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Quantitative Analysis of CO₂ Uptake and Mechanical Properties of Air Lime-Based Materials

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Abstract: In the cement industry, utilization of a sustainable binder that has a lower energy consumption and carbon dioxide (CO_2) emission than Portland cement is becoming increasingly important. Air lime is a binder that hardens by absorbing CO2 from the atmosphere, and its raw material, hydrated lime, is manufactured at a lower temperature (around 900 °C) than cement (around 1450 °C). In this study, the amount and rate of CO_2 uptake by air lime-based materials are quantitatively evaluated under ambient curing conditions of 20 °C, 60% relative humidity, and 0.04% CO_2 concentration. In addition, the effects of the water-to-binder ratio (w/b) and silica fume addition on the material properties of the air lime mortar, such as strength, weight change, carbonation depth, and pore structure, are investigated. Unlike hydraulic materials, such as Portland cement, the air lime mortar did not set and harden under a sealed curing condition, however, once exposed to dry air, the mortar began to harden by absorbing CO_2 . During the first week, most of the internal water evaporated, thus, the mortar weight was greatly reduced. After that, however, both the weight and the compressive strength consistently increased for at least 180 days due to the carbonation reaction. Based on the 91-day properties, replacing 10% of hydrated lime with silica fume improved the compressive and flexural strengths by 27% and 13% respectively, whereas increasing the w/bfrom 0.4 to 0.6 decreased both strengths by 29% due to the increased volume of the capillary pores. The addition of silica fume and the change in the w/b had no significant impact on the amount of CO_2 uptake, but these two factors were effective in accelerating the CO₂ uptake rate before 28 days. Lastly, the air lime-based material was evaluated to be capable of recovering half of the emitted CO₂ during the manufacture of hydrated lime within 3 months.

Keywords: greenhouse gas; global warming; air lime mortar; hydrated lime; CO₂ uptake; carbonation; calcium hydroxide; calcium carbonate; thermogravimetric analysis

1. Introduction

The cement industry is associated with huge amounts of energy consumption and greenhouse gas emissions [1]. It consumes 2%–3% of global energy consumption and is responsible for about 7% of carbon dioxide (CO₂) emissions [2], which is mostly attributed to the manufacture of Portland cement, which requires a very high temperature of 1400 °C–1500 °C [3]. Since the crisis of climate change is on the rise, many eco-friendly techniques have been developed and applied in all industries to achieve near zero CO₂ emissions by 2050 [4]. Nevertheless, the demand for Portland cement has steadily increased [5]. Consequently, efforts to mitigate our dependency on Portland cement or cement

clinkers are urgently required in the field of construction materials. In this context, the widespread use of clinker-free binders based on industrial byproducts, such as fly ash, various types of slag (ground granulated blast-furnace slag, steel slag, and magnesium slag), and studies on their CO_2 uptake capacity have received much attention [6,7]. Indeed, it is quantitatively evaluated that the use of eco-friendly materials in place of existing construction materials significantly reduces carbon footprint and energy consumption [8,9]. A safe and rational utilization of industrial solid waste, such as fly ash, is an increasingly important environmental concern because its cumulative landfill deteriorates water and soil contamination [10]. In particular, carbonation reaction of such waste has been reported to promote heavy metal stabilization, as well as uptake of atmospheric CO_2 [11]. Therefore, recent studies on the CO_2 uptake of building materials have examined the properties related to the carbonation reaction, such as strength development, carbonation depth, and weight change under atmospheric CO_2 concentration (i.e., around 0.04%) rather than under accelerated carbonation conditions (i.e., 1%–100% of CO_2 concentration) [12,13].

Along with the materials that utilize the carbonation reaction as a second reaction, the more active use of binders, such as air lime, that absorb CO₂ for the primary chemical reaction, is a promising way to reduce CO₂ emissions and fossil fuel dependency in the construction industry. Moreover, its raw material, hydrated lime, is manufactured at a low temperature of about 900 °C [14], which is why it is considered to be a much less energy-intensive binder compared to Portland cement. As one of the representative building materials of humankind, hydrated lime has been used to construct buildings and infrastructure all over the world for over 10,000 years [15]. The long history of its use is well documented [16,17]. Although the use of non- or sub-hydraulic binders has rapidly declined since the advent of the stronger and fast-setting hydraulic binder, Portland cement [18], research on lime-based materials has recently received renewed attention due to concerns about climate change and a rediscovery of the materials' durability [19].

The chemical reaction involved in the hardening of air lime is completely different from that of hydraulic binders. As summarized in previous studies [20,21], CO₂ absorbed from the atmosphere dissolves in the alkaline pore solution inside the lime mortar and reacts with the calcium hydroxide (Ca(OH)₂) provided by hydrated lime. As a result, calcium carbonate (CaCO₃) precipitates with an exothermic reaction. Because it hardens by absorbing atmospheric CO₂, most of the CO₂ released during the manufacture of the raw material can be recovered. For this reason, air lime has been continuously studied not only for better preservation of historic buildings [22] but also for the development of sustainable construction materials [23].

Hydrated lime, the raw material of air lime, is mostly composed of calcium hydroxide, which has a hexagonal plate-like crystal structure. For this reason, a large amount of water (e.g., water-to-binder ratio (w/b) = around 1) is required to manufacture lime-based mortars. However, the water contained in the mortars cannot be used for a chemical reaction or strength development, and it evaporates while increasing shrinkage cracks and the volume of capillary pores, thus leading to low strength. To cope with this, various additives, such as nanosilica, superplasticizers, viscosity modifiers, water repellents, and synthetic fibers have been tried with lime mortars [24–26]. In addition, concurrent use of air lime and hydraulic binders, such as natural hydraulic lime and Portland cement, has been proposed [27–29]. Among these attempts, Fernández et al. reported an improvement in the mechanical properties of air lime mortar by using a polycarboxylate-type superplasticizer [30], which is attributed to a uniform distribution of the newly formed crystals (i.e., CaCO₃) over the volume of mortar and the refinement of pore structure. Despite these efforts, its mechanical properties (typically, 28-day compressive strength < 3 MPa) are still regarded as considerably lower than those of hydraulic materials.

To more actively use CO_2 -curable construction materials, their CO_2 uptake capacity must be clearly understood, because these materials can exhibit structural performance by a chemical reaction such as carbonation. Moreover, attempts to improve the mechanical properties should be performed efficiently. In this study, therefore, air lime mortars with a relatively low w/b of 0.4–0.6 were manufactured using a polycarboxylate-type superplasticizer and ultrafine particles, such as silica fume. The strength development, weight change, carbonation depth, and pore structure of the mortars were measured by experiments. Moreover, the effects of the w/b and the addition of silica fume on the amount and rate of CO₂ uptake of these materials were quantitatively investigated by thermogravimetric analysis.

2. Materials and Methods

2.1. Materials

To manufacture air lime mortars, industrial hydrated lime (Baekkwang Mineral Products Co., Ltd., Korea), silica fume (Grade 940U, Elkem, Norway), water, a polycarboxylate-type superplasticizer (Flowmix 3000S, Dongnam, Korea), and ISO standard sand were prepared. Table 1 shows the chemical composition of the lime and silica fume used, which was determined by X-ray fluorescence analysis (S8 Tiger, Bruker, Germany). The hydrated lime consisted mainly of CaO (70.6%), and the silica fume was almost entirely comprised of amorphous SiO₂ (97.0%). In particular, the lime showed a high LOI (24.1%), because the water and CO₂ contained are removed from Ca(OH)₂ and CaCO₃ at a high temperature of 1000 °C. Furthermore, quantitative analysis using thermogravimetric analysis confirmed that the lime contained 85.1% Ca(OH)₂ and 4.0% CaCO₃. This method is described in detail in Section 2.3.5.

Table 1. Chemical composition of hydrated lime and silica fume.

Materials	CaO	SiO ₂	MgO	Al ₂ O ₃	Fe ₂ O ₃	SO ₃	K ₂ O	Na ₂ O	P_2O_5	Cl	LOI ¹	Total
Hydrated lime	70.6	1.7	1.6	0.8	0.3	0.6	0.1	-	-	-	24.1	99.9
Silica fume	0.3	97.0	0.4	0.7	0.1	0.2	0.8	0.3	0.1	0.1	-	100.0
¹ Loss on ignition.												

The particle size distributions of the materials are shown in Figure 1. The analysis method is explained in Section 2.3.1. As shown in the figure, the particle size range of silica fume is about 30–500 nm, hence, it consists of nanoparticles. The size of hydrated lime is in the range of 600–180 μ m. Based on this, it is confirmed that the size ranges of the two materials do not overlap. In addition, the particle size of the standard sand rages between 0.08–2 mm, as specified in ISO 679 [31].



Figure 1. Particle size distribution of hydrated lime and silica fume.

2.2. Sample Preparation

Three different air lime mortars were produced based on the mix proportion shown in Table 2. The sample name was determined by the combination of the w/b and the replacement ratio of hydrated lime with silica fume. For instance, the sample 0.4_SF0 is an air lime mortar with w/b = 0.4 but without silica fume. In the samples 0.4_SF10 and 0.6_SF0, 10% of hydrated lime was replaced with silica fume, and the w/b was increased to 0.6, respectively. The content of superplasticizer was determined based on

the target flow range of 145 ± 5 mm using the ASTM C230 method [32], and the fine aggregate-to-binder ratio was determined to be 3 according to BS EN 459-2 [33]. The raw materials were mixed using a 5-L mortar mixer, and then the manufactured fresh mortars were put into molds and sealed. All specimens were demolded after 7 days of sealed curing at 20 °C, and then cured in a chamber that had been set at 20 °C, 60% relative humidity and 0.04% CO₂ concentration, until the test day.

Sample Name	Hydrated Lime	Silica Fume	Water	Super- Plasticizer ¹	Fine Aggregate	Curing Condition	
0.4_SF0	1	0	0.4	0.06	3	Sealed curing (20 °C) for 7 days followed by air dry curing	
0.4_SF10 0.6_SF0	0.9 1	0.1 0	0.6	0.03	C	(20 °C, Relative humidity 60% and CO ₂ concentration 0.04%)	
			¹ I	olycarboxylate-ty	pe.		

Fable 2. Mix p	roportion	of air lime	mortars (v	vt % of binder)
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2.3. Test Methods

2.3.1. Particle Size of Raw Materials

To obtain particle size information of two key materials, hydrated lime and silica fume, two different techniques were used. The size distribution of hydrated lime was determined by a laser diffraction method (Mastersizer 3000, Malvern Panalytical, UK). Accuracy, repeatably, and reproducibility of Mastersizer 3000 are 99.4%, >99.5%, and >99% respectively, based on the equipment specifications. On the other hand, to exclude the nature of aggregation of silica fume, its size was determined by an image-processing technique using a scanning electron microscope (SEM) (JSM-7800F Prime, JEOL, Japan) [34].

2.3.2. Mechanical Properties

To examine the strength development of the air lime mortar, the compressive strength was measured at 7, 14, 28, 56, 91, and 180 days. According to ASTM C109, cube specimens with a size of 50 mm were loaded using a hydraulic testing machine, and the strength on each day was determined by dividing the maximum load by the loaded area. In addition, the flexural strength test was performed at 91 days. According to ISO 679 [31], prismatic specimens with the size of 40 mm \times 40 mm \times 160 mm were loaded by the machine, and the strength was determined. All the strength values were determined as the average of three repeated test results.

2.3.3. Weight Change

The weight change of the mortar was recorded to investigate the evaporation of internal water and the uptake of atmospheric CO_2 . The weight of the 50-mm mortar (the same as the specimen for compressive strength) was measured using an electronic scale (precision: 0.001 g) from immediately after demolding (i.e., 7 days after casting) to 180 days. A representative value on each day was determined as the average of three specimens. Following the recording, all the results were presented as relative weights to the initially measured weight.

2.3.4. Carbonation Depth

On the 91st day, the carbonation depth of the mortar was measured. Using a precision cutter, the cube specimen was cut horizontally at the midpoint of the height (i.e., 25 mm). Immediately after cutting, the section was sprayed with a phenolphthalein indicator solution (concentration: 1%), and the depth of the area where no color change occurred was measured. Phenolphthalein creates a pink or fuchsia color between pH 8.2–10 [35]. Using this, the depth of the area where pH is lowered to <10 (i.e.,

carbonated part) can be visually confirmed. The carbonation depth of each mortar was determined as the average of four depths, which were measured at the center of the four sides, and the representative value for each sample was determined using two mortar specimens.

2.3.5. Pore Size Distribution

The pore size distribution of the mortar was analyzed using mercury intrusion porosimetry (MIP). At 91 days, the 50-mm cube was cut into 5-mm pieces using the aforementioned precision cutter. The pieces were immersed into isopropanol to remove any internal water and then dried at 40 °C [36]. Pore structure analysis was performed using a device for MIP (AutoPore IV 9500, Micromeritics, Norcross, GA, USA) [37]. For this measurement, the mercury parameters were set at 0.7 kPa–414 MPa, 130°, and 485 mN/m for pressure range, contact angle, and surface tension, respectively.

2.3.6. Thermogravimetry-Based Quantitative Analysis

Thermogravimetric analysis was conducted to quantitatively evaluate the changes in the constituents of the air lime. This technique can be used simply and accurately for the analysis of specific components, especially for Ca(OH)₂ and CaCO₃ [38], thus, it is one of the most suitable methods for chemically characterizing air lime-based materials as a function of time. At 7, 28, and 91 days, the paste sample that did not contain fine aggregate was finely ground, and its internal moisture was removed by the solvent-exchange method using isopropanol and diethyl ether. A more detailed description of this method can be found elsewhere [39]. The prepared powder, as much as 20 ± 1 mg, was placed in a holder of the analyzer (SDT Q600, TA Instruments, USA), and the weight change between 25 °C and 1000 °C was measured under N₂ atmosphere, with a condition of heating rate of 10°C/min. The Ca(OH)₂ and CaCO₃ content was determined by rapid weight losses from 350 °C–500 °C and 550 °C–800 °C, respectively. To accurately estimate these contents, the derivative thermogravimetry (DTG) curve and the tangential method were adopted [40]. The estimated contents were then normalized to the weight of the hydrated lime, where the weight change during the conversion of Ca(OH)₂ to CaCO₃, which is caused by the absorption of CO₂ and water loss, was also considered.

3. Results and Discussion

3.1. Mechanical Properties and Weight Change

Compressive strength development, flexural strength, and the weight change of the air lime mortar are shown in Figure 2a–c, respectively. The standard deviations are also presented as error bars. The case where the error bars are hidden from the markers means almost perfect reproducibility of the test results.



Figure 2. Properties of air lime mortar: (**a**) compressive strength development for 180 days, (**b**) flexural strength at 91 days, and (**c**) weight change for 180 days.

As shown in Figure 2a, although the compressive strength was measured from 7 days after casting of the mortar, the strength obtained at this time was almost 0 MPa. In other words, a chemical reaction

related to the mortar hardening did not occur under the sealed curing condition. This clearly shows the characteristics of air lime-based materials, which cannot harden without absorption of CO₂. Once the mortar was exposed to dry air, setting and hardening started between 7–14 days. As a result, 4 MPa–7 MPa of compressive strength was obtained at 28 days. This is a high strength compared to 1 MPa–6 MPa of the lime mortar containing nanosilica and superplasticizer [30], which might be caused by a relatively low w/b of 0.4–0.6 in the present study. The strength increased steadily up to 180 days, at which time the mortars exhibited 5 MPa–9 MPa of strength. Meanwhile, the flexural strength measured at 91 days was in the range of 2 MPa–3.2 MPa.

The silica fume addition and increase of the w/b had a significant effect on the mechanical properties. When 10% of hydrated lime was replaced with silica fume, the 91-day compressive and flexural strengths increased by 27% and 13%, respectively. On the other hand, when the w/b increased from 0.4 to 0.6, both compressive and flexural strengths decreased by 29%. The enhancement of the mechanical properties by the addition of silica fume can be explained by the pore-filling effect (i.e., the capillary pores are filled with ultrafine particles) and the pozzolanic reaction [41,42]. This positive effect of the silica fume addition was more pronounced in compressive strength than in flexural strength, as reported previously [43]. In addition, a remarkable increase in the long-term (>28 days) strength due to the addition of silica fume suggests the possibility of a pozzolanic reaction, which progresses slowly at room temperature (compare the blue and red lines in Figure 2a) [44].

Figure 2a,b demonstrate that the mechanical properties of the air lime mortar are significantly reduced as more water is added. The cause can be explained by the weight change shown in Figure 2c. The weight of all samples rapidly decreased between 7 and 14 days. Based on the mix proportion shown in Table 2, the water content in the samples with w/b = 0.4 is calculated to be 9% (by wt % of mortar) and 13% in the sample with w/b = 0.6. Their weights were reduced by about 8% and 12% respectively, for 7 days after exposure to dry air. This means that once exposed to a dry atmosphere, most of the water contained in the mortar rapidly evaporates, leaving empty capillaries. For this reason, when manufacturing CO₂-curable materials using a greater amount of water, the volume of the capillary pores inevitably increases without a positive influence, such as the formation of hydration products, as in hydraulic binders. This volume increase is known to negatively affect the strength of porous materials, such as concrete or mortar [45]. The change of pore structure as a function of the *w/b* is discussed further in Section 3.2.

In the air lime mortar, the weight increase due to CO_2 absorption occurs simultaneously with the weight loss due to rapid evaporation. This is a unique feature of air lime-based materials that is different from Portland cement-based materials, which generally show a long-term weight loss due to drying. As shown in Figure 2c, since the rates of water evaporation and CO_2 absorption are not equal [35], two different time slots of weight loss and increase are distinguished. Unlike long-term and steady CO_2 uptake, rapid water evaporation would have had a decisive impact on determining the turning point of the weight change.

3.2. Carbonation Depth and Pore Structure

Figure 3 shows the carbonation depth of the mortars at 91 days. The carbonated area was not discolored, because the pH was lower than 8.2. The result also confirms that the incorporation of silica fume does not have a notable effect on the carbonation of the mortar at 91 days. However, as the w/b of the mortar increases, the carbonated area is greatly expanded. The carbonation of samples with w/b = 0.4 proceeded to about 7 mm from the surface, whereas the carbonated area of the sample with w/b = 0.6 was 10.6 mm from the surface. This is possibly because CO₂ gas could penetrate deeper due to the increased volume of the capillary pores, as mentioned.



Figure 3. Carbonation depth of air lime mortars at 91 days. The non-carbonated area in the mortar was discolored by phenolphthalein solution.

The pore structure of the mortar at 91 days is shown in Figure 4, in which the size ranges of the gel pores, capillary pores, and air voids are presented with different colors [46]. As expected, the gel pores (<10 nm), which are formed as a result of the hydration reaction, are not found, and the pore sizes were mostly in the range of the capillary pores and air voids. In particular, the change in pore structure due to the addition of silica fume and the *w/b* increase are confirmed in the size range larger than 100 nm. Due to the addition of silica fume, the volume of pores decreased between 100 nm–200 nm without a change in other size ranges. This can be explained by the pore-filling effect, as mentioned. In addition, as the *w/b* increases from 0.4 to 0.6, the volume of the capillary pores is remarkably increased between 200 nm–5 μ m. By this result, the decrease of strength (Figure 2a,b), the acceleration of water evaporation (Figure 2c), and the increase of carbonation depth (Figure 3) caused by the *w/b* change can be clearly explained.



Figure 4. Pore size distribution of air lime mortars at 91 days: (**a**) log differential intrution and (**b**) cumulative pore volume. The size ranges of the gel pores, capillary pores, and air voids were determined according to previous studies [46,47].

3.3. Component Change and CO₂ Uptake Rate

Figure 5 shows the results of the thermogravimetric analysis of air lime. When looking at the red lines, two dramatic weight losses are observed at around 400 °C and 700 °C. These are the results of the decomposition of Ca(OH)₂ and CaCO₃, respectively. The DTG curves (blue lines) also show two peaks clearly, which means that the air lime is composed almost entirely of Ca(OH)₂ and CaCO₃. Comparing Figure 5a–c reveals that the content of these two calcium-based crystals contained in air lime varies

with time. The Ca(OH)₂ content decreased while the CaCO₃ content increased with time, the latter possible by absorbing CO₂ from the atmosphere. Thus, air lime mortar adsorbed CO₂ steadily between 7 and 91 days. This steady CO₂ uptake would also have been possible later on, since the lime still contained Ca(OH)₂ at 91 days.



Figure 5. Results of thermogravimetric analysis at (a) 7 days, (b) 28 days, and (c) 91 days. Red and blue lines in each graph mean weight loss and derivative of weight loss as a function of temperature, respectively.

Using the results shown in Figure 5, CO_2 uptake of the air lime was quantitatively evaluated. This is possible by estimating the $CO_{2,uptake}(t)$, which is the amount of CO_2 absorbed by 100 g of hydrated lime until the time *t*, as expressed in Equation (1) [48]. In this equation, CO_2 (t = 0) and CO_2 (t) refer to the CO_2 content in the air lime at the beginning (i.e., before mixing with water) and at time *t*, respectively, where the amount of CO_2 that is originally contained in the raw material (i.e., hydrated lime) is also considered.

$$CO_{2,uptake}(t) \ [\%] = \left\{ \frac{CO_2(t) - CO_2(t=0)}{100 - CO_{2,uptake}(t)} \right\} \times 100$$
(1)

The amount of CO_2 uptake, $Ca(OH)_{2,}$ and $CaCO_3$ contents are shown in Figure 6a–c. Between 7 and 28 days, CO_2 was rapidly absorbed into the air lime, and $CaCO_3$ content also increased. During this period, the CO_2 uptake was accelerated due to the silica fume addition and the *w/b* increase. These could be attributed to the acceleration of the carbonation reaction due to the silica fume [34] and the increase in permeability, which is closely related to the volume of the capillary pores (as shown in Figure 4). However, the CO_2 uptake rate of sample 0.4_SF0 was much more pronounced between 28 and 91 days than the other samples, and eventually, there was no significant difference in the amount of CO_2 uptake at 91 days among all samples. Another notable result is that, at 91 days, there was no difference between the two samples of 0.4_SF0 and 0.4_SF10 in terms of the CO_2 uptake and $CaCO_3$ content, but the sample with silica fume showed a lower $Ca(OH)_2$ content. This could be an evidence of the pozzolanic reaction, as mentioned in Section 3.1.



Figure 6. (a) CO₂ uptake rate, (b) Ca(OH)₂, and (c) CaCO₃ contents of air lime as a function of time.

Based on the CO₂ uptake at 91 days, it is estimated that atmospheric CO₂ equal to as much as 25 wt % of hydrated lime was utilized to make the air lime hard regardless of the silica fume addition and the w/b. With the same trend as the CO₂ uptake, Ca(OH)₂ decreased, and CaCO₃ increased with time. On the 91st day, the content of Ca(OH)₂ was 30–35 wt %, which is much lower than the initial content (75–80 wt %), while the content of CaCO₃ was about 70–75 wt %, which is very high compared to the initial content (10–20 wt %).

One of the key findings of this study is that within three months of being exposed to the atmosphere, air lime-based materials can recover more than half of the CO_2 emitted during the manufacture of the raw material. This is an extremely fast rate compared to Portland cement-based materials, which take several decades to absorb 43% of the CO_2 that was released into the atmosphere during cement manufacturing [49]. Therefore, using more air lime-based materials instead of cement can be a great help in achieving the goal of near zero CO_2 emissions by 2050. Lastly, numerical information on the changes in the strength and CO_2 uptake due to silica fume addition or w/b change in the air lime mortar are summarized in Table 3.

Table 3. Quantitative evaluation of the w/b and silica fume addition on the mechanical properties and CO₂ uptake of air lime mortar at 91 days.

	Effectiveness ¹						
Method	Compressive	Flexural	Carbonation	CO ₂			
	Strength	Strength	Depth	Uptake			
Silica fume addition instead of 10% hydrated lime	+27%	+13%	-1%	-7%			
Increase of the w/b from 0.4 to 0.6	-29%	-29%	+49%	+3%			

¹ The "+" and "-" symbols indicate increase and decrease, respectively.

4. Conclusions

Air lime-based materials harden while absorbing the CO_2 emitted during the production of hydrated lime. However, quantitative evaluation of the carbonation and CO_2 uptake has been lacking. In this study, to clearly understand this CO_2 -curable binder and to make it more widely used, the effects of the *w*/*b* and silica fume addition on the mechanical properties and CO_2 uptake of air lime mortars were investigated. The main findings of this study can be summarized as follows:

- The setting and hardening of the mortars were made possible by absorbing CO₂ from the atmosphere.
- Within three months, the air lime-based binder recovered more than half of the CO₂ released during the manufacturing process of the raw material.
- The weight and compressive strength of the mortar steadily increased due to CO₂ uptake and carbonation reaction for 180 days.
- When 10% of hydrated lime was replaced with silica fume, the strength of the mortar significantly improved without noticeable changes in carbonation depth and the amount of CO₂ uptake. On the other hand, when the *w/b* of the mortar was increased from 0.4 to 0.6, the strength and carbonation depth were significantly decreased and increased, respectively.

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