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Influence of hydroxyethyl cellulose on the stability of foamed concrete

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Abstract

As a lightweight material, foamed concrete has been widely used in construction because of its excellent lightweight properties, heat preservation and sound absorption. However, due to its low strength, its further application is limited. Hydroxyethyl cellulose (HEC) was employed in this study to modify the sodium dodecyl sulfate (SDS) based foaming agent to enhance the stability and performance of foamed concrete. The effects of HEC content on foam stability, bleeding, fluidity, strength, water absorption and internal pore structure were systematically investigated. The results indicate that as the HEC content increases, the foam stability improves, while the fluidity and water absorption of the foamed concrete slurry decrease. Compared with the control group (without HEC), the content of 0.15% HEC increased the 28-day compressive strength by 33.66%, reaching 2.75 MPa. Furthermore, HEC optimized the pore structure, significantly reducing the average pore diameter. When the HEC content reached 2%, the proportion of small pores was approximately 99%. These findings suggest that HEC effectively improves the overall performance of foamed concrete, offering a theoretical foundation for its broader application in engineering.

1. Introduction

Foamed concrete has gained wide applications in subgrade backfill, building insulation, and lightweight structural components due to its lightweight nature, strong fluidity, excellent thermal insulation, energy efficiency, and environmental benefits [1-3]. However, despite its advantages, foamed concrete faces significant challenges such as low strength, high water absorption, and poor stability, which limit its engineering applications, especially in scenarios that require high strength and long-term stability [4].

Recent studies have shown that the pore structure of foamed concrete plays a crucial role in its mechanical properties and stability. The formation and retention of foam, as well as the stability during mixing and curing processes, are key factors determining its final performance [5, 6]. Many studies have demonstrated that adding various chemical additives can significantly improve foam stability and mechanical properties. For instance, Chao Liu et al. [7] investigated the effects of hydroxypropyl methylcellulose (HPMC) and silica flour (SF) on the stability, rheology, and printability of foamed concrete. The results showed that HPMC significantly increased the yield stress and plastic viscosity of the concrete. Dong and Zhang [8] explored the combinations of common foaming agents (such as LAS, SDS, and magnesite) with HPMC and found that adding

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HPMC could effectively reduce the foam bleeding rate. Ailar Hajimohammadi et al. [9] studied the effects of xanthan gum on the viscosity of foaming liquids and foam stability, demonstrating that it significantly increased the liquid viscosity and reduced foam bleeding rate. Han Zhu et al. [10] showed that when the xanthan gum concentration reached 0.5%, the surface tension and foam multiplication of the foaming solution were 28.68×10^{-3} N/m and 21 times, respectively. To further improve foam stability in foamed concrete, researchers have also tested the addition of CO_2 [11], WLP [12], UEO [13], Ca $(OH)_2$ [14], H-SNP [15] and other foam stabilizers [16-18] to enhance foam stability and improve the overall performance of foamed concrete.

While many studies focus on individual additives, research on the synergistic effects of multiple additives on the long-term stability and mechanical properties of foamed concrete is limited. Zhang et al. [19] modified sodium dodecyl sulfate (SDS)-based foaming agents with amphiphilic nano-silica (ANS) and found that ANS significantly improved the microstructure of the foamed concrete. Specifically, the addition of ANS increased the proportion of small pores (less than 500 μm) to about 99%, creating a more uniform pore distribution. This change enhanced both the strength and stability of the foamed concrete. The authors attributed these improvements to the synergistic effect between SDS and ANS, where ANS stabilized the foam structure and prevented pore coalescence during curing. These findings highlight the need for further exploration of additive combinations to optimize foamed concrete's properties for high-performance engineering applications like building insulation and road construction.

In addition to research on additives, the type and selection of foaming agents also play a crucial role in the quality of foamed concrete [20-22]. Li Hou et al. [23] investigated the effects of four types of surfactants (anionic, cationic, nonionic, and amphoteric) as foaming agents on the properties of foamed concrete. They found that SDS exhibited the best stability as a foaming agent. Chao Sun et al. [24] compared synthetic surfactants (SS) with plant-based surfactants (PS) and animal glue/blood-based surfactants (AS), revealing that synthetic surfactants outperformed the others in terms of foam stability and strength. L. Korat and V. Ducman [25] assessed the combination of SDS with hydrogen peroxide (H2O2) as a foaming agent, showing that an appropriate amount of SDS and H2O2 significantly improved the foam stability and durability. However, despite these advancements in the performance of foaming agents and stabilizers, there remains a lack of comprehensive research on the combined effects and interactions of different additives, particularly on the synergistic mechanisms between stabilizers and foaming agents.

Hydroxyethyl cellulose (HEC), a water-soluble polymer, has been widely applied in cement-based materials because it significantly improves their rheological properties and stability. Research has shown that HEC enhances the workability and stability of concrete, promotes uniform pore distribution, and prevents segregation during curing, thereby further improving the material's mechanical properties [26]. However, despite the extensive studies on the use of HEC in cement-based materials, its role in foamed concrete, particularly its synergistic effects with other additives, has not been fully explored.

This study aims to address this gap by systematically investigating the synergistic effects of HEC as a stabilizer and SDS as a foaming agent. Specifically, the study has two main objectives: (1) to examine the impact of different HEC content on foam stability, slurry fluidity, compressive strength, and water absorption in foamed concrete; and (2) to use scanning electron microscopy (SEM) to analyze the pore morphology and size distribution of foamed concrete, revealing the mechanism through which HEC enhances foam stability. By optimizing the HEC content, this study aims to improve the overall performance of foamed concrete, facilitating its broader application in high-rise building insulation, lightweight partition walls, and road construction.

2. Materials and Methods

2.1. Materials

In this study, Ordinary Portland cement (P.O. 42.5) produced by Nanjing Cement Co., LTD was used. The cement's main physical properties and chemical compositions are detailed in Table 1 and Table 2, respectively. Additionally, we employed a commercially available composite foaming agent, primarily composed of sodium dodecyl sulfate (SDS). The foam stabilizer used was hydroxyethyl cellulose (HEC) with a viscosity of 100,000, and its physical indexes are presented in Table 3. In this paper, H0, H1, H2, H3 and H4 were used to represent the HEC content of 0%, 0.05%, 0.1%, 0.15% and 0.2%, respectively. The percentage range of HEC was determined based on preliminary testing and the recommended range provided in reference [19].

Table 1. Physical properties of cement

Cement Type	Density (kg/m^3)	Specific Surface Area (m^2/kg)	Standard Consistency (%)	Setting Time (min)		Comp. Strength (MPa)		Flexural Strength (MPa)		Stability
				Initial	Final	3d	28d	3d	28d	
P.O 42.5	3100	358	28.3	193	277	30.1	59.6	5.0	8.7	Qualified

Table 2. Chemical composition of cement

Component	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	Insoluble Residue	Loss on Ignition
Content (%)	64.63	21.96	4.73	3.68	2.59	0.3	0.63	2.89

Table 3. Physical properties of HEC

Code	Molar substitution (M.S.)	Moisture (%)	Water-insoluble substances (%)	Heavy metals (μg/g)	PH	Ash content (%)	Lead (%)
Content	1.8-2.0	≤10	≤0.5	≤20	6.0-8.5	≤5	≤0.001

2.2. Specimen Preparation

In this experiment, the foam was prepared using the pre-foaming method. Firstly, clean water was added to the container according to the prescribed quantity, and hydroxyethyl cellulose (HEC) was added under low-speed stirring. After stirring until all the materials were completely dissolved, the foaming agent was slowly poured into the water according to the quantity to obtain the foaming liquid. Then, the foaming liquid is transported to the foaming machine through the catheter, and the foam is prepared by air compression.

Table 4. Proportions of FC (per m^3)

Group	Wet density (kg/m^3)	Cement (kg)	Water (kg)	Foam (kg)	HEC (g)
H0	700	464	208.8	27.3	0
H1	700	464	208.8	27.3	5.27
H2	700	464	208.8	27.3	10.53
H3	700	464	208.8	27.3	15.8
H4	700	464	208.8	27.3	21.06

In this study, the mix ratio of foamed concrete was designed by controlling the wet density of the slurry, with a water-cement ratio of 0.45, as detailed in Table 4. The preparation process is illustrated in Fig. 1. After mixing the cement slurry, prepared foam was added, and the mixture was stirred to ensure uniformity before being poured into molds for curing. As depicted in the figure, the water and cement were first poured into the mixing bucket sequentially, and the mixture was stirred using a handheld mixer at high speed (600 r/min) for 60 seconds until the cement slurry was thoroughly blended. Afterward, the prepared foam was added, and the mixture was stirred at low speed (300 r/min) for an additional 90 seconds to ensure uniformity. The preparation was conducted at room temperature (20 ± 2°C). The prepared slurry was then weighed, and once the wet density of the slurry was within 3% of the target wet density, the foamed concrete slurry was poured into prepared molds. The surface of the molds was covered with plastic film to prevent moisture loss. After being placed in a standard curing environment for 48 hours, the specimens were demolded and continued curing until the specified curing period was reached.

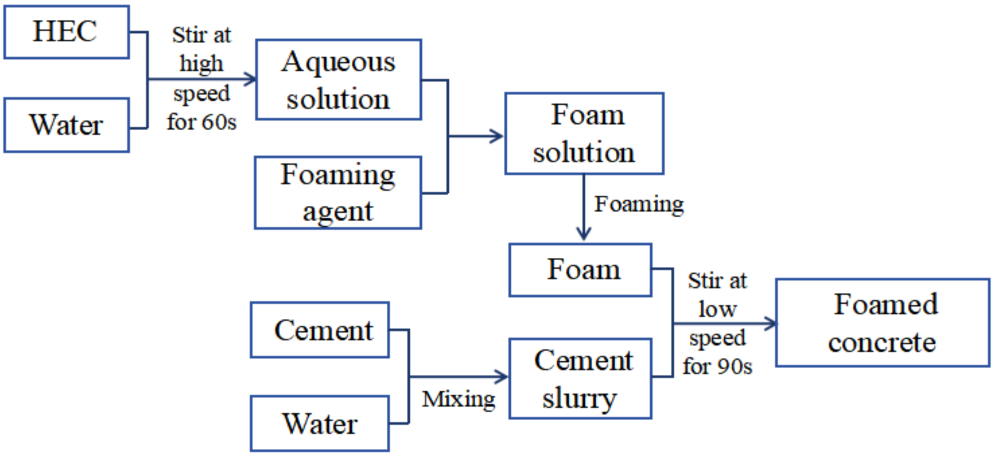


Fig. 1. Preparation process of foamed concrete

2.3. Test Method

2.3.1. Foam Stability Test

Foam stability is a critical factor in ensuring the successful casting of foamed concrete and is primarily evaluated by measuring the water bleeding rate and settlement distance. The testing method is as follows: First, the prepared foam is placed into a 1L container, and the surface is leveled with a spatula. A square piece of paper with a 2cm side length is then placed on top of the foam, and the timer is started. As the foam breaks down, water gradually bleeds out. The exuded water is collected and weighed to calculate the water bleeding rate, which is the ratio of the mass of the exuded water to the original foam mass. Simultaneously, the settlement distance of the foam over 1h is recorded. Each test is repeated three times for different amounts of foam stabilizer added to the foaming agent, and the results' arithmetic average is taken as the final value.

2.3.2. Flowability Test

The freshly mixed foamed concrete is poured into a hollow cylindrical mold (inner diameter of 80 mm, height of 80 mm) placed vertically on a smooth glass plate. After the mold is filled, it is lifted vertically, allowing the foamed concrete to spread naturally on the glass surface. After standing for 1 minute, the maximum horizontal diameter of the spread sample is measured using a vernier caliper, which is taken as the flowability of the material.

2.3.3. Compressive Strength

The 100mm × 100mm × 100mm cube specimen maintained to the specified age is placed in the center of the lower pressure plate of the universal testing machine to ensure that the bearing surface of the specimen is perpendicular to the top surface. A universal testing machine with a measuring range of 50 kN and an accuracy of 0.5% is used to apply pressure at a constant loading rate of 0.2 kN/s to record the maximum pressure value when the specimen is broken. The arithmetic average of the peak strength from three parallel specimens in each group was calculated to determine the unconfined compressive strength of the group.

2.3.4. Water Absorption

The water absorption of foamed concrete was determined according to GB/T 11969-2020 [27]. After 28 days of curing, the specimens were dried in an oven at 105 °C until a constant mass was reached, and the dry weight (m_1) was recorded. The specimens were then immersed in water for 1, 3, 5, 7, 12, 24, 36, 48, and 72 hours. After each interval, they were removed, surface water was wiped off, and the specimens were reweighed to obtain the wet weight (m_2). The water absorption of the foamed concrete was calculated as the percentage increase in weight due to water uptake using the following formula (1). The average water absorption value was reported based on at least three specimens.

$$Water\ absorption\ (\%) = \frac{m_2 - m_1}{m_1} \times 100 \tag{1}$$

Where, m_1 is the dry weight of the specimen; m_2 is the wet weight of the specimen after immersion.

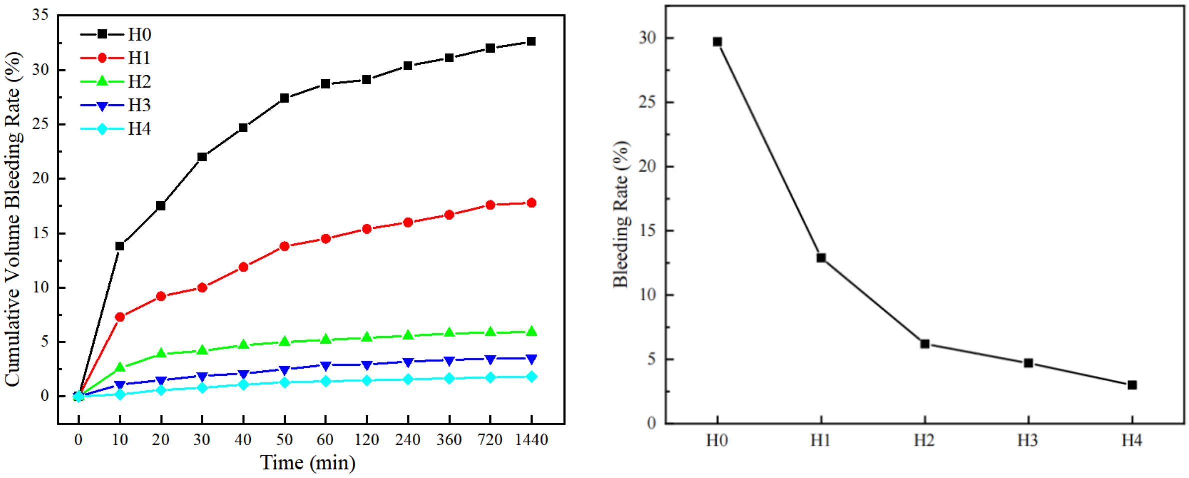
3. Results and Discussion

3.1. Foam Stability

Foam stability is a crucial factor influencing the mechanical properties of foamed concrete. The foam stability results, shown in Fig. 2, illustrate the positive effect of increasing HEC content on foam persistence. Foam stability improves with higher HEC content, with the foam lasting nearly intact at higher content (H3 and H4). In contrast, without HEC (H0), most foam dissipates within 1 hour. This suggests that the inclusion of HEC has a substantial positive effect on the long-term stability of the foam.

Fig. 2. The stability of foam with different HEC content in air

Fig. 3(a) shows the cumulative bleeding rate of foam with different HEC content in the air. As observed from the figure, the cumulative bleeding rate of foam without HEC (H0) increases significantly over time, exceeding 30% at 240 minutes. In contrast, when the HEC content exceeds 0.15% (H3), the cumulative bleeding rate continues to rise but gradually stabilizes after 60 minutes. Fig. 3(b) shows the cumulative bleeding rate of different groups at 60 minutes. It is evident that the bleeding rate for the control group without HEC (H0) reached 29.7%. However, the content of HEC as a stabilizer reduced the bleeding rates to 15.1%, 5.2%, 2.9%, and 1.4% for H1 through H4, respectively. Fig. 3(b) further illustrates the stabilizing effect of HEC decreases when the concentration exceeds 0.15% (H3), suggesting an optimal range for HEC content to maximize foam stability.



(a)

(b)

Fig. 3. Change of volume bleeding rate of foamed concrete with time

Experimental results show that incorporating HEC significantly enhances foam stability and reduces foam rupture. This improvement is primarily due to its unique physical and chemical properties, which affect the foam system in several ways. Firstly, HEC is a nonionic, water-soluble polymer with excellent thickening properties. When dissolved in cement paste, HEC forms a high-viscosity solution. This increased viscosity makes the paste more resistant to flow, which slows the rising speed of air bubbles within it. As the bubbles rise more slowly, the chances of bubble collision and coalescence are reduced, helping to maintain foam uniformity and stability. Furthermore, the higher viscosity prevents the rapid rupture of bubbles after their formation, effectively extending the foam's lifespan. Secondly, HEC molecules have hydrophilic hydroxyethyl groups and a hydrophobic cellulose backbone. This unique molecular structure allows HEC to adsorb at the gas-liquid interface of bubbles, forming a protective film around them. This film plays a crucial role in preventing bubble coalescence and rupture, thereby enhancing foam stability [28]. It also helps reduce the effects of surface tension differences, which can cause bubble instability and rupture. Emil D. Manev [29] similarly proposed that a thicker, more uniform film provides greater resistance to external forces, further reducing the likelihood of bubble collapse. Our results support Manev's hypothesis, as higher HEC content led to the formation of more robust protective films around the bubbles.

In addition to HEC's direct stabilizing effects, its synergistic interaction with SDS significantly improves foam performance. Sodium dodecyl sulfate (SDS), an anionic surfactant, reduces surface tension at the air-liquid interface, promoting the formation of smaller, more uniform bubbles. When combined with HEC, SDS molecules adsorb onto the bubble surface, creating a stable interface that prevents bubble rupture. This dual mechanism produces a dynamic stabilization effect, where SDS provides surface-level stability, and HEC reinforces the bulk properties of the foam, collectively enhancing foam preservation.

3.2. Flowability

In practical applications, foamed concrete is typically poured in situ. If the slurry fluidity is too low, it can cause difficulties during mixing and pouring, reducing construction efficiency. Conversely, if the slurry fluidity is too high, it may result in insufficient foam stability, weakening the structure and compromising performance. Therefore, optimizing the balance between fluidity and foam stability is crucial when preparing foamed concrete.

Fig. 4. shows the slurry fluidity of freshly mixed foamed concrete with different HEC contents, while Fig. 5 displays the corresponding flow values. As shown in Fig. 5, it can be seen that the flow values for H0, H1, H2, H3, and H4 are 185 mm, 163 mm, 157 mm, 149 mm, and 128 mm, respectively.

These results demonstrate a clear decrease in slurry fluidity as the HEC content increases. This trend aligns with the findings of Dong and Zhang [8], who reported that stabilizers like HEC increase the viscosity of the cement slurry, leading to reduced flowability. However, unlike other stabilizers such as HPMC, HEC exhibits a stronger ability to balance fluidity and foam stability, making it particularly advantageous for high-performance applications. HEC is a nonionic water-soluble polymer, when dissolved in water, its long-chain molecules unfold to form a three-dimensional network structure. This network interacts with water molecules, significantly increasing the viscosity of the solution. As the HEC content increases, the concentration of HEC molecules in the solution also rises, resulting in a denser network structure.

Fig. 4. Fresh foamed concrete slurry with different HEC content

Furthermore, the high viscosity of HEC enhances the adhesion between solid particles in the slurry, promoting the formation of flocculation structures. These structures further increase the slurry's viscosity and yield stress, making the slurry more viscous and reducing its fluidity. While HEC content reduces fluidity by increasing slurry viscosity, it simultaneously improves foam stability. HEC molecules adsorb onto the surface of air bubbles, forming a viscoelastic film that thickens and strengthens the bubble walls, preventing rupture and coalescence.

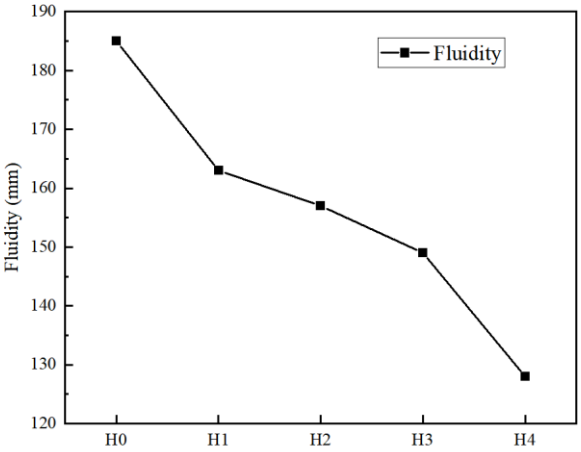


Fig. 5. Fluidity of fresh foamed concrete with different HEC content

The increased viscosity of the slurry also slows the drainage of liquid from the bubble film, reducing the likelihood of thinning and rupture of the foam. From the above, it can be concluded that while HEC has a positive effect on foam stability, this comes at the expense of slurry fluidity. In practical applications, achieving a balance between fluidity and foam stability is crucial. Excessive HEC content can cause the slurry overly viscous, complicating construction operations. Conversely, insufficient HEC content may not adequately stabilize the foam. This can lead to uneven pore structure distribution within the specimen, ultimately resulting in poor mechanical properties of the material. Therefore, optimizing the HEC content is critical to achieving both good workability and desirable physical and mechanical properties in foamed concrete.

3.3. Compressive Strength

The relationship between different HEC contents and the 7-day and 28-day compressive strength of the specimens is shown in Fig. 6. As can be seen from the figure, at 0.15% HEC content (H3), the compressive strength reaches its peak, with 7-day and 28-day compressive strengths of 1.52 MPa and 2.75 MPa, respectively. These values represent increases of 49.02% and 36.14% compared to the control group without HEC (H0). However, when the HEC content increases further to 0.2% (H4), the compressive strength shows a slight decrease. Nonetheless, the 28-day compressive strength remains 33.66% higher than that of the H0 group. This indicates that selecting the optimal HEC content (0.1%-0.15%) is critical to balancing foam stability and mechanical performance. Excessive HEC content, while enhancing foam stability, may lead to over-thickened slurry and uneven pore structure, which negatively impacts load-bearing capacity.

This significant increase aligns with the findings by Zhang et al. [19], who reported that using nano-silica as a stabilizer resulted in a more rounded and uniform pore structure, enhancing the strength of foamed concrete. Similarly, HEC improves the microstructure of foamed concrete by refining pore distribution and enhancing foam stability. Additionally, this study demonstrates that HEC also improves the elasticity and strength of the bubble films, further enhancing the mechanical properties of foamed concrete.

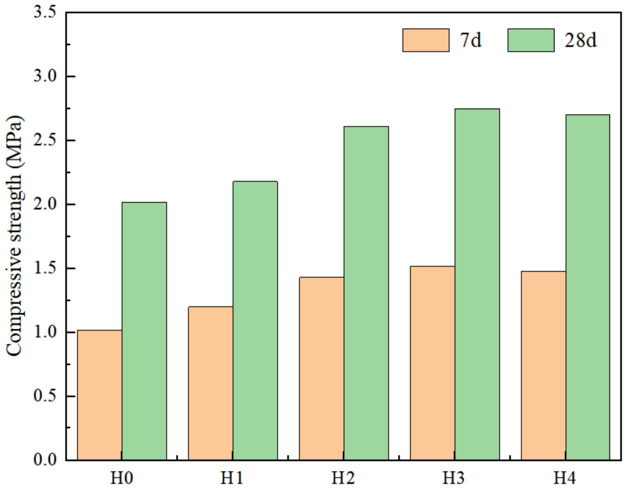


Fig. 6. The compressive strength of foamed concrete with different HEC content

The mechanism underlying these improvements is attributed to the ability of HEC to enhance the strength and elasticity of bubble films. As a result, bubbles are stably encapsulated within the concrete slurry, forming a small and evenly distributed pore structure. This structure helps distribute external stresses uniformly, thereby enhancing the material's overall load-bearing capacity [30]. Similarly, Wei She [31] observed that strengthening the bubble film reduces internal gas diffusion and increases the bubbles' resistance to external disturbances. These findings align with our results, demonstrating that HEC not only reinforces bubble films but also reduces gas escape, which collectively contributes to the improved compressive strength of the foamed concrete. Additionally, as the HEC content increases, the consistency of the solution improves significantly. This leads to more even distribution of water within the cement paste. As a result, the cement in the material becomes fully hydrated, which further enhances the material's strength.

However, as the HEC content continues to increase, foam stability improves, but bubble size and distribution have already reached stability. This limits any further contribution to compressive strength. Excessive HEC can adsorb and bind moisture from the mixture, inhibiting the cement hydration reaction and reducing the density of the cement paste. Moreover, the stabilizer forms a film at the bubble interface, weakening the bond between the cement particles and the bubbles, which lowers the strength of the interfacial transition zone. Ji and Sun [32] also observed that excessive stabilizer content overly stabilizes the bubbles, preventing their necessary rupture. This leads to excessive porosity, which undermines the compressive strength of the material. In practical applications, maintaining HEC within the range of 0.1%-0.15% achieves the best balance between foam stability, workability, and mechanical performance.

Fig. 7. Failure pattern of specimen

Fig. 7 shows the damage condition of the foamed concrete sample after the compressive strength test. The figure reveals longitudinal cracks and local spalling are present on the surface of the specimen, indicating a typical brittle failure mode. The cracks may be caused by weak interfaces within the foamed concrete, which cannot withstand stress effectively during the loading process and gradually fracture. The propagation path of the cracks is closely related to the material's pore distribution and foam stability. Although HEC was used as a stabilizer in this study to improve foam stability, the interfacial strength may still be insufficient under higher loads, resulting in brittle failure. This phenomenon indicates that the mechanical properties of foamed concrete depend on more than just the material's intrinsic strength. Factors such as pore structure distribution and interfacial bond strength also play a significant role. Therefore, in follow-up studies, the effect of different stabilizer contents on pore structure will be further analyzed to optimize the mechanical performance of foamed concrete.

3.4. Water Absorption

In this study, the immersion test was conducted over a period of 72 hours to evaluate the initial water absorption rate of the specimens. The results provide deeper insights into the long-term performance of the foamed concrete. Fig. 8 shows that foamed concrete exhibited a high-water absorption rate during the initial stage. With the extension of soaking time, the water absorption rate of foamed concrete gradually tended to be stable and showed a gradual decline with the increase of HEC content. After 12h, the water absorption rate of the material gradually slowed down. After 24h immersion, the mass water absorption of 5 groups reached 31.2%, 28.7%, 26%, 19.6% and 16.2%, respectively.

The decline in water absorption with higher HEC content can be attributed to several factors. First, as a thickening agent, HEC increases the viscosity of the cement paste, which helps to evenly disperse air bubbles and prevent them from coalescing and rising. Secondly, the addition of SDS further stabilizes the bubble structure by reducing surface tension. The combination of HEC and

SDS reduces the connectivity of voids within the cement matrix, creating a denser microstructure that limits water penetration. These observations align with the findings of Li et al. [12], who reported that stabilizers improve the homogeneity of pore structures, reducing water pathways and enhancing durability. They also highlighted that stabilizer minimize the formation of micro-cracks, contributing to the long-term durability of cement-based materials. Similarly, this study found that higher HEC content results in a denser cement matrix with fewer micro-cracks, further improving water resistance and overall durability.

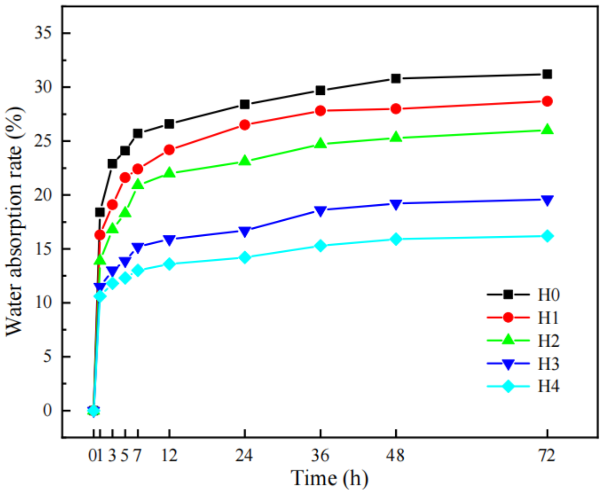
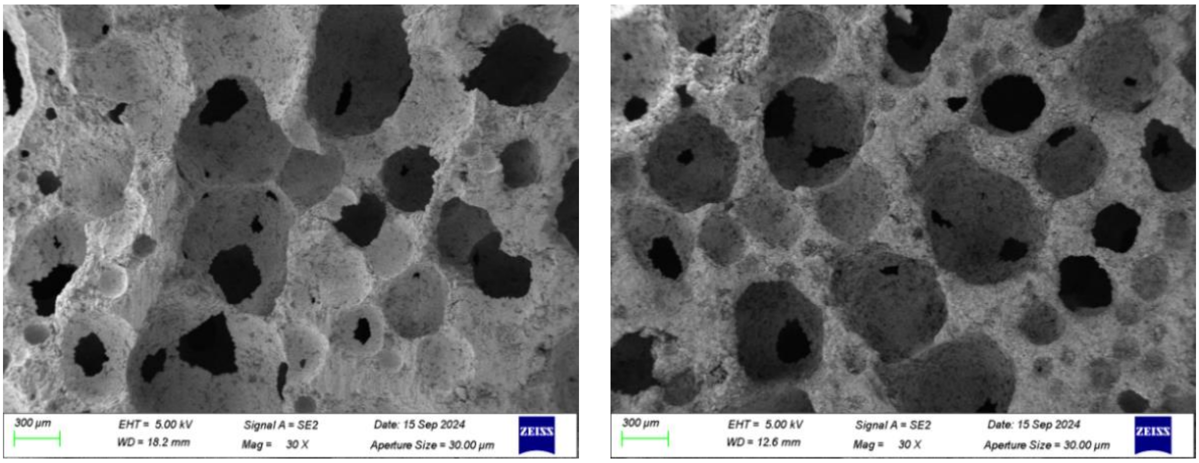


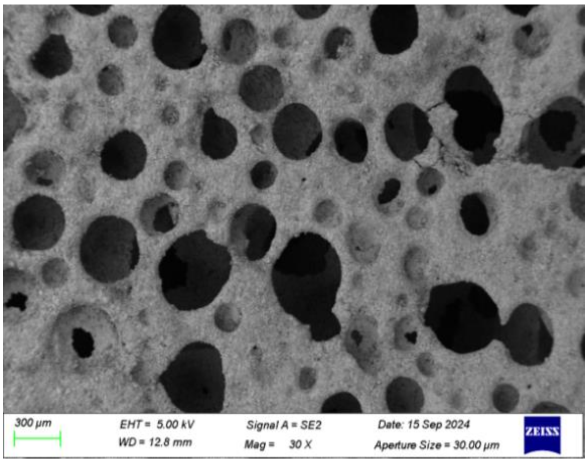
Fig. 8. Water absorption of foamed concrete with different HEC content

3.5. Pore Structure

Numerous studies have demonstrated that the pore structure of foamed concrete plays a crucial role in determining its overall performance. Fig. 9 displays scanning electron microscope (SEM) images reveal the internal pore structure of samples with varying HEC content. Fig. 10 illustrates the pore size distribution calculated using Image-J software. From Fig. 9, it is evident that the internal pore structure undergoes significant changes as the HEC content increases. When no HEC is added, the pores are interconnected and unevenly distributed. At 1% HEC content, pore connectivity decreases, and the number of small pores increases. At 2% HEC content, the pore distribution becomes more uniform, with smaller pore sizes throughout the specimen. As the HEC content increases, the pores become more uniform, the pore walls thinner, and the number of small pores increases. These changes in pore structure have a direct impact on the engineering properties of the material. For instance, in lightweight partition walls and insulation layers, a stable and uniform pore structure reduces thermal conductivity while maintaining structural integrity under load.

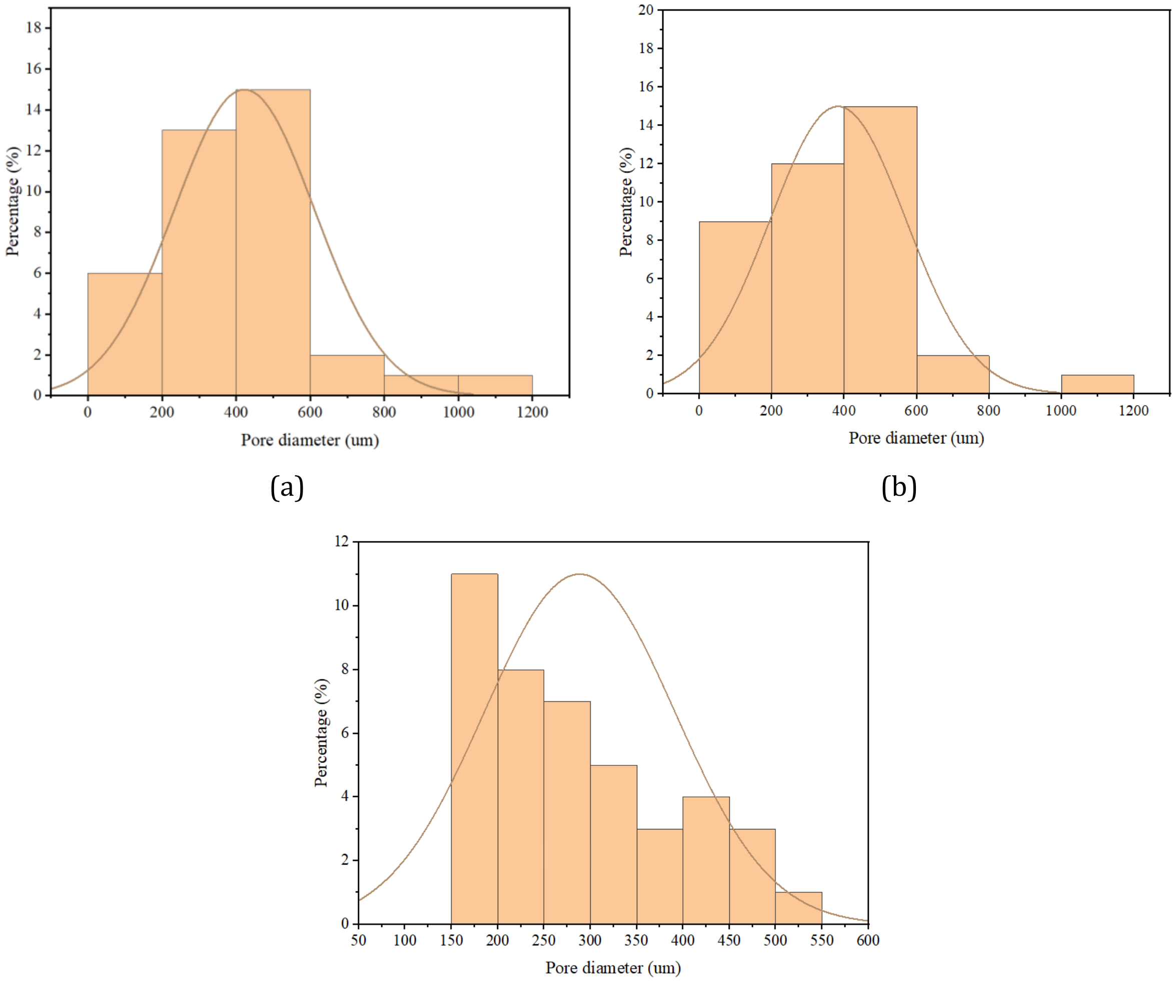


(a) (b)



(c)

Fig. 9. SEM scanning images of specimens with different HEC content. (a) HEC=0%; (b) HEC=1%; (c) HEC=2%



(a)

(b)

(c)

Fig. 10. Diagrams of the pore size distribution. (a) HEC=0%; (b) HEC=1%; (c) HEC=2%

Furthermore, minimizing the number of large pores significantly decreases water absorption, enhancing the material's long-term durability, particularly in moisture-prone environments. Fig. 10 illustrates the pore size distribution within the specimens with different HEC contents. As shown in Fig. 10, when the HEC content was 0%, 1%, and 2%, the average pore size was 422.18 μm, 382.76 μm, and 288.39 μm, respectively. According to the classification in reference [19], pores with diameters larger than 500 μm were defined as large-diameter pores, while those smaller than 500 μm were classified as small-diameter pores. In the H0 group, the proportion of small pores was 95.7%, while in the groups with 1% and 2% HEC content, the proportion of small pores increased to 97.2% and 99%, respectively. These changes align with findings by Qiu et al. [21] who reported that the particle size distribution of bubbles gradually Narrows as the stabilizer concentration increases. The analysis of the micro-pore structure reveals that the incorporation of HEC significantly influences the pore size and distribution within foamed concrete. HEC not only reduces the average pore size but also creates a more uniform pore distribution, optimizing the material's microstructure. This regulation of pore size and distribution is crucial for enhancing the material's properties, making it more suitable for engineering applications. Microstructural analysis confirms that HEC plays a critical role in improving the quality and performance of foamed concrete.

4. Conclusions

This study explores the impact of Hydroxyethyl Cellulose (HEC) on the stability, mechanical properties, and pore structure of foamed concrete. A series of experiments were conducted to analyze the effects of varying HEC content on foam stability, slurry fluidity, compressive strength, water absorption, and internal pore structure. The goal was to determine the optimal HEC dosage to improve the overall performance of foamed concrete without compromising its workability. The mechanism of HEC was revealed. The main conclusions reached by this paper are as follows:

- The content of Hydroxyethyl Cellulose (HEC) significantly enhances the stability of foam in foamed concrete. By forming high-viscosity solutions and protective films around bubbles, HEC reduces bubble rupture and coalescence. When the HEC content is 0.15%, the cumulative bleeding rate of the foam decreased from 29.7% without HEC to only 1.4%.
- The use of HEC decreases water absorption in foamed concrete. As the HEC content increases, the material absorbs less water, with the highest HEC group showing only 16.2% water absorption after 24 hours of immersion.
- HEC also improves the compressive strength of foamed concrete. At the HEC content of 0.15%, the 28-day compressive strength increases by 33.66%, reaching 2.75 MPa. The study shows that the optimal HEC content for strength improvement lies between 0.1% and 0.15%.
- While HEC improves stability and strength, excessive content increases viscosity and reduces fluidity, affecting construction workability. Therefore, maintaining an optimal HEC dosage is essential to achieve the desired balance between stability, strength, and fluidity.
- The content of HEC significantly improved the pore structure of foamed concrete. At the HEC content of 2%, the average pore diameter decreased to 288.39 μm, compared to 422.18 μm without HEC, representing a reduction of approximately 31.6%. Additionally, the proportion of small pores increased to 99%, indicating a more uniform pore distribution and a denser overall structure.

This study highlights the significant potential of HEC as a stabilizer for enhancing the stability, strength, and durability of foamed concrete. Future research should focus on evaluating its long-term performance under environmental conditions such as freeze-thaw cycles, wet-dry cycles, and chemical exposure, which are critical for ensuring material durability in practical applications. From a practical standpoint, HEC-enhanced foamed concrete offers a cost-effective and sustainable solution for lightweight, durable, and moisture-resistant construction materials. Its ability to refine pore structure, reduce water absorption, and improve compressive strength makes it ideal for energy-efficient buildings, thermal insulation systems, and lightweight partition walls.

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