

Article

The Effects of Sodium Silicate and Sodium Citrated on the Properties and Structure of Alkali-Activated Foamed Concrete

Hao Liu ¹, Gaoke Zhang ², Jixin Li ¹, Jiaqi Xuan ², Yongsheng Wang ¹, Huiwen Wan ³ and Yun Huang ^{3,*}

- ¹ China Construction Second Engineering Bureau Limited East China Branch, Shanghai 200135, China; liuhao-2@cscec.com (H.L.); lijixin@cscec.com (J.L.); wangyongsheng_@cscec.com (Y.W.)
² School of Resources and Environmental Engineering, Wuhan University of Technology, Wuhan 430070, China; gkzhang@whut.edu.cn (G.Z.); 307257@whut.edu.cn (J.X.)
³ School of Materials Science and Engineering, Wuhan University of Technology, Wuhan 430070, China; wanhw@whut.edu.cn
* Correspondence: huangyun_wh@whut.edu.cn; Tel.: +86-189-7124-9047

Abstract: Alkali-activated slag cementitious (AASC) foamed concrete (FC) has presented challenges such as rapid setting time and poor working performance. The use of sodium citrate (Na_3Cit) as a retarding agent can improve the workability and microstructure of AASC foamed concrete. The effects of the dosage, modulus of water glass (WG, the main component is $\text{Na}_2\text{O} \cdot n\text{SiO}_2$), and retarding agent on the properties and structure of FC were studied in this paper. The results indicated that using a water binder ratio of 0.4, WG with a modulus of 1.2, and an additional amount of 15% and 0.5% of Na_3Cit , the prepared FC had a flowability of 190 mm. Its initial and final setting times were 3.7 h and 35.3 h. Its 7 d and 28 d compressive strengths reached 1.1 MPa and 1.5 MPa, respectively. After hardening, the pore walls were dense and consistent in size, with few larger pores and nearly spherical shapes. The addition of Na_3Cit resulted in the formation of calcium citrate, which adsorbed onto the slag surface. This hindered the initial dissolution of the slag, reduced the number of hydration products produced, and decreased the early strength. With increasing curing time, the slag in the FC mixture dissolved further. This led to the decomposition of a portion of calcium citrate and the release of Ca^{2+} . The Ca^{2+} reacted with $[\text{Si}(\text{OH})_4]^{4-}$ and $[\text{Al}(\text{OH})_4]^-$, creating more C-(A)-S-H gel. This gel filled the voids in the FC and repaired any defects on the pore walls. Ultimately, this process increased the compressive strength of the FC in the later stages.

Keywords: alkali-activated slag cementitious; foamed concrete; retardation; workability; microstructure; mechanism



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1. Introduction

Foamed concrete (FC), a novel lightweight porous material [1], possesses properties such as thermal insulation, low carbon emission, lightweight, high strength, sound absorption, and energy dissipation [2]. It also has a lower production cost, easier production and construction than traditional concrete due to the presence of numerous foam voids; therefore, it finds extensive applications in the fields of building insulation and fill materials of the road base [3].

FC is generally made by mixing cementing materials (cement, fly ash, slag powder, etc.) with foam [4], which is different from lightweight aggregate concrete. Lightweight aggregate concrete is generally made of cementing material mixed with lightweight aggregate (perlite, clay ceramsite, shale ceramsite, pumice stone, etc.) [5], which is mainly used in fire prevention, heat insulation, sound insulation, and other engineering fields. In recent years, with the improvement of the production process of foam agents, the quality of foam agents has been significantly improved [6–9], and the application of FC is more and more extensive, especially in the fields of road traffic [10,11]. When FC is used as roadbed filling material instead of ordinary filling soil, it is also called foamed lightweight soil. Yu

Junyan [12], Nong Feibi [13], Tae-Hyung Kim, et al. [14] used foamed lightweight soil as subgrade filling material and found that the roadbed settlement value was small, far less than the allowable settlement value, and it was an ideal material to replace ordinary soil filling. Yongsheng Wang, Huiwen Wan, et al. [15] successfully used 680,000 m³ of foamed lightweight soil in the roadbed of the intelligent connected vehicle test field in 2022.

Alkali-activated slag cementitious (AASC) materials are a novel type of cementitious material that take advantage of the principle that slag with potential water hardness reacts with an alkaline activator to produce a cementitious material. This is a combination of strength, environmental friendliness, and economic benefits [16,17]. Many scholars have researched the preparation of FC with AASC materials due to its potential for producing high-strength FC. Wang Lingling et al. [18] used potassium hydroxide and sodium hydroxide water glass as a base activator to study the effects of activators on the properties of slag cementing materials under different conditions, and based on this, the optimal ratio was obtained. Ji [19] investigated the impact of different matrix components on FC's strength and pore structure. Liguori [20] found that the mechanical properties of FC significantly improved with the gradual increase in diatomite content by partially substituting diatomite for kaolin in the preparation of diatomite-based FC. Wan [21] prepared high-performance geopolymer-based FC with a dry density of 409 kg/m³ and a compressive strength of 1.6 MPa by using glass powder, slag, and an alkali activator. Wang [22] studied the effect of different ratios of slag and diatomite on the properties of polymer-based FC and revealed that the material exhibited the highest specific strength when the slag content reached 80%. Hao [23] determined that sodium dodecyl sulfate was used as a foaming agent to prepare fly ash–slag-based FC by assessing the stability of bubbles in the slurry and the mechanical behavior and concluded that its compressive strength was higher than that of ordinary Portland cement-based FC at the same density. By testing 15 concrete slurries, Yang [24] utilized three types of alkali activators to produce FC from activated slag and found that alkali-activated slag FC exhibited higher compressive strength and a lower adverse environmental impact than traditional concrete. Numerous research studies have shown that using AASC materials to prepare FC is feasible and has many advantages.

However, the AASC slurry suffers from challenges such as high viscosity, poor rheological properties, and rapid setting time [25], which impacts the flowability and foaming performance of FC. Many studies have shown [26–28] that in cement, gypsum, mortar, and concrete systems, using sodium citrate as a retarder to adjust the setting time has achieved very good results, especially in high-efficiency water-reducing agents, which can be mixed with good retarding high-efficiency water reducing agents only by adding a small amount of sodium citrate [29]. Therefore, this study prepared FC with good performance by adjusting the dosage and modulus of the activator (water glass, WG). At the same time, the proper amount of sodium citrate (Na₃Cit) was added to the system to adjust the setting time, improve the flowability and microstructure of FC after hardening, and explore the mechanism of Na₃Cit on the hydration of alkali-activated slag.

2. Materials and Methods

2.1. Materials

Ground Granulated Blast furnace Slag (GGBS) is S95-grade produced by Hubei Jinshenlan Metallurgical Technology Co., Ltd. (Wuhan, Hubei, China), with a density of 2800 kg/m³ and a glass content exceeding 95%. The chemical composition is provided in Table 1, and the XRD analysis pattern is illustrated in Figure 1.

Table 1. Chemical composition of GGBS.

CaO	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	SO ₃	K ₂ O	Na ₂ O	TiO ₂	LOI
39.92	31.23	14.12	0.78	7.34	2.23	0.61	0.72	0.76	−0.29

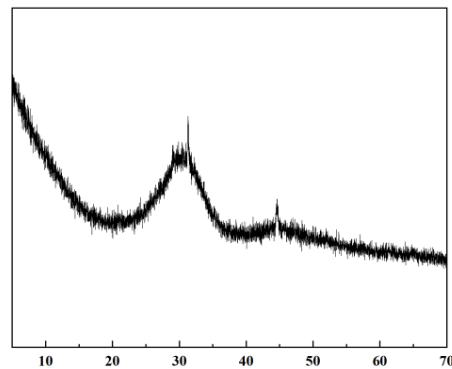


Figure 1. XRD analysis pattern of GGBS.

Activator: water glass solution (main component is $\text{Na}_2\text{O} \cdot n\text{SiO}_2$, WG) produced by Jiashan County Youruinai Refractory Materials Co., Ltd. (Jiaxing, Zhejiang, China), with the model SP38, modulus 3.30, and density 1.38 g/cm^3 . $\text{Na}_2\text{O} \cdot n\text{SiO}_2$, n is the molar ratio of SiO_2 and Na_2O , called the water glass modulus.

Sodium hydroxide (NaOH): content $\geq 99\%$, analytical grade, produced by Sinopharm Chemical Reagent Co., Ltd. (Shanghai, China).

Retarder: sodium citrate (Na_3cit), content $\geq 99\%$, analytical grade, with a molecular formula of $\text{Na}_3\text{C}_6\text{H}_5\text{O}_7 \cdot 2\text{H}_2\text{O}$, produced by Sinopharm Chemical Reagent Co., Ltd.

Foaming agent: A compound foaming agent belonging to ether alcohol is produced by Guangdong Shengrui Technology Co., Ltd. (Guangzhou, China), model JY-SRN2, which is diluted 100 times with water when used.

2.2. Mix Ratio of Experiment

In a large number of studies on AASC materials, it is generally believed that WG as an activator has a better effect [30–32]. In this experiment of preparing FC, 12%, 15%, and 18% of WG with different moduli were added, respectively, to optimize the excitation effect of the activator on the GGBS. At the same time, in the FC system with 15% and 1.2 moduli of WG as the activator, in order to adjust the setting time of FC and improve its working performance, the addition of Na_3cit was 0, 0.25%, 0.5%, 0.75%, and 1.0%, respectively. The proportions of the AASC foamed concrete are shown in Table 2.

Table 2. Experimental proportion of AASC foamed concrete.

No.	WG/%	Modulus	Sodium Citrate/%	GGBS/g	Water Binder Ratio	Foam */g
M1	12	1.0	0	1200	0.4	115
M2	12	1.2	0			
M3	12	1.5	0			
N1	15	1.0	0			
N2	15	1.2	0			
N3	15	1.5	0			
P1	18	1.0	0	1200	0.4	115
P2	18	1.2	0			
P3	18	1.5	0			
1#	15	1.2	0			
2#	15	1.2	0.25			
3#	15	1.2	0.5			
4#	15	1.2	0.75			
5#	15	1.2	1.0			

* The volume of each set of AASC foamed concrete was approximately 3.2 L. Foam was produced by diluting the original foaming agent with water at a 1:100 ratio using a foaming machine.

2.3. Preparation Method

The preparation and determination of AASC foamed concrete slurry was conducted as follows: Initially, based on the proportions in Table 2, measured quantities of GGBS, WG, Na₃Cit, and water were individually poured into a container and mixed for 2 min to produce the slag powder slurry. Subsequently, the diluted foaming solution was processed into foam with a density of $50 \pm 2 \text{ kg/m}^3$ using an intelligent micro-foaming machine and then added to the slurry according to the ratio, followed by an additional 2 min of mixing. Next, the wet density, flow value, and setting time of the FC were determined according to the specifications. Finally, the FC was cast into a $100 \text{ mm} \times 100 \text{ mm} \times 100 \text{ mm}$ mold, covered with plastic film, and demolded after air curing at 20°C – 25°C in lab room for 48 h. The test blocks were sealed in plastic bags and placed in a standard curing chamber (temperature: $20^\circ\text{C} \pm 2^\circ\text{C}$, relative humidity: 95%) until the desired curing days were reached. The preparation process is illustrated in Figure 2.

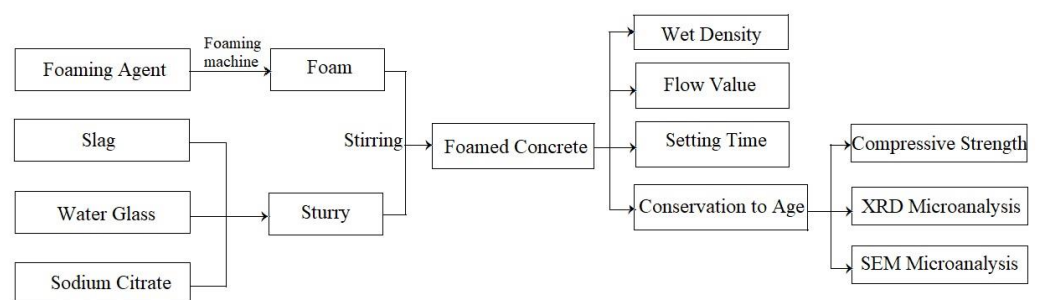


Figure 2. Preparation process of FC.

2.4. Technical Indicators and Test Methods

2.4.1. Requirements for Technical Specifications for FC

This research employed FC as a road base fill material, and its technical specifications needed to meet the requirements outlined in the “Specifications for Design of Highway Subgrades” (JTG D30-2015), which were as follows: wet density of $(600 \pm 30) \text{ kg/m}^3$; foam density of $(50 \pm 2) \text{ kg/m}^3$; freshly mixed FC flow value (flow degree) of $(180 \pm 10) \text{ mm}$; 7 d compressive strength $\geq 0.5 \text{ MPa}$; 28 d compressive strength $\geq 1.0 \text{ MPa}$.

2.4.2. Test Methods

The wet density, flow value, and compressive strength of FC were evaluated by “Technical code for cast-in-place foam light soil” (CECS 249-2008) and “Foamed Concrete” (JG/T 266-2011). The wet density of FC was directly added to a 1 L density container for weighing. The flow value of FC was measured with a metal cylinder with an inner diameter of 80 mm, a net height of 80 mm, and a wall thickness of 2 mm. First, the cylinder was placed on a flat plate, filled the cylinder with the freshly mixed FC slurry and scraped off the excess FC slurry on the upper surface of the cylinder with a ruler, then slowly lifted the cylinder; finally, the diameter of the cake paste was measured with a ruler. The compressive strength of FC was measured with a pressure testing machine with a range of 0–50 kN, and the pressure speed was controlled at $(0.5\sim 1.5) \text{ kN/s}$.

The setting time was determined following the methods outlined in “Test methods for water requirement of normal consistency, setting time and soundness of the Portland cement” (GB/T 1346-2011) and relevant literature [33,34]. Near the initial setting time, measured every 5 min; near the final setting time, tested every 15 min.

X-ray powder diffraction analysis (XRD) adopted the D8 discover X-ray diffractometer produced by Bruker (AXS) Company in Germany, with Cu Ka radiation; scanning speed was $5^\circ/\text{min}$, step size was 0.02° , current was 150 mA, voltage was 40 kV. Scanning electron microscope (SEM) was used to characterize JSM-5610LV scanning electron microscope produced by JEOL, Japan. The resolution was 3 nm, the magnification was $18\times\sim 300,000\times$ (continuous and adjustable), and the acceleration voltage was 0.5–30 kV.

3. Results and Discussion

3.1. Effects of Activator on Flowability, Setting Time, and Compressive Strength of AASC Foamed Concrete

In order to ensure that the density of the FC was roughly the same, the wet density of the FC was first measured after mixing, and the results show that the wet density of all samples was between 602 kg/m³ and 615 kg/m³.

Table 3 shows the results of the influence of the content and modulus of the activator (WG) on the flowability, setting time, and compressive strength of the AASC foamed concrete. The relationship between the content of NaOH, the modulus of WG, and the effective content of Na₂O + SiO₂ in the WG solution should be balanced when using the WG activation GGBS system. Zhu Hongbo et al. [35] believe that the OH[−] in alkali can penetrate the surface of slag particles and enter the internal holes, depolymerize the polymers composed of silicon–oxygen tetrahedrons of slag, and enable the free SO₄^{2−} to interact with Ca²⁺ to form a large number of stable compounds (C-S-H) to stimulate mineral activity, which is a prerequisite for AASC materials to obtain cementitious properties. However, because OH[−] mainly produces C-S-H on the surface of depolymerized slag in the early stage, and the amount of hydration products in the late stage is insufficient, the strength will be reduced. As can be seen from Table 3, when the modulus of WG is the same, with the increase in its dosage, the flow value of foamed concrete is gradually reduced, the setting time is also shortened, and the compressive strength is gradually increasing. The effective content of Na₂O+SiO₂ in the WG solution increased. The more [SiO₄]^{4−} ions and OH[−] ions brought into the system, the more [Si (OH)₄]^{4−} and [Al (OH)₄][−] are dissolved from the slag, and the more C-S-H gel is generated in the system. When the WG content in the system is the same, with the increase of its modulus (n), that is, the concentration of SiO₄^{4−} in the system is high, while the concentration of OH[−] is low, so the lack of sufficient depolymerization on the slag makes it difficult to form a condensation structure dominated by low-basicity C-S-H gel [36]. This is the reason why P3, N3 have a lower compressive strength than P2 and N2, respectively. However, when the WG modulus is small (1.0), due to the high concentration of OH[−] in the system and the fast activation rate, a dense hydration product layer is formed on the surface of the slag earlier, which hinders the further formation of hydration products, resulting in a decrease in the total amount of hydration products of C-S-H gel and small compressive strength. Therefore, in the WG activation GGBS system, the WG module should not be too large but also not too small; WG usage is not the same as the greater effect of stimulation [37].

Table 3. Influence of WG content and modulus on performance of AASC foamed concrete.

No.	WG/%	Modulus	Flow Value/mm	Setting Time/h		Compressive Strength/MPa	
				Initial Setting	Final Setting	7 d	28 d
M1	12	1.0	230	1.3	18.4	0.72	1.50
M2	12	1.2	195	2.3	24.5	0.95	1.08
M3	12	1.5	210	3.1	27.3	0.61	1.29
N1	15	1.0	222	0.7	15.2	1.22	1.67
N2	15	1.2	185	1.2	20.4	1.62	1.77
N3	15	1.5	215	2.7	26.6	0.91	1.21
P1	18	1.0	205	0.4	12.9	1.35	1.72
P2	18	1.2	175	0.8	14.3	1.71	2.03
P3	18	1.5	210	2.6	24.1	0.92	1.36

Considering the relationship between the flow value, setting time, and compressive strength of AASC foamed concrete, it is considered that the most suitable slag initiator is as follows: the content of WG is 15%, the modulus is 1.2, and the performance of AASC foamed concrete prepared by it can meet the technical requirements of the Code for Design of Highway Subgrade (JTG D30-2015).

3.2. Effects of Na_3Cit on Flowability, Setting Time, and Compressive Strength of AASC Foamed Concrete

Figure 3 illustrates the trends in the effect of Na_3Cit content on FC's workability and setting time. The abscissa axes 0, 0.25, 0.50, 0.75, and 1.0 represent the content of Na_3Cit in samples 1#~5#, respectively. The left ordinate represents the setting time of FC, and the right ordinate represents the flow value of FC. Figure 3 shows the properties of a slurry with a water binder ratio of 0.4, a WG modulus of 1.2, a 15% addition, and a Na_3Cit dosage of 0%. The slurry displayed high viscosity, fast hardening, and a short initial setting time of 1.2 h, with a final setting time of 20.4 h. The difference between the initial and final setting times of the FC was due to the dependence of its hydration rate on the dissolving rate of activators in slag particles, which was different from cement-based materials. When the Na_3Cit dosage gradually increased, the slurry viscosity decreased significantly, the flow value increased, and the setting time was prolonged. The high slurry viscosity caused it to collapse during mixing, making transportation difficult. Conversely, a low slurry viscosity promoted uniform mixing of the foam with the slurry, enhancing foam stability and flow values and making transportation easy. However, when the flow value exceeded 200 mm, surface seepage occurred, and localized collapse or segregation phenomena were observed in the FC. When the Na_3Cit dosage was 0.5%, the slurry with a flow value of 190 mm exhibited suitable viscosity, and the initial and final setting times of the FC were 3.7 h and 35.3 h, respectively, which reached the construction requirements of the actual project.

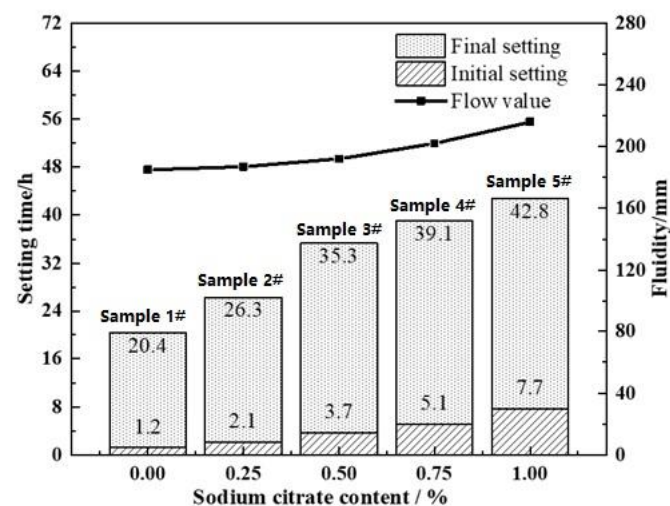


Figure 3. Effects of Na_3Cit content on setting time and fluidity of FC.

It is widely known that retarders used in concrete production generally have a greater impact on its early strength but have a minor or negligible effect on its later-stage strength. However, when Na_3Cit is used as a retarder in preparing FC, it affects the compressive strength after 7 days and causes a significant decrease in the compressive strength after 28 days. Figure 4 shows the pattern of Na_3Cit content on the compressive strength of FC. As shown in Figure 4, as the Na_3Cit content increases, both the compressive strengths of the FC decrease gradually after 7 and 28 days. When Na_3Cit was not added into the system, the 7 d and 28 d compressive strengths of the FC were 1.6 MPa and 1.8 MPa, respectively. When the content of Na_3Cit was 0.5%, the compressive strengths of the FC at 7 d and 28 d were 1.1 MPa and 1.5 MPa, respectively, which was a decline of 31% and 17% compared to the samples without Na_3Cit . When the Na_3Cit content reached 1%, the decline in the compressive strength of the FC became more pronounced, and neither the compressive strengths after 7 nor 28 days met the required technical specifications. The reasons and mechanisms behind the reduction in the mechanical properties of FC caused by Na_3Cit will be discussed later.

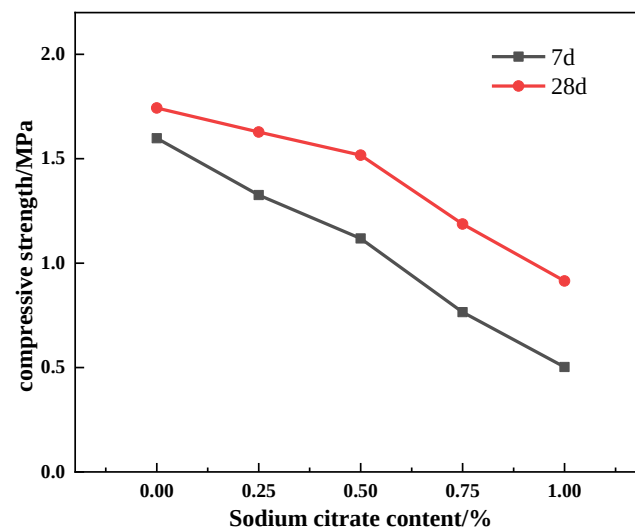


Figure 4. Effect of Na_3Cit content on compressive strength of FC.

3.3. Microstructure and Mechanism Analysis

Figure 5 depicts the XRD analysis of two samples, 1# without Na_3Cit and 3# containing 0.5% Na_3Cit cured for 28 days. The results showed that the hydration products of both samples were entirely similar, except that the characteristic peaks of sample 1# were slightly stronger than those of sample 3#. The primary hydration product of both samples was predominantly C-(A)-S-H, which was consistent with the findings of Shi [38], Burciag [39], and Huang [40]. No other hydration products were observed in sample 3# due to the addition of Na_3Cit .

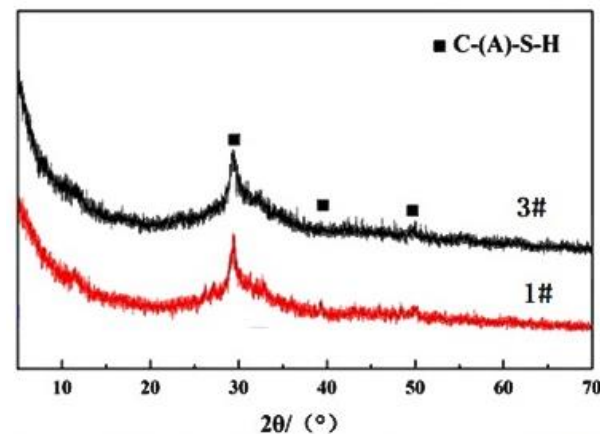


Figure 5. XRD analysis of samples 1# and 3# for curing for 28 d.

The structure of the FC (a type of concrete) differed from that of dense concrete. In the FC, over 80% of the structure comprised foam voids that were a few millimeters in size, with only a tiny portion made up of gel pores. Figure 6a,c shows the structure of sample 1# (without Na_3Cit) after 7 days of curing, while Figure 6b,d shows the structure of sample 3# (with 0.5% Na_3Cit) after 7 days of curing. As seen in Figure 6a, FC presents uneven pore sizes, a few large pores, a higher prevalence of interconnected pores, and relatively poor roundness. However, the thick foam walls provided firm support and increased compressive strength. Figure 6b shows the structure of sample 3#, which has fewer large voids, more uniform void diameters, thinner foam walls, and lower compressive strength than sample 1#.

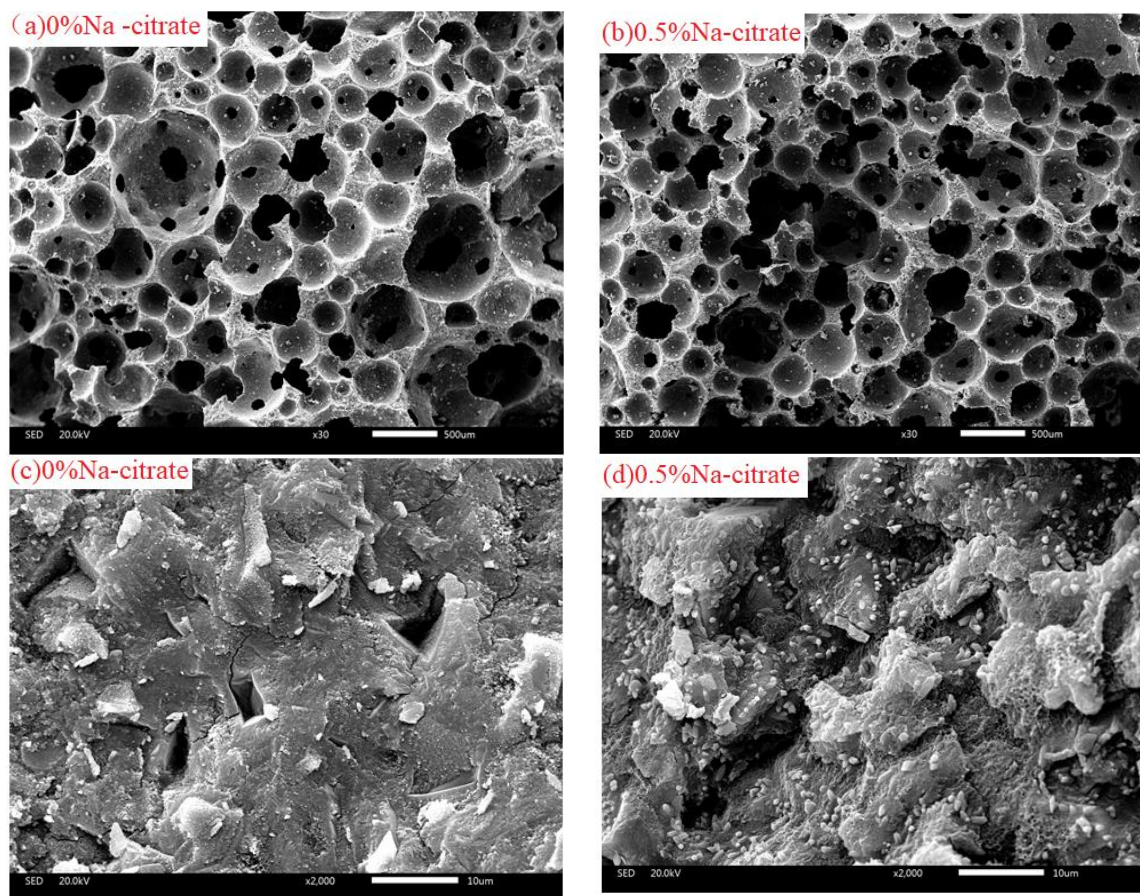


Figure 6. SEM photos of samples 1# (a,c) and 3# (b,d) at the age of 7 d.

Upon analyzing the microstructure of the pore walls shown in Figure 6c,d, it is observed that both sample 1# and sample 3# have significant formation of hydration gel. On the one hand, sample 1# has a denser structure in which the hydration products entirely enveloped unreacted raw mineral particles. On the other hand, sample 3# has a looser structure with a small amount of citrate adhered to the mineral particle surfaces. This hindrance prevented the dissolution of mineral particles, prevented the hydration process, and obstructed the interlocking of the hydration gel network, ultimately leading to a decrease in compressive strength for sample 3#.

Figure 7a,b shows the SEM microstructure of samples 1# and 3#, respectively, after being cured for 28 days. Figure 7a shows that sample 1# has thicker void walls that are unevenly sized. The sample has high porosity and numerous connected pores. Furthermore, Figure 7b illustrates that sample 3# has thinner void walls with fewer large voids. The voids are more uniformly sized and have improved roundness compared to sample 1#. This indicates that the addition of Na_3Cit improved the slurry's viscosity, foam uniformity, and stability. Figure 7c,d represents the microscopic structure of hydration products in the foam walls of samples 1# and 3#. Both samples display dense hydration products. However, sample 1# exhibits conspicuous local cracks, while sample 3# has fine and inconspicuous cracks [41]. This indicates that sample 1# is sensitive to shrinkage and prone to cracking, whereas sample 3# is not.

AASC materials undergo three stages: slag particle dissolution, solid-phase nucleation and growth, and boundary diffusion and interaction [39,42]. When Na_3Cit was not added to the system, the WG in the sodium silicate solution was hydrolyzed to produce NaOH and hydrated silica gel. The chemical bonds such as Si-O , Al-O , and Ca-O on the surface of the slag particles (glassy phase) were broken by the polarization of OH^- , which produced Ca^{2+} , $[\text{Si}(\text{OH})_4]^{4-}$, and $[\text{Al}(\text{OH})_4]^-$ into the liquid phase. $[\text{Si}(\text{OH})_4]^{4-}$ combined with the

hydrated silica gel and Ca^{2+} in the solution to form C-S-H gel, while $[\text{Al}(\text{OH})_4]^-$ reacted with Ca^{2+} in the solution to form C-A-H. The continuous generation and stacking of gel promoted the reduction in $[\text{Si}(\text{OH})_4]^{4-}$, $[\text{Al}(\text{OH})_4]^-$, and Ca^{2+} concentration, facilitating further dissolution of hydrated Na_2SiO_4 and slag. Consequently, the setting sites were concentrated near the surface of the slag particles, and the gel formed in the later stage filled the voids between the slag particles, making the structure denser.

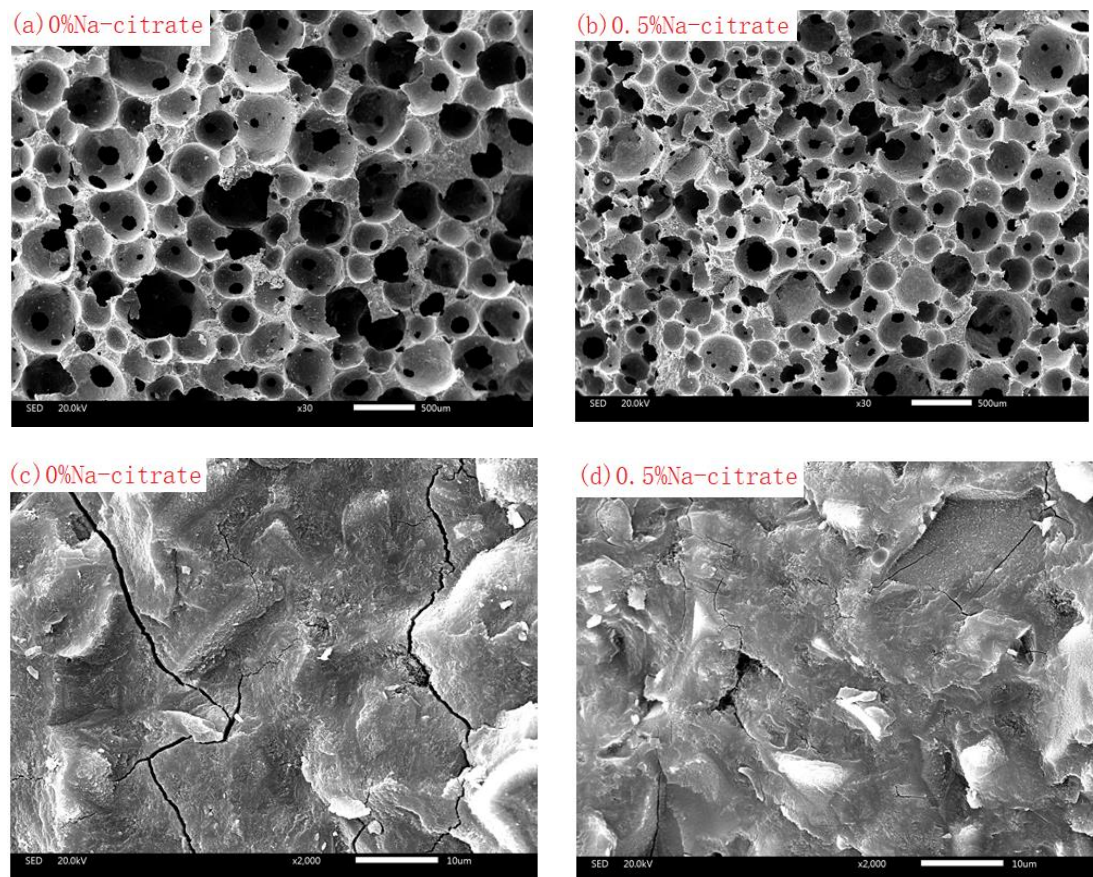


Figure 7. SEM photos of samples 1# (a,c) and 3# (b,d) at the age of 28 d.

When Na_3Cit was added into the system during the slag dissolution stage, the citrate ions adsorbed onto the slag's surface, hindering its initial dissolution [43]. As a result, the concentrations of Ca^{2+} , $[\text{Si}(\text{OH})_4]^{4-}$, $[\text{Al}(\text{OH})_4]^-$ were lowered, which in turn reduced the initial generation of C-(A)-S-H. However, adding a small amount of Na_3Cit to the system resulted in the reaction between citrate ions and Ca^{2+} to form calcium citrate ($\text{Ca}_3(\text{C}_6\text{H}_5\text{O}_7)_2$). This causes the redistribution of cations. Since the solubility products of C-S-H gel and $\text{Ca}_3(\text{C}_6\text{H}_5\text{O}_7)_2$ were 1.0×10^{-24} and 1.8×10^{-11} , respectively, and significantly lower than the solubility product of $\text{Ca}(\text{OH})_2$ of 5.5×10^{-6} , there was no $\text{Ca}(\text{OH})_2$ product in the system, and the generated C-S-H gel and a small amount of $\text{Ca}_3(\text{C}_6\text{H}_5\text{O}_7)_2$ precipitated on the surface of the slag particles. After curing for 28 days, the slag continued to dissolve, and some of the $\text{Ca}_3(\text{C}_6\text{H}_5\text{O}_7)_2$ gradually decomposed, leading to the release of Ca^{2+} due to a smaller solubility product of C-S-H gel than that of $\text{Ca}_3(\text{C}_6\text{H}_5\text{O}_7)_2$. Ca^{2+} reacted with $[\text{Si}(\text{OH})_4]^{4-}$ and $[\text{Al}(\text{OH})_4]^-$ again to form more C-(A)-S-H gel. This gel filled the pores of the FC after hardening, repaired the defects on the pore wall, improved the expansion of internal fine cracks, and benefited the growth of compressive strength.

As the content of Na_3Cit increased in the system, the compressive strength of the FC decreased gradually. This was due to the properties of the AASC materials, which belonged to a low-calcium system. In contrast to cement-based high-calcium systems, the AASC ma-

terials contained fewer calcium ions. Due to the increase in Na_3Cit content, the deposition of early $\text{Ca}_3(\text{C}_6\text{H}_5\text{O}_7)_2$ increased, which reduced the generation of C-S-H gel in the system. Even after an increase in the curing days, some $\text{Ca}_3(\text{C}_6\text{H}_5\text{O}_7)_2$ decomposed to release Ca^{2+} , but re-reaction of Ca^{2+} with $[\text{Si}(\text{OH})_4]^{4-}$, $[\text{Al}(\text{OH})_4]^-$ generated less C-(A)-S-H gel than in samples without Na_3Cit . Furthermore, the small amount of $\text{Ca}_3(\text{C}_6\text{H}_5\text{O}_7)_2$ in the system hindered the interlocking of the C-S-H gel network, which affected the compactness.

4. Conclusions

(1) When preparing foamed concrete with AASC materials, WG with a content of 15%, and a modulus of 1.2 used as the activator, the excitation effect is better. However, the slurry viscosity of AASC foamed concrete is large, the initial setting time is short, and the working performance is poor. When Na_3Cit is used as a retarder in the system and its content is 0.5%, the slurry viscosity is moderate, the foam uniformity and stability are good, and the initial setting time and final setting time of the foamed concrete are 3.7 h and 35.3 h, respectively, the flow value can reach 190 mm, the compressive strength of 7 d and 28 d can reach 1.1 MPa and 1.5 MPa, respectively. The performance of the foamed concrete is suitable for practical engineering.

(2) The AASC foamed concrete prepared with a 15% addition of WG, a modulus of 1.2, and 0.5% Na_3Cit as the retarding agent exhibited dense pore walls with consistent pore sizes, fewer large pores, and nearly spherical pore shapes. Its primary hydration product was C-(A)-S-H.

(3) The AASC foamed concrete system had low calcium ion content. When the Na_3Cit content increased, more $\text{Ca}_3(\text{C}_6\text{H}_5\text{O}_7)_2$ precipitated, resulting in less C-S-H gel formation. As the curing days grew, the slag dissolved further, and some of the $\text{Ca}_3(\text{C}_6\text{H}_5\text{O}_7)_2$ decomposed and released Ca^{2+} . This Ca^{2+} reacted with $[\text{Si}(\text{OH})_4]^{4-}$ and $[\text{Al}(\text{OH})_4]^-$ to form more C-(A)-S-H gel, which filled the pores of the FC and helped the compressive strength to grow. However, a small amount of $\text{Ca}_3(\text{C}_6\text{H}_5\text{O}_7)_2$ hindered the connection of the C-S-H gel network structure, which affected the compactness.

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