity of other pore sizes increased, especially in the range of 0.01–0.02 μm and above 0.15 μm. The addition of a large amount of γ-C2S significantly increases the quantity of large capillary pores. Figure 7 also shows the total porosity of the noncarbonated sample increases as γ-C2S increases. The reduction in the total amount of hydration products due to the nonhydraulic characteristic of γ-C2S probably results in an increase in porosity.

In Figure 6(b), the pore diameters of the OPC-MC and γ10-MC samples were concentrated between 0.1 and 0.2 μm. γ40-MC carbonated sample had distinct peak at 0.5 μm. Overall, the amount of large capillary pores in all three carbonated samples was more than that in uncarbonated samples. This coarsening of the pore structure can be explained by the formation of amorphous SiO2 gel due to the decomposition of C-S-H during carbonation [2, 36, 37]. As seen in Figure 7, total porosity of carbonated samples was significantly less compared to noncarbonated samples. It attributed to the formation of carbonation products which blocked pores, although the relatively larger capillary pore increased.

According to the total porosity results shown in Figure 7, the porosity of the noncarbonated samples of OPC-MC, γ10-MC, and γ40-MC are 13.9%, 16.16%, and 18.79%, respectively. The porosity of the carbonated samples of OPC-MC was 11.25%, which is 19.1% less compared to noncarbonated samples of OPC-MC. For γ10-MC and γ40-MC, more calcium carbonates were produced due to the addition of γ-C2S as shown in TGA results. The total porosity of γ10-MC and γ40-MC was 22.42% and 22.97% less than γ10-M and γ40-M, respectively. The gaps between porosity of noncarbonated and carbonated samples were more obvious as the replacement ratio increases. Vaterite formed by the carbonation of γ-C2S is denser than calcite and aragonite (vaterite: 2.645 g/cm³, calcite: 2.711 g/cm³, and aragonite: 2.944 g/cm³) [42]. Thus, volume expansion caused by vaterite and the formation of highly polymerized silica gel result in pores blocking in cement mortar samples incorporating γ-C2S.

3.5. Carbonation Depth. The carbonation depth at 3, 7, 14, and 28 days after the accelerated carbonation is shown in Figure 8.

**Table 6:** Estimated CO₂ fixation of carbonated cement paste samples at 84 days (weight (%)).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>OPC-PC (%)</th>
<th>γ5-PC (%)</th>
<th>γ10-PC (%)</th>
<th>γ20-PC (%)</th>
<th>γ40-PC (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimated CO₂ fixation</td>
<td>23.34</td>
<td>24.18</td>
<td>24.65</td>
<td>25.04</td>
<td>26.40</td>
</tr>
</tbody>
</table>

**Table 7:** Estimated CaCO₃ content of carbonated cement paste samples at 84 days (weight (%)).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>OPC-PC (%)</th>
<th>γ5-PC (%)</th>
<th>γ10-PC (%)</th>
<th>γ20-PC (%)</th>
<th>γ40-PC (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimated CaCO₃ content</td>
<td>53.05</td>
<td>54.95</td>
<td>56.02</td>
<td>56.91</td>
<td>60.00</td>
</tr>
</tbody>
</table>
When the replacement ratio of γ-C₂S is low (γ5-MC and γ10-MC), the carbonation depth decreases at all ages as substitution increases. When the substitution ratio reaches 20%, the carbonation depth begins to increase but is still lower than that of OPC-MC. However, the carbonation depth of γ40-MC was higher at all ages than that of OPC-MC. This is probably due to the dual effects of CO₂ sequestration and alkalinity change. For the samples with a low replacement ratio (γ5-MC and γ10-MC), the addition of γ-C₂S led to the increased consumption of CO₂ in the cement mortar, and then the diffusion rate could be slowed down. Also, the subsequent intrusion channels for CO₂ were limited due to the formation of more carbonates. Thus, the diffusion rate simultaneously decreased even further. For the samples with a high replacement ratio (γ20-MC and γ40-MC), the hydration products decreased significantly which led to the decrease in alkalinity of the systems, and then an internal environment of the samples became neutral soon after carbonation started. This phenomenon can be widely observed in cement-based composite materials containing supplementary cementitious materials (SCMs) [2, 4, 25]. Based on experimental results, it is considered that incorporating γ-C₂S at a low replacement ratio can improve the carbonation resistance of the cement mortar.

### 4. Conclusions

In this study, the carbonation resistance of cement-based composite materials incorporating 0%, 5%, 10%, 20%, and 40% of γ-C₂S was evaluated. The feasibility of methods incorporating γ-C₂S into cement mortar to capture CO₂, reduce CO₂ diffusion, and improve the pore structure to
inhibit the carbonation reaction was verified. The main conclusions are as follows:

(1) Calcite, aragonite, and vaterite were the carbonation products formed in the cement paste during the accelerated carbonation. Vaterite is considered the main carbonation product of γ-C2S, which increased significantly in carbonated cement paste samples containing 40% γ-C2S.

(2) In the DSC-TG study, the mass loss between 500°C–850°C is associated with the decomposition of crystallized and amorphous calcium carbonate. The results show that the CaCO3 content and amount of CO2 fixation increased with increasing replacement of γ-C2S.

(3) The porosity of the noncarbonated cement mortar increased as the substitution of γ-C2S increased, which was caused by the relatively low hydration degree due to the dilution effect of γ-C2S replacement. The porosity of the carbonated cement mortar was less than noncarbonated samples due to the formation of carbonates in the capillary pores. The carbonation products of γ-C2S are mainly vaterite and highly polymerized silica gel which could block the pores off effectively and limit the diffusion of CO2 into the system.

(4) For the samples with a low replacement ratio (γ5-MC and γ10-MC), the carbonation depth shows a downward trend at all ages with the increase in replacement rate, and γ10-MC had the lowest carbonation depth. However, porosity was increased and susceptibility to carbonation was increased with further increase in replacement rate of γ-C2S. The carbonation depth began to increase with more than 20% replacement of cement with γ-C2S. The carbonation depth of γ40-MC was higher than that of OPC-MC at all ages. The experimental results revealed that the incorporation of γ-C2S at a lower substitution rate can improve the carbonation resistance of the cement mortar.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors’ Contributions

Zhengxin Chen and Hanseung Lee conceptualized the study; Zhengxin Chen and Yunsu Lee performed the experiments and analyzed the data; Hyeongkyu Cho synthesized γ-C2S; Zhengxin Chen prepared the original draft; Seungmin Lim reviewed and edited the manuscript; and Hanseung Lee supervised the research.

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