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Performance of CO₂-Cured Alkali-Activated Slag Pastes During Curing and Exposure

Yubin Jun, Seong Ho Han and Jae Hong Kim^{*} D

Abstract



This study investigated the efficiency of CO_2 curing in blast-furnace slag pastes activated with three concentrations of KOH solution (3, 4, and 5 M). The CO_2 curing was applied into the alkali-activated slag paste for 3 days. The CO_2 -cured pastes were subjected to subsequent curing in a water bath or exposed to seawater. The mechanical properties and characteristics of the reaction products were compared. Full strength can be obtained within 3 days of the early CO_2 curing. The strength remained almost constant regardless of the activator concentration. The CO_2 -cured samples produced more $CaCO_3$ after exposure to the seawater. The carbonates filled the micropores of the samples, and no strength reduction was observed. The hydrates $Ca(OH)_2$ and C-S-H(I) are carbonated, forming calcite and amorphous $CaCO_3$ during the subsequent curing and exposure to seawater as well as the CO_2 curing. A less dense matrix with a lower activator concentration facilitated the diffusion of CO_2 and promoted early carbonation in the paste. The polymerization of C-S-H(I) was relatively slow with low activity, and within the period of CO_2 curing, more carbonates were produced in the sample prepared at a low activator concentration.

Keywords: CO₂ curing, Amorphous CaCO₃, Calcite, CCUS, Alkali-activated slag

1 Introduction

The risks of extreme weather and climate change due to greenhouse gas emissions have continuously increased worldwide. In the construction industry sector, efforts to reduce carbon dioxide emissions, one of the most serious greenhouse gases, are concentrated on improving construction materials that are abundantly used worldwide. It is well-known that the production of one tonne of Portland cement generates approximately one tonne of carbon dioxide in the atmosphere (Imbabi et al., 2012; Vafaei et al., 2020). Alkali-activated binders, which are made by industrial by-products, are among the most promising alternatives to Portland cement (Bernal et al., 2011; Pacheco-Torgal et al., 2008; Provis, 2018). In addition to efforts to reduce carbon dioxide emissions, attempts have been made to utilize carbon dioxide in construction

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Department of Civil and Environmental Engineering, Korea Advanced Institute of Science and Technology, Daejeon 34141, Korea materials (Jun et al., 2019; Shi et al., 2012; Zhan et al., 2013). Carbon dioxide curing, or called carbonation curing, is one possible way to utilize CO_2 (Sean & Yixin, 2010) for the production of construction materials.

CO₂ curing precipitates calcium carbonate (CaCO₃) via a reaction between CO₂ and calcium compounds at a very early age (Liu & Meng, 2021), leading to refinement of the pore structure. In general, the reaction reportedly occurs following the steps: (1) the dissolution of CO₂ and release of CO₃^{2–} (CO₂+H₂O \rightarrow H₂CO₃ \rightarrow H⁺ +HCO₃^{$-\rightarrow$} 2H⁺ +CO₃^{2–}); (2) the release of Ca²⁺ from calcium compounds; and (3) the precipitation by the reaction between Ca²⁺ and CO₃^{2–} (Hermawan et al., 2001; Liu & Meng, 2021; Schmitz, 2018). As a result, CO₂ curing is reportedly helpful in promoting the early age strength development of cement-based materials (Pan et al., 2017; Rostami et al., 2012).

First of all, considering the environmental aspect, it is necessary to apply CO_2 curing to alkali-activated binders as alternatives to cement to reduce the usage of cement and recycle industrial by-products (Jun et al., 2019,



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2021a; Prabahar et al., 2022; Worrell et al., 2001). However, the efficiency of CO₂ curing in alkali-activated slag materials is strongly influenced by the type and concentration of the alkali activator and curing conditions (Jun et al., 2019, 2021a; Li et al., 2017). Li et al. (Li et al., 2017) showed that the compressive strength of NaOH/Na₂SiO₃activated slag mortars decreases after CO₂ curing. Jun et al. (Jun et al., 2021a) reported an increase in strength with CO_2 curing when a paste sample was activated by a mixture of NaOH and Na₂SiO₃ (5:5). In addition, CO₂ curing at a constant CO₂ concentration of 20% was more effective than in a CO_2 -pressure vessel (Jun et al., 2019). The effect of CO_2 curing is dependent on various factors, including the binder type, water-to-binder ratio, activator type, activator concentration, and curing conditions (e.g., temperature, relative humidity, CO₂ concentration, and curing time) (Jun et al., 2019, 2021a; Li et al., 2017; Suescum-Morales et al., 2022).

Several studies have investigated the effect of further curing processes (water curing and lime saturated water) after 3 to 6 h of the CO_2 curing (He et al., 2016; Lu et al., 2021; Pan et al., 2019). The cement pastes and mortars with further moisture curing maintained early age strength and showed higher strength later owing to further hydration. However, the effect of CO_2 curing on the subsequent curing process is not clear in alkali-activated slag compared with Portland cement-based materials. From the viewpoint of CO_2 utilization, the CO_2 curing of alkali-activated slag remains an area requiring further research, such as the durability and sustainability of the materials. The long-term performance of these materials depends on the degree of carbonation. The durability of CO₂-cured alkali-activated slags can also be dependent on external factors, such as marine environments. Therefore, this study considered seawater as an environmental factor affecting long-term durability.

Our previous study evaluated the development of compressive strength of alkali-activated slags before and after CO_2 curing (Jun et al., 2021a). This study is the followup study of the work done in 2021, and alkali-activated slag samples after CO_2 curing are discussed. This study further examines the effect of subsequent curing process after the CO_2 -cured samples and investigates the longterm strength even when they were exposed to seawater. The factors to be investigated also include the degree of carbonation in alkali-activated slag pastes according to different alkali concentration and CO_2 curing. The mechanical properties and characteristics of the reaction products in CO_2 -cured pastes after subsequent curing and exposure to seawater were investigated. Tests regarding the compressive strength, X-ray diffraction (XRD), thermogravimetry (TG), mercury intrusion porosimetry (MIP), and measurement of chloride ion concentration were performed to evaluate the effect of CO_2 curing.

2 Experimental Program

2.1 Materials

Blast-furnace slag (BFS) was obtained from H Steel Co. Ltd. (Dangjin, Korea). The chemical composition of the BFS, as measured by X-ray fluorescence, is presented in Table 1. Fig. 1 shows the X-ray diffraction pattern of the BFS. KOH (pellets, \geq 85% purity) was acquired from S Chemical Co., Ltd. (Pyeongtaek, Korea). The seawater used in this study was collected from Gwangchigi Beach (33°27′08.0″ N, 126°55′29.9″ E) in Jeju, Korea. Table 2 presents the ion concentrations of the seawater sample.

2.2 Experimental Design

The BFS was mixed with an alkaline activator. The activator used was a KOH solution with three different concentrations (3, 4, and 5 mol/L). KOH solutions were prepared by dissolving the KOH pellets in deionized water and then cooling them to room temperature. Water is an essential factor for CO_2 curing, because gaseous CO_2 does not react by itself. However, excessive water in a sample can block the diffusion of CO_2 , while insufficient water can hinder the dissolution of CO_2 (Young et al., 1974). The weight ratio of the activator solution to the BFS was determined at 0.45 with consideration of effect of CO_2 curing and workability. After mixing

Table 1 Chemical compositions (oxides in wt.%) of BFS

CaO	SiO2	Al ₂ O ₃	SO ₃	MgO	TiO ₂	Fe ₂ O ₃	K ₂ O	P ₂ O ₅	Na ₂ O	MnO
45.9	31.4	12.9	3.3	3.2	0.7	0.6	0.6	0.6	0.5	0.2

Table 2 Ion concentrations of seawater (ppm)

Ca ²⁺	K+	Mg ²⁺	Na ⁺	CI⁻	SO4 ²⁻	Salinity
420	510	1000	7900	19,000	2500	31,330



in accordance with ASTM C305, the fresh pastes were cast in 25 mm cubic molds and placed in a water bath at 23 °C. The specimen size of paste was chosen with reference to Sandberg and Doncaster (2004). After demolding, all samples were dried in a vacuum desiccator for 3 h before CO₂ curing to remove free pore water (Jun et al., 2021a; Zhang et al., 2017). The 3 h dry pre-conditioning time was selected based on a previous study, where it was found to improve the CO₂ curing efficiency (Jun et al., 2021a).

 CO_2 curing was performed in a CO_2 chamber at 20% CO_2 , 23 °C, and 80% relative humidity. After CO_2 curing, paste samples for each activator concentration were placed under two different conditions: a water bath at 23 °C and a storage container at 23 °C filled with seawater.

The mix proportions and experimental sequences of the samples are listed in Table 3. The letters in the sample label represent the solution concentration and the following process after CO_2 curing, where WB and SW, represent a water bath and seawater, respectively.

2.3 Test Methods

2.3.1 Strength

With 25 mm cube specimens, the compressive strength was measured at 3, 7, and 28 days. For each mixture, five replicated specimens were tested, and the average of the measurements was reported at each testing time. Compressive strength tests were performed using a universal testing machine (PWS-400A, Woo Jin Co.). A load was applied at a rate of 1.0 kN/s.

	1 1						
Sample label	Activator-to- binder ratio	Binder	Activator	Pre-conditioning 0–3 h	CO ₂ curing 4 h–3 d	After CO ₂ curing 4 d–28 d	
5M-WB	0.45	BFS	5 M KOH	Drying	CO ₂ chamber	Water bath	
5M-SW	0.45	BFS	5 M KOH	Drying	CO ₂ chamber	Immersion in seawater	
4M-WB	0.45	BFS	4 M KOH	Drying	CO ₂ chamber	Water bath	
4M-SW	0.45	BFS	4 M KOH	Drying	CO ₂ chamber	Immersion in seawater	
3M-WB	0.45	BFS	3 М КОН	Drying	CO ₂ chamber	Water bath	
3M-SW	0.45	BFS	3 М КОН	Drying	CO ₂ chamber	Immersion in seawater	

Table 3 Mix proportions and experimental sequence for samples

CO₂ chamber: 20% CO₂ concentration, 23 °C, and 80% relative humidity; Water bath (container with heated water maintained at a constant temperature; samples are not contacted with water): 23 °C

2.3.2 XRD

After the compressive strength test, the specimens were broken into small blocks and ground into a fine powder by passing through a 75 μ m mesh sieve. The powders were then immersed in isopropanol to prevent further hydration. The powder samples were dried in a vacuum desiccator to remove isopropanol before the XRD test. XRD experiments were performed using high-resolution powder XRD (SmartLab, Rigaku) employing Cu K α radiation (λ =1.5406 Å). Data were collected at a scanning rate of 2°/min from 5° to 60° for 2 θ . The obtained XRD patterns were analyzed using the International Centre for Diffraction Data (ICDD) and the Inorganic Crystal Structure Database (ICSD) (Belsky et al., 2002).

2.3.3 TG

The powder samples, prepared in the same manner as the XRD measurements, were subjected to TG measurements. TG measurements were performed using an SDT Q600 V20.9 Build 20 instrument (TA Instruments, Inc.) at a heating rate of 10 °C/min from room temperature to 1000 °C in a nitrogen atmosphere. TG and differential TG (DTG) curves have been reported.

2.3.4 MIP

For the MIP experiment, the core parts of the 25 mm cubic samples were cut into $5 \text{ mm} \times 5 \text{ mm} \times 5 \text{ mm}$ cubes. After immersion in isopropanol to stop hydration, the specimens were dried in a vacuum desiccator. MIP measurements were then conducted using an AutoPore IV 9500 (Micromeritics Instrument Corp.)

2.3.5 Chloride-Ion Binding

The powder samples, prepared for the XRD measurements, were subjected to chloride-ion concentration measurements. Chloride ions can exist either in the form of free chloride or bound chloride. Free chlorides exist as free ions in the pore solution and bound chlorides are immobile chloride ions, attached to reaction products. The bound chloride content can be obtained by subtracting the free chloride content from the total chloride content. The free chloride and total chloride contents can be determined by measuring water-soluble and acid-soluble chloride contents, respectively. In this study, water-soluble and acid-soluble chlorides in the samples immersed in seawater were measured at 7 and 28 days according to ASTM C1218 and ASTM C1152, respectively.

3 Results and Discussion

3.1 Strength Development

Fig. 2 shows the compressive strength of the alkaliactivated slags subjected to subsequent curing or seawater immersion. Here, it should be noted that the effect of CO_2 curing was confirmed in our previous study (Jun et al., 2021a). When the paste samples were subjected to the same protocol of CO_2 curing, the 3-day strength was improved from 26.2 MPa (control) to 48.4 MPa, 84.7% increase, where the activator-to-binder ratio was 0.4. In this study, CO_2 curing had no negative effect on the strength development when the samples were subjected to further curing or seawater immersion. The compressive strength of the CO_2 -cured alkali-activated slag remained almost constant after further curing, and it was valid even



with seawater immersion. Therefore, it can be said that the CO_2 curing makes alkali-activated slag complete its hydration within 3 days. In addition, a higher KOH concentration resulted in a higher compressive strength. This is in agreement with previous findings that the compressive strength of alkali-activated binders increases with increasing activator concentration (Altan & Erdoğan, 2012; Fernández-Jiménez & Pal-

3.2 XRD Analysis

omo, 2005).

Fig. 3a and b show the XRD patterns of alkali-activated slag subjected to CO_2 curing and (a) further water bath

curing or (b) seawater immersion, respectively, where the patterns were dictated by the KOH concentration. In Fig. 3a, regardless of the KOH concentration, the crystalline phases identified after CO_2 curing were consistent: C_4AH_{13} , calcite, $Ca(OH)_2$, calcium silicate hydrate (C–S–H), calcium silicate hydrate I (C–S–H(I)), gypsum, hydrocalumite, hydrotalcite, K_2SO_4 , and quartz. Here, gypsum and quartz were originally contained in the raw BFS, while the others were reaction products. The types of identified crystalline phases at 7 and 28 days after subsequent curing or immersion in seawater did not differ from those at 3 days. However, the peak intensity of calcite increased at a low activator concentration, whereas



seawater immersion

relatively high-intensity peaks for the other reaction products (i.e., C_4AH_{13} , $Ca(OH)_2$, C-S-H, C-S-H(I), hydrocalumite, hydrotalcite, and K_2SO_4) were found at a high KOH concentration. The use of a lower concentration of KOH, forming a less dense matrix in the samples, would lead to a more effective penetration of CO_2 and, to a greater extent, carbonation. In addition, at the highest KOH concentration of 5 M, the degree of carbonation after CO_2 curing was relatively low. This is discussed in detail later in this paper.

Fig. 3b presents the XRD patterns of the alkali-activated slag after immersion in seawater and CO_2 curing. As shown in Fig. 3b, the crystalline phases formed in each sample immersed in seawater did not differ from those identified in the samples cured in a water bath. Nevertheless, higher peaks for the reaction products were found in the samples exposed to seawater than in those exposed to water bath curing. CO_2 curing and immersion in seawater resulted in a slight increase in compressive strength, while there was little change with subsequent water bath curing (see Fig. 2). The 3M-WB/SW sample is an exceptional case; however, abundant dissolved ions in seawater induce the continuous hydration of the BFS, forming more reaction products and improving the strength of the samples (Jun et al., 2021b).

BFS is an amorphous material that typically contains less calcium than Portland cement. As a result, calcium hydroxide, $Ca(OH)_{2}$ is uncommon in the hydrates of alkali-activated BFS unless CaO and Ca(OH)₂ are added as activators (Gebregziabiher et al., 2015; Kim et al., 2013). A small amount of Ca^{2+} is related to gypsum (CaSO₄·2H₂O) and anhydrite (CaSO₄) in the raw BFS (see Fig. 1) and interacts with OH⁻ from the KOH activator $CaSO_4 + KOH \rightarrow Ca(OH)_2 + K_2SO_4$. In the XRD patterns, the anhydrite disappeared in advance, and the peak intensity of gypsum decreased. The Ca(OH)₂ formed in the samples was affected by the CO_2 curing. In Fig. 3a and b, after CO_2 curing, the intensity of the $Ca(OH)_2$ peak decreased with time (see the black arrows in the figures). $Ca(OH)_2$ is consumed to form calcite (Matsuya et al., 2007). The calcite peak increased with time, although the 3M-WB/SW sample was an exceptional case.

C–S–H and C–S–H(I) are reportedly the main reaction products in alkali-activated BFS, which contribute to strength development (Ben Haha et al., 2011; Richardson et al., 1994). For the 5M-WB/SW and 4M-WB/SW samples, the peak intensity of C–S–H increased, whereas the C–S–H(I) peak intensity decreased with CO₂ curing (for 3 days). Although the samples showed no reduction in compressive strength, carbonation of C–S–H(I) occurred. C–S–H with a lower Ca/Si ratio was carbonated faster than that formed with a higher Ca/Si ratio, and the ratio of Ca/Si in C–S–H(I) was comparatively low (Li et al., 2011; Wu & Ye, 2019). A previous study found that carbonation of C–S–H(I) resulted in the formation of amorphous CaCO₃ (Black et al., 2007). This was confirmed by the TG measurements. In the case of the 3M-WB/SW sample, during subsequent water bath curing or immersion in seawater, the C–S–H peak increased and then decreased, and the opposite tendency was observed in the case of calcite. The intensity of the C–S–H(I) peak shows little change after CO₂ curing.

3.3 TG Analysis

Fig. 4 shows the TG and DTG curves of the CO_2 -cured alkali-activated BFS after subsequent curing in a water bath or immersion in seawater. Weight loss below 200 °C includes losses in C_4AH_{13} [130–170 °C (Wang & Scrivener, 1995)], C–S–H [50–200 °C (Ben Haha et al., 2011)], and C–S–H(I) [90–110 °C (Wang & Scrivener, 1995)], and gypsum [100–200 °C (Vassileva & Vassilev, 2005)]. The peak in the DTG curve at approximately 300 °C and 420 °C is related to the presence of hydrocalumite [300 °C (Palmer et al., 2011)], hydrotalcite [420 °C (Richardson & Li, 2018)], and Ca(OH)₂ [420 °C (Hartman et al., 1994)]. Overlapping temperature ranges made it difficult to estimate each value.

The peaks below 200 °C in the DTG curves (owing to the weight loss of C_4AH_{13} , C–S–H, C–S–H(I), and gypsum) decreased after 3 days, except for the sample of 3M-WB/SW. The DTG peaks of the 3M-WB/SW sample first increased and then decreased. There was little change in the XRD peak intensities of C_4AH_{13} , C–S–H(I), and gypsum with time; therefore, the increase in the DTG curve is probably attributed to C–S–H decomposition.

The weight loss in the range of 450-750 °C was due to the decomposition of $CaCO_3$ (Jun et al., 2019; Nedeljković et al., 2018). For all samples, bimodal curves were observed in DTG. The peak in the temperature range between 450 and 620 °C is related to the decomposition of amorphous CaCO₃, while the peaks between 620 and 750 °C are due to the crystalline CaCO₃ phase decomposition (Nedeljković et al., 2018). The concentrations of amorphous CaCO₃ and calcite were estimated from the weight loss measured from the TG curve, corresponding to the DTG peaks between 450 and 620 °C and 620 and 750 °C, respectively. The total amount of CaCO₃ after CO₂ curing in the alkali activated BFS was 8.27% (calcite 2.68%; amorphous CaCO₃ 5.59%) with 5 M KOH, 11.22% (calcite 4.18%; amorphous $CaCO_3$ 7.04%) with 4 M KOH, and 10.91% (calcite 5.26%; amorphous CaCO₃ 5.65%) with 3 M KOH. Except for 3M-WB/SW, the total amount of CaCO3 increased with time. This was consistent with the XRD results. The amount of amorphous CaCO₃ also increased in 5M-WB/SW (Fig. 4a and b) and



the content of a morphous ${\rm CaCO}_3$ produced later is relatively low.

The immersion in seawater after the 3-day CO_2 curing promoted higher carbonation of C–S–H(I), forming amorphous CaCO₃ compared to the water bath-cured samples. The XRD peak intensity of C–S–H(I) in the seawater-immersed samples was lower than that in the water-bath-cured samples. Gaseous CO_2 was dissolved in the interstitial water in the samples, and carbonation proceeded for 3 days. However, after the 3-day CO_2 curing, some carbonate and bicarbonate ions remained. They were then carbonated more quickly in a relatively high pH seawater environment.

3.4 Chloride Concentration in Seawater-Immersed Samples

Fig. 5 shows the variation in chlorides in the alkaliactivated samples during immersion in seawater after the 3-day CO_2 curing. The chloride penetration in CO_2 -cured alkali-activated samples overall increased with the decreasing of activator concentration. This will be due to less dense microstructure of the lower activator concentration sample, causing easy penetration of chlorides inside pores. It can be seen from Fig. 5 that there was little change or slightly increased in bound chloride contents with time for each activator concentration. The presence of chlorides within samples with seawater immersion did not cause strength loss with time.

The ratios of bound chloride to total chloride from 5M-SW, 4M-SW, and 3M-SW samples were 0.243, 0.17, and 0.211, respectively, at the age of 7 days. At the age of 28 days, the ratios of bound chloride to total chloride from 5M-SW, 4M-SW, and 3M-SW samples were 0.18, 0.225, and 0.203, respectively. Chloride ions in alkali-activated BFS can be bound by a reaction product. Among reaction products identified in the samples of this study, C–S–H and C–S–H(I), hydrocalumite, and hydrotalcite reportedly have chloride in samples can be attributed to these reaction products. However, in case of the C–S–H(I), the role of chloride binding would have been gradually diminished due to its carbonation.

3.5 MIP Analysis

Fig. 6 shows the MIP results of the CO_2 -cured alkali-activated BFS after further curing in a water bath or immersion in seawater. Regardless of the type of process after CO_2 curing, the total porosity of the samples increased as the activator concentration decreased. The samples with higher activator concentrations contained more reaction products and thus, a denser matrix, resulting in higher strength development.





The seawater-immersed samples had fewer pores below 20 nm compared to the water bath-cured samples. This can be attributed to more $CaCO_3$ formed in seawater-immersed samples. $CaCO_3$ may have played a role in filling micropores. Pores with diameters smaller than 50 nm influence durability, such as drying shrinkage and creep (Mehta & Monteiro, 2006). Thus, the seawater-immersed samples after CO_2 curing are more favorable for higher durability.

In addition, further water bath curing resulted in pore size refinement in the CO_2 -cured alkali-activated samples. The number of pores larger than 50 nm decreased with time. However, there was no noticeable change over time when the CO_2 -cured alkali-activated samples were immersed in seawater. The total porosity of the seawater-immersed samples was also higher than that of the samples cured in a water bath. Nevertheless, the pore structure development is not significant for strength development. Neither of these processes had a negative effect on the strength of CO_2 -cured alkali-activated samples.

3.6 Further Discussion

Since the activator concentration influences the rate of reaction (Altan & Erdoğan, 2012), the lower-activator-concentration sample provided a smaller amount of reaction products, such as C–S–H, C–S–H(I), and Ca(OH)₂, resulting in a less dense matrix and lower strength. Ca(OH)₂, by the reaction between the anhydrite in the raw BFS and the KOH activator, was carbonated by CO₂ curing. The common ion effect in the pore solution disturbed the additional dissolution of Ca(OH)₂ in the presence of excess Ca²⁺ ions. However, C–S–H decalcification to produce calcite (Bakharev et al., 2001) continued, especially at low activator concentrations. A less dense matrix, due to the low reactivity, also makes it easy to further diffuse CO₂ promoting carbonation. As a result, when the CO_2 curing was completed, the amounts of calcite were 2.68%, 4.18%, and 5.26% for activator concentration of 5, 4, and 3 M, respectively. Calcite was then more generated in a lower activator concentration at 28 days.

Although all samples were dried before CO₂ curing to facilitate CO_2 diffusion (Jun et al., 2021a), relatively more moisture remained in the 3 M concentration sample (i.e., low concentration) than in the other concentrations (4 and 5 M). Thus, in the case of 3M-WB/SW, it appears that the remaining water readily reacts with calcite and silica gel released from the BFS to form C-S-H (Jun et al., 2019). In the XRD results of the samples, the calcite content decreased, while the C-S-H content increased. Further C-S-H formation at 7 days most likely contributed to the increase in the strength of 3M-WB/SW (see Fig. 2). However, the strength of 3M-WB/SW slightly decreased after the age of 28 days. Furthermore, more calcite was formed with a decrease in the amount of C-S-H. This was related to the decalcification of C-S-H, which resulted in a decrease in strength (Bakharev et al., 2001). For the 5M-WB/SW and 4M-WB/SW samples, the peak intensity of C-S-H in the XRD analysis increased with time; carbonation of C-S-H did not occur.

4 Conclusions

Alkali-activated BFS pastes subjected to CO_2 curing showed full strength development within 3 days of CO_2 curing and maintained their strengths during the subsequent curing in a water bath and immersion in seawater. This trend was consistent regardless of the activator concentration used. On the other hand, samples with higher activator concentrations produced more hydrates and thus had a denser matrix, which resulted in a higher compressive strength.



 $Ca(OH)_2$ and C-S-H(I) in the alkali-activated samples are associated with CO_2 , and they are carbonated further during the subsequent curing as well as during the CO_2 curing. Their immersion in seawater brought more carbonation. Gaseous CO_2 during the CO_2 curing diffuses less in the samples with higher activator concentrations. Therefore, during the early 3-day CO_2 curing, more calcite was formed in the samples with lower activator concentrations. Amorphous $CaCO_3$ related to C-S-H(I) carbonation was more easily found in which samples with higher activator concentrations were further cured (or immersed in seawater) over a period of days. In addition, the CO_2 -cured alkali-activated BFS samples produced more $CaCO_3$ upon immersion in seawater,

because a relatively high-pH environment is favorable for carbonation. However, the resultant filling in micropores does not contribute to the strength improvement.

Under these experimental conditions, the CO_2 -cured alkali-activated slag pastes complete their hydration after 3 days and can then be utilized in a marine environment and a humid climate.

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Author contributions

YJ designed the experiments. SHH performed the experiments. YJ analyzed the data and all authors discussed the experiment. YJ wrote the manuscript and JHK reviewed this study. All authors read and approved the final manuscript.

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Availability of data and materials

The data and materials are included in the manuscript.

Declarations

Competing interests

The authors declare that they have no competing interests.

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