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Research Article

Experimental Study on Application Performance of Foamed Concrete Prepared Based on a New Composite Foaming Agent

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The performance of foaming agent plays a key role in the forming quality of foamed concrete. In order to overcome the limitation of single composition of traditional foaming agent, this paper adopts the research method of multicomponent composite combined with the foaming theory and preparation technology of foaming agent, a new protein composite foaming agent was prepared using a mixture of anionic surfactant (SCA), nonionic surfactant (APG), and foam stabilizer (AR), and then, the effects of different surfactant mass ratios and foam stabilizer concentrations on the properties of composite foaming agent were studied by a series of tests. The results show that the optimal mass ratio of surfactants is m_{APG}: $m_{SCA} = 2:1$, and the optimal concentration of foam stabilizer is 0.5 g/L, which verified that the self-made composite foaming agent system in this paper has the advantages of strong foaming ability, excellent foam stability, and low cost. In addition, foamed concrete was prepared on the basis of the optimized composite foaming agent system, and the influence rules of different foaming agent solution volumes, water-cement ratios, and diatomite dosages on the performance of foamed concrete were revealed through laboratory tests and SEM images. At the same time, the optimal ratio of each component required for the preparation of high-quality foamed concrete was further obtained by using the response surface analysis of compressive strength. The research results provide an important reference for the preparation of high-performance foamed concrete and corresponding foaming agent, which is beneficial for solving the disadvantages of poor foam stability in the existing foaming agents and improving the application level of foamed concrete in engineering construction.

1. Introduction

Foaming agent is a class of substances that produces pore structure inside the matrix through physical or chemical method [1]. In general, the foaming agent is divided into two types: generalized foaming agent and narrow foaming agent according to the difference of concept, so as to distinguish the applicability of foaming agent [2]. The aqueous solution of generalized foaming agent is a surfactant or surface active material that can produce a large amount of foam when air is introduced. It has requirements on the ability to produce a large amount of foam, but it has no strict requirements on the technical properties such as foam multiple and foam stability and has no specific requirements on whether the generated foam has practical application value. Compared with the generalized foaming agent, the narrow foaming agent emphasizes its application value and requires excellent foaming performance to achieve technical indexes of various products so as to be applied in practical production and life [3]. In the field of engineering construction [4–6], foaming agent is often used to prepare porous materials, such as adding foaming agent in plastic, rubber, and concrete that can be prepared into foam products, which opens up a broad space for the application of foaming agent. Particularly in the field of concrete, using foaming agent to prepare foamed concrete is of great significance to the application and popularization of foaming agent [7]. Compared with ordinary concrete slurry, foamed concrete greatly improves its application performance due to the introduction of a large number of bubbles, so that it has a series of advantages such as lightweight, high mobility, heat insulation, and construction convenience and has good shock absorption performance and stress dispersion ability [8–13]. The self-made foaming agent in this paper is mainly applied to the production of foamed concrete, so the relevant elaboration and discussion will be made from the perspective of concrete foaming agent.

Foaming agent acts as the "truck" that introduces air into the concrete, and pores are formed in the concrete under its action, which reduces the surface tension of the liquid and maintains its shape for a long time [14]. In addition, the foaming agent controls the density and strength of the foamed concrete through the number of bubbles in the concrete matrix, which makes the density and strength of foamed concrete adjustable in a certain range [15, 16]. In order to further explore the relationship between foam form and the performance of foamed concrete, Kräme et al. [17, 18] studied the three-phase structure of foam in concrete and revealed the mechanism of foam action in concrete slurry, which has important guiding significance for improving the performance of foam concrete. Zingg et al. [19] studied the influence of pore volume and pore size on the performance of foamed concrete and prepared two kinds of foamed concrete with high strength and low strength. Therefore, there is no doubt that the performance of foaming agent is crucial to the forming quality of foamed concrete.

The development of concrete foaming agents has undergone several generations of change, from the rosin resin foaming agent in the early stage to the protein foaming agent and artificial foaming agent and then to the present composite foaming agent. Among them, the composite foaming agent is the most common foaming agent on the market at present. It is a kind of foaming agent that combines foaming agents with different properties through physical mixing, which integrates the advantages of various single foaming agents. For the research on the selection of foaming agent types and their own properties, Niu et al. [20] investigated foam properties of several protein foaming agents currently on the market from the perspectives of foaming multiple, bleeding rate, and foam particle size distribution, and the effects of protein foaming agent on the pore distribution, water absorption, and compressive strength of foamed concrete have been further studied. Drenckhan and Langevin [21] have studied the applicability of several different synthetic surfactants in foamed concrete and proposed the influence of preparation conditions on the density and stability of foam.

Based on the research status of foaming agent and foamed concrete, although foaming agent plays an important role in the preparation of foamed concrete, there are still many problems to be solved in the application process: ① the single-component foaming agent performs better in some aspects, but sometimes it cannot meet the actual requirements of the project; ② some foaming agents still have some shortcomings such as weak foaming ability, uneven foaming, and poor foam stability, which lead to a narrow application range of foaming agents and restrict the application and promotion of foamed concrete in engineering construction; ③ most foaming agents have poor degradability and will pollute or even destroy the ecological environment; ④ there are many kinds of foaming agents on the market, and the quality difference between different foaming agents is greatly affected by the cost, preparation technology, and other factors, resulting in the uneven quality of foamed concrete. Therefore, combined with the dynamics of engineering requirements, it is necessary to make use of the synergistic effect of several single-component foaming agents to prepare the composite foaming agent with strong foaming ability, good foaming stability, and strong applicability under the premise of economic and environmental protection, which lays a solid foundation for obtaining high-quality foamed concrete.

For the composite foaming agents, if the foam film has enough viscoelasticity and strength, then the foam will exist stably in the concrete slurry, and the foam prepared by the polymer surfactant has this characteristic. As a kind of polymer surfactant, the protein surfactant shows good ability in stabilizing foam; at the same time, it also has certain foaming ability and good degradability, which is a kind of surfactant in line with the concept of sustainable development [22]. The protein surfactant and small molecule surfactant are compounded to form a uniform and stable system, the interaction with components of the cement mortar mixture can be effectively improved by the synergistic effect between the surfactants, and a foaming agent system with excellent foam performance can be obtained.

In this paper, the authors aim at preparing high-performance foamed concrete based on a self-made composite foaming agent system. Firstly, in order to solve the disadvantages of traditional foaming agents such as weak foam stability, uneven foaming, and poor biodegradable, a new protein composite foaming agent was prepared using the mixture of anionic surfactant (SCA), nonionic surfactant (APG), and foam stabilizer (AR) under the premise of economy and environmental protection. Secondly, the effects of different surfactant mass ratios and foam stabilizer concentrations on the properties of the composite foaming agent were studied by a series of tests, which further optimized the composition system of the composite foaming agent. In addition, based on the optimized composite foaming agent system, the influence rules of different foaming agent solution volumes, water-cement ratios, and diatomite dosages on the performance of foamed concrete were proposed through laboratory tests and SEM images. At last, the optimal ratio of each component required for the preparation of high-quality foamed concrete was further determined through the response surface analysis.

2. Experimental Procedure

2.1. Test Raw Materials

2.1.1. Foaming Agent. Foaming agent is a class of substances composed of surfactant, foam stabilizer, and whipping aid, among which the surfactant is the most important component of the conventional foaming agent [23]. The surfactant refers to a substance with surface activity, which mainly affects the stability of foam by changing the arrangement of the adsorption layer or using the synergistic effect of different surfactants [24]. For foaming agent in foamed concrete, it is very important to select the appropriate surfactant. If the foam film has enough viscoelasticity and relatively high strength, the foam will exist stably in the concrete slurry.

Surfactants mainly include anionic, cationic, nonionic, and other types. Among them, SCA is an anionic surfactant, which has good water-carrying capacity and can slow down the flow rate of liquid on the foam surface due to its polymer characteristics, but its foam stability is poor when it is used as a foaming agent alone. On the other hand, compared with cationic and amphoteric surfactants, APG is a nonionic surfactant with good water solubility, foam stability, and biodegradation, which can adjust the interaction between foam and cement particles and has little impact on the environment, but its foaming ability is slightly worse when it is used as foaming agent alone. In general, in order to overcome the limitation of single composition of traditional foaming agent [25], SCA and APG are selected as surfactants in this paper to improve the compatibility between foaming agent and concrete through the synergistic effect between different surfactants, and AR is also selected as a foam stabilizer to improve the stability of the foam and the viscosity of the solution. This paper is committed to preparing a new composite foaming agent with high foaming performance and excellent foam stability. The composite foaming agent raw materials selected are shown in Table 1.

2.1.2. Foamed Concrete. Foamed concrete refers to a lightweight material with many pores; that is, the foaming agent is prepared into foam by the physical method first, and then the foam is mixed into the well-mixed cement slurry in a certain proportion and hardened by physical and chemical action [26]. From the research status of foamed concrete [27, 28], foamed concrete is mainly formed by adding a curing agent, water, and foam in a certain proportion after full mixing and mixing. Among them, the curing agent is divided into the main agent and the auxiliary agent. The main agent mainly refers to cement, which has the effect of consolidating and strengthening the soil skeleton, while the auxiliary agent refers to fine aggregates such as fly ash, which achieves the purpose of reducing the amount of the main agent and reducing the cost. In addition to the above-mentioned self-made composite foaming agent, the raw materials required for preparing foamed concrete in this paper also include cement, fly ash, diatomaceous Earth, and water. The main parameters are shown in Table 2.

2.2. Experimental Procedure

2.2.1. Preparation Process of Foaming Agent and Performance Tests. For the foaming agent in foamed concrete, foaming capacity and foam stability are two important indicators to characterize its performance. Among them, foaming capacity determines the foaming efficiency of the foaming agent. The higher the foaming efficiency, the lower the production cost, but the foaming efficiency should be a suitable range in the preparation process of foamed concrete. Foaming capacity is generally measured by foaming multiple, which is specifically expressed as foaming volume or foam density. Foam stability is generally measured by bleeding rate, settling distance, and half-life of foam. When the bleeding rate and settling distance of the foam are smaller and the half-life is longer, it means that the stability of the foam is better. In order to examine the performances of the self-made composite foaming agent in this paper, the foaming ability of the foaming agent is evaluated by measuring the foaming volume, and the stability of the foaming agent is characterized by measuring the surface tension and viscosity of the solution, foam half-life and electrical conductivity. Meanwhile, the microstructure and particle size distribution range of the foam are analyzed by means of the scanning electron microscope.

On the other hand, in order to optimize the composition ratio of the composite foaming agent system prepared in this paper, the effects of different surfactant mass ratios and xanthan gum concentrations on the performance of the composite foaming agent were analyzed by a series of performance tests. Firstly, SCA and APG were prepared into composite foaming agent aqueous solutions with different mass ratios, and the surface tension and viscosity of the solution were measured under different mass ratios. Then, the foaming agent aqueous solution was stirred at a constant speed to 2100 r/min within 20 minutes until fully foamed. Finally, the volume, half-life, electrical conductivity, and particle size distribution of the foam were measured to evaluate the performances of the self-made composite foaming agent. On the basis of the above test results, the same test methods were used to compare and analyze the effects of different concentrations of xanthan gum on the properties of a self-made compound foaming agent so as to optimize the optimal concentration of xanthan gum as a foam stabilizer.

2.2.2. Preparation Process of Foamed Concrete and Performance Tests. The preparation of foamed concrete with excellent performance is the ultimate goal of developing a new composite foaming agent system, and it is also an effective means to further verify the performance of the above-mentioned composite foaming agent. For foamed concrete, density and strength are two important indicators to measure its molding quality. Generally speaking, when the density of foamed concrete is smaller and its compressive strength is higher, its performance is better. According to the relevant standard of foamed concrete [29], there is a one-to-one relationship between density and strength of foamed concrete; that is, each density grade of foamed concrete has a corresponding range of compressive strength. Compared with ordinary concrete, foamed concrete has a lower density due to the introduction of a large number of bubbles in the internal structure, but its compressive strength is generally lower, which limits the application range of foamed concrete to a certain extent. The decrease in the density of foamed concrete would inevitably lead to a decrease in its compressive strength. Therefore, how to improve strength as much as possible under the condition of low density is the key to preparing high-quality foamed concrete. In previous studies,

Table 1: Composite foaming agent raw materials.

Name of raw materials		Advantages	Disadvantages
Anionic surfactant	Sodium caseinate (SCA)	Strong foaming ability and low price	Poor foam stability
Nonionic surfactant	Alkyl glycosides (APG)	Good water solubility, excellent foam stability, and good biodegradability	Slightly poor foaming ability
Foam stabilizer	Xanthan gum (AR)	Increase the viscosity of solution and improve the stability of foam	—

Table 2: Main parameters of foamed concrete raw materials.

Name of raw materials	Parameter indicators	Measured value
Cement	Species	Ordinary Portland cement
	Strength grade	42.5
	Density (kg/m³)	3069
Fly ash	Category	Class-F II
	Density (kg/m³)	2148
Diatomaceous Earth	Porosity (%)	87
	Wet density (kg/m³)	460

most scholars focused on improving the strength of foamed concrete by adding admixtures instead of cement but ignored the influence of the foaming agent's own properties on the forming quality of foamed concrete.

In view of this, this paper makes use of the optimized composite foaming agent system to prepare high-quality foamed concrete from the perspective of improving the properties of the foaming agent. The preparation process of foamed concrete is shown in Figure 1. Firstly, the aqueous solution of the composite foaming agent was stirred at the speed of 2100 r/min until fully foamed. Then, the foam was added to the cement slurry for 10 minutes of rapid stirring. Finally, the mixed aqueous solution was poured into the mold for solidification and demoulding forming, and the natural curing lasted for 28 d. After many trial calculations and verifications, the proportion of each component of cement slurry should be m_1: m_2: $m_3 = 21:14:14\sim18$.

In addition, considering that the volume of foaming agent solution, water-cement ratio, and diatomite content have significant effects on the performance of foamed concrete, the influence laws of the above three main factors on the performance of foamed concrete were revealed by measuring the dry density, compressive strength, and water absorption according to the orthogonal test scheme in Table 3. Combined with the response surface test results of compressive strength, the optimal ratio of foamed concrete prepared based on the new composite foaming agent was also selected.

3. Results and Discussion

3.1. *Effect of Surfactant Mass Ratio on Properties of the Composite Foaming Agent*

3.1.1. Surface Tension and Viscosity. Surface tension and viscosity are two important performance indexes for the composite foaming agent. The surface tension determines the difficulty level of foaming; the smaller the surface tension, the better the foaming ability. While viscosity determines the flow rate of foaming agent solution and the elastic modulus of foam film, the greater the viscosity of the solution, the more stable the foam. In order to ensure the foam stability of the composite foaming agent, the foaming agent prepared in this paper has lower surface tension and higher viscosity by adjusting the mass ratio of different surfactants.

The surface tension and viscosity change curves of composite foaming agent solution under different surfactant mass ratios are shown in Figure 2. As can be seen from Figure 2, the surface tension of the solution changes a little with the increase of SCA content. Considering the specific surface energy of the foam film, low surface tension is beneficial to form foam and improve the foaming ability of the composite foaming agent. However, the surface tension of the solution in Figure 2 has basically not changed, which means that the foaming ability of the solution has not changed. In addition, it can also be seen from Figure 2 that the viscosity of the solution increases with the increase of SCA content, especially after m_{APG}: $m_{SCA} = 2:1$, and the viscosity of the solution shows a trend of substantial increase, showing the characteristics of SCA polymer thickening. However, if the viscosity of the solution is too large, it is more difficult to form the liquid film, and the self-repair ability of the foam film will be worse, resulting in poor stability of the solution. In view of the surface tension and viscosity that cannot fully reflect the properties of the composite foaming agent, it is necessary to further optimize the mass ratio of surfactants by measuring other performance indicators of the composite foaming agent (such as foaming volume and half-life).

3.1.2. Foaming Volume and Half-Life. The foaming ability and foam stability of the foaming agent can be intuitively characterized by measuring the foaming volume and half-life of the foaming agent solution. Foaming volume refers to

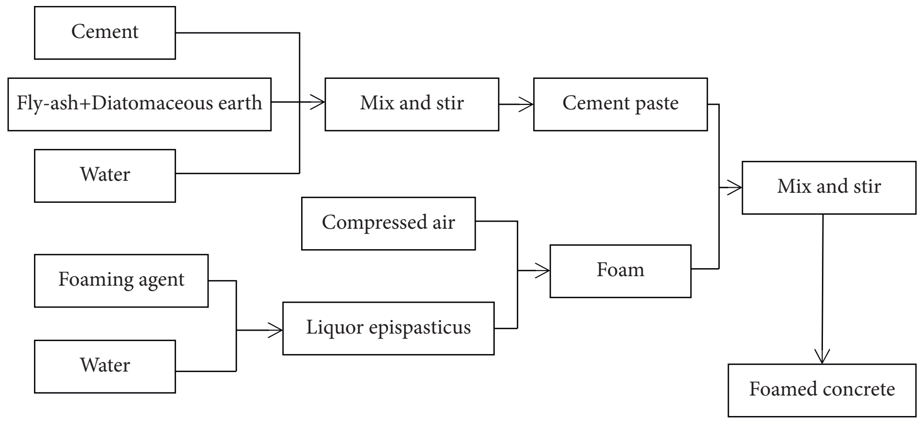


Figure 1: The preparation process of foamed concrete.

Table 3: Orthogonal test scheme.

Test number	Volume of foaming solution (mL)	Water-cement ratio	Diatomaceous Earth content (%)	Influencing factor
1–1	40	0.60	1	Volume of foaming solution
1–2	50	0.60	1	
1–3	60	0.60	1	
1–4	70	0.60	1	
1–5	80	0.60	1	
1–6	90	0.60	1	
1–7	100	0.60	1	
2–1	90	0.54	1	Water-cement ratio
2–2	90	0.56	1	
2–3	90	0.58	1	
2–4	90	0.60	1	
2–5	90	0.62	1	
2–6	90	0.64	1	
2–7	90	0.66	1	
3–1	90	0.60	0	Diatomaceous Earth content
3–2	90	0.60	1	
3–3	90	0.60	2	
3–4	90	0.60	3	
3–5	90	0.60	4	
3–6	90	0.60	5	
3–7	90	0.60	6	

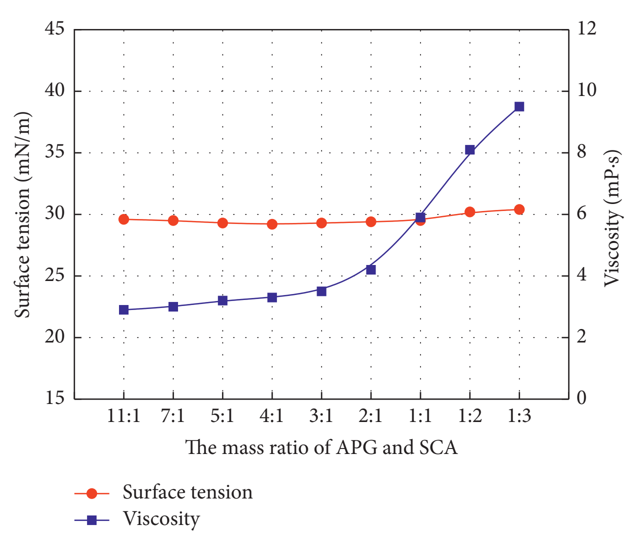


Figure 2: The curve of surface tension and viscosity under different surfactant mass ratios.

a certain volume of foaming agent solution that is mechanically stirred to produce a large amount of foam and then measure the volume of the generated foam. Obviously, the larger the volume of foam produced, the better the foaming ability of this foaming agent. The half-life of foam refers to the time when the liquid discharged from the foam is half the volume of the original solution after the solution is completely foamed by mechanical stirring. When the half-life of foam is larger, the rate of foam merging and drainage is slower, which indicates that the foam prepared by this foaming agent has good stability. Under different mass ratios of APG and SCA, the test results of foaming volume and half-life of the composite foaming agent solution are shown in Figure 3.

As can be seen from Figure 3, with the increase of SCA content, the foaming volume of the composite foaming agent solution presents a trend of gradual decrease, while the half-life of foam presents a trend of substantial increase, especially after m_{APG}: $m_{SCA} = 2:1$. When m_{APG}: $m_{SCA} = 2:1$, the composite foaming agent prepared in this paper has both good foaming ability and foam stability. The above change law shows that adding a small amount of SCA will improve the foam stability under the condition of ensuring foaming performance, but when SCA content reaches a certain amount, the foaming volume of the composite foaming agent will be greatly reduced, and the stability of foam will be reduced. The reason is that the addition of excessive SCA will increase the viscosity of the composite foaming agent solution and the viscosity of foam film, and the self-repair ability of foam film will be reduced, resulting in the decrease of the foam stability.

3.1.3. Relative Conductivity. In order to further comprehensively evaluate the stability performance of the composite foaming agent, the relative conductivity method is used to determine the change rule of foam conductivity with time. Due to the difference in conductivity between the solution and the air, its size can reflect the amount of solution contained in the foam film layer, which is called the drainage rate of liquid film. The change trend of the foam relative conductivity with time is smaller, which indicates that the drainage speed of the liquid film is slower and the stability of the foam is better. Figure 4 shows the curve of foam relative conductivity changing with time under different surfactant mass ratios.

It can be seen from Figure 4 that no matter how the mass ratio of APG and SCA changes, the relative conductivity of foam generated by the composite foaming agent solution gradually decreases with the increase of time. In fact, the decrease in the foam relative conductivity is directly related to the drain of foam; that is, the drain of foam directly leads to the decrease in the conductivity of foam.

The fitting of the parts with rapid changes in relative conductivity is carried out, and fitting linear equations of foam relative conductivity changing with time were obtained, as shown in Table 4. It is obvious from Table 4 that, with the increase of the SCA content, the slope absolute value of fitting linear equations gradually decreases; that is to say, the decrease rate of the foam relative conductivity also gradually decreases. This indicates that the drainage speed of foam is decreasing, and the thinning speed of the foam liquid film is also decreasing, thus increasing the stability of foam. It can be concluded that the increase of the SCA content can reduce the drainage speed of the foam liquid film and enhance its stability.

3.1.4. Microstructure and Particle Size Distribution. The size of foam particles has a direct influence on the performance of foamed concrete. For foamed concrete, the smaller the pore size distribution, the better the performance of foamed concrete, especially for water absorption. In other words, when the particle size distribution of the foam is smaller, it is more advantageous to prepare foamed concrete with uniform pore size distribution and a small proportion of connected pores, thereby reducing the water absorption rate of the foamed concrete. Therefore, a composite foaming agent with good foam uniformity should be selected to prepare foamed concrete. In order to verify the microstructure and particle size distribution characteristics of the composite foaming agent mentioned above, a metallographic microscope and desktop scanning electron microscope were used to analyze the particle size of the foam. The test results are shown in Figures 5 and 6.

As can be seen from Figure 5, with the increase of the SCA content, the particle size and deformation degree of the foam prepared by the composite foaming agent gradually decreased, and the uniformity of the foam also gradually improved. It can be seen that the addition of SCA can enhance the strength of foam film, increase its elastic modulus, and improve its ability to maintain its shape when preparing foamed concrete, resulting in the fact that foam is not easy to deform, thus improving the stability of foam. On the other hand, it can be seen from Figure 6 that, with the increase of SCA content, the particle size distribution of foam gradually becomes narrower, which is conducive to improving the pore diameter uniformity of foamed concrete and reducing the proportion of harmful pores, thus improving the performance of foam concrete.

In summary, through the performance measurement and analysis of the self-made composite foaming agent in this paper, combined with the foam microstructure and particle size distribution characteristics, it is determined that the optimized mass ratio of APG and SCA is m_{APG}: $m_{SCA} = 2:1$, and this foaming agent has both excellent foaming ability and foam stability.

3.2. Effect of Foam Stabilizer Concentration on Properties of the Composite Foaming Agent. Considering the thickening effect of xanthan gum, on the basis of the above test results, xanthan gum was selected as the foam stabilizer and added to the composite foaming agent solution with m_{APG}: $m_{SCA} = 2:1$ in order to further improve the performance of the composite foaming agent. The effects of different xanthan gum concentrations on the performance of the composite foaming agent were analyzed by using the same methods above to determine the optimal concentration of

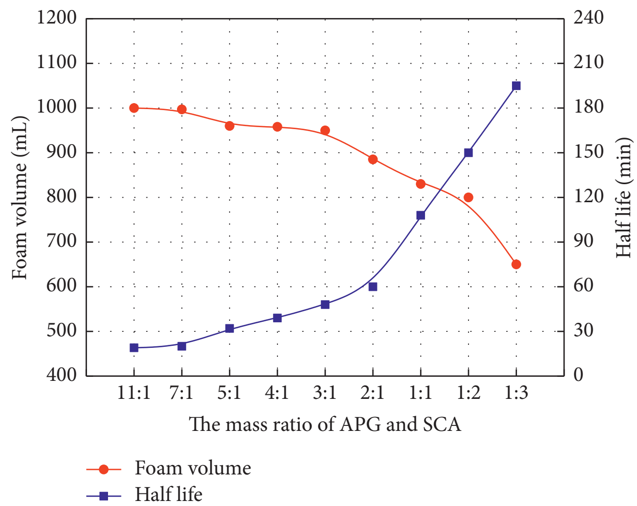


Figure 3: The curve of foaming volume and half-life under different surfactant mass ratios.

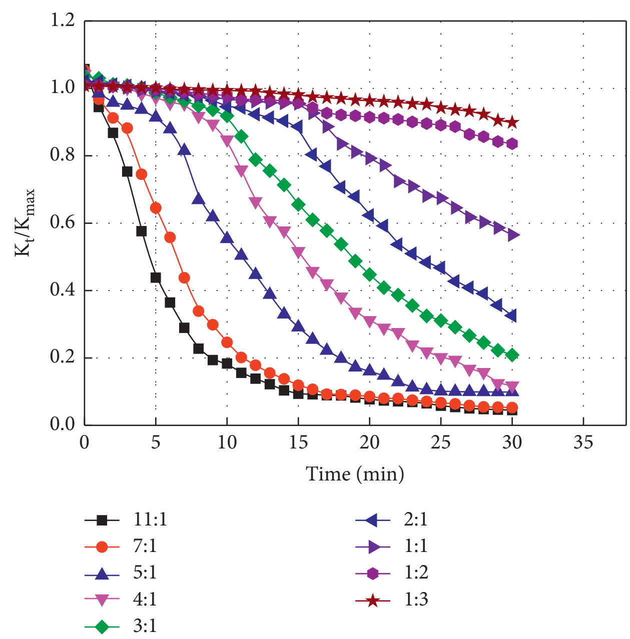


Figure 4: The curve of foam relative conductivity changing with time under different surfactant mass ratios.

Table 4: The fitting linear equations of foam relative conductivity with time under different mass ratios.

Mass ratio of APG and SCA	Fitting linear equations	Fitting degree
11 : 1	$y = -0.1079x + 1.0773$	0.9323
7 : 1	$y = -0.0901x + 1.1450$	0.9533
5 : 1	$y = -0.0577x + 1.1881$	0.9852
4 : 1	$y = -0.0483x + 1.2624$	0.9908
3 : 1	$y = -0.0387x + 1.2351$	0.9941
2 : 1	$y = -0.0371x + 1.3857$	0.9920
1 : 1	$y = -0.0236x + 1.2650$	0.9901
1 : 2	$y = -0.0078x + 1.0772$	0.9610
1 : 3	$y = -0.0057x + 1.0634$	0.9278

x is the time (min); y is the relative conductivity of the foam.

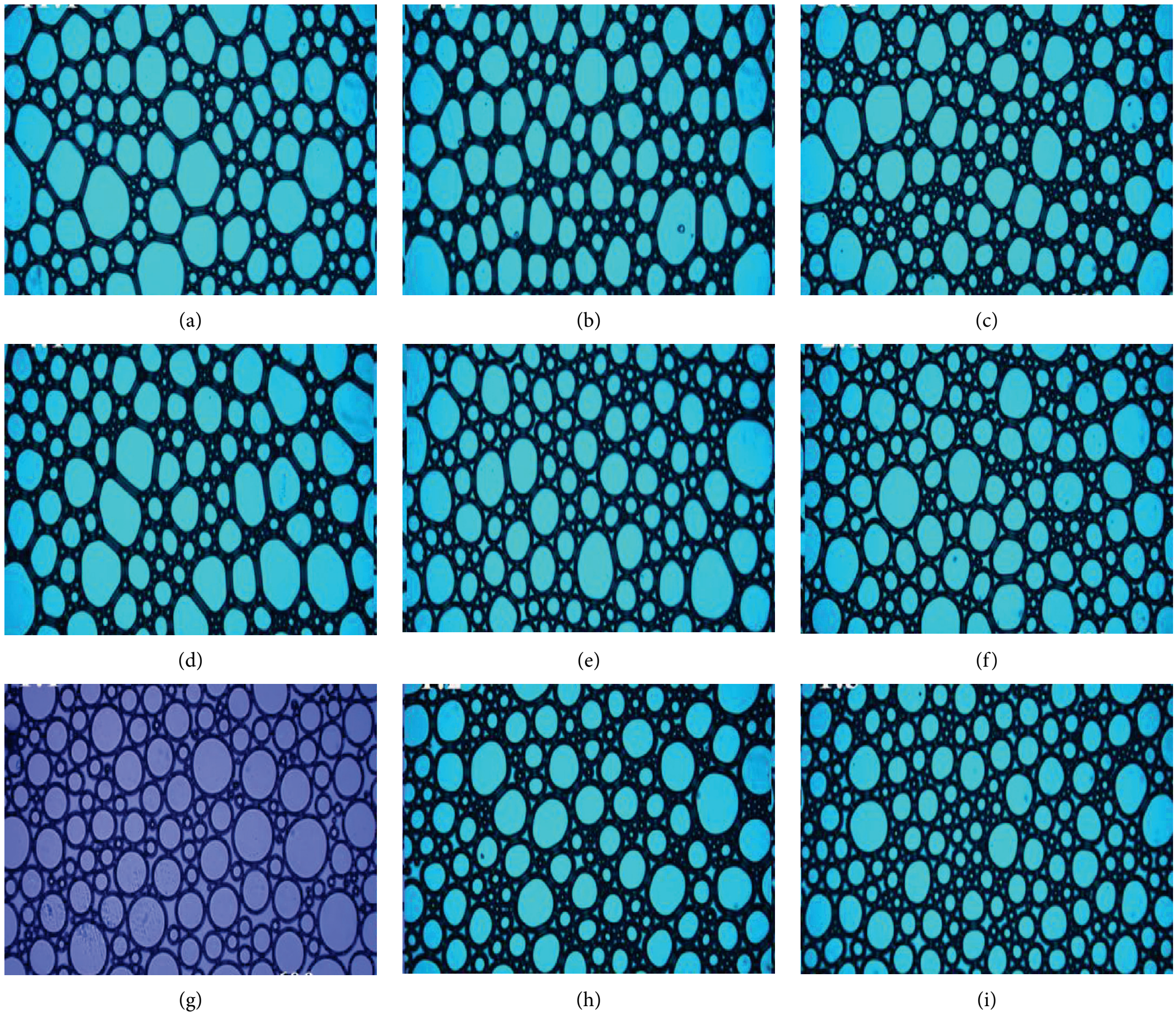


Figure 5: Microstructure of the foam under different surfactant mass ratios: (a) 11 : 1; (b) 7 : 1; (c) 5 : 1; (d) 4 : 1; (e) 3 : 1; (f) 2 : 1; (g) 1 : 1; (h) 1 : 2; (i) 1 : 3.

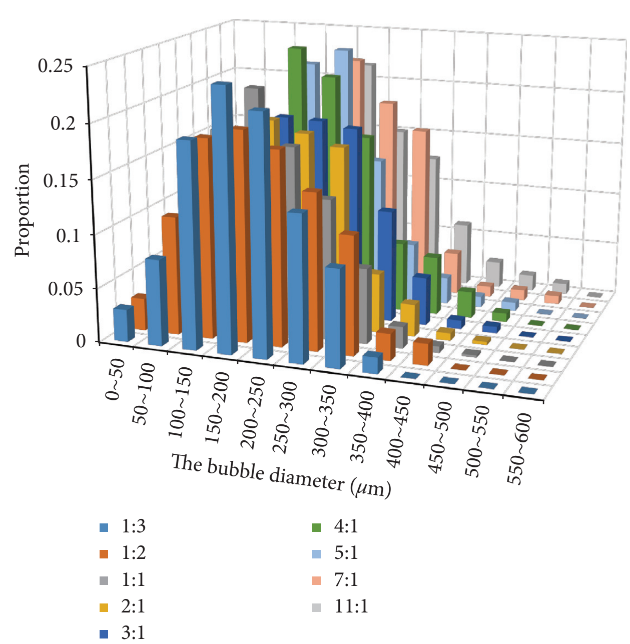


Figure 6: Particle size distribution of the foam under different surfactant mass ratios.

xanthan gum so as to improve the composition of the whole composite foaming agent system.

Figure 7 is the curve of surface tension and viscosity of composite foaming agent solution under different concentrations of xanthan gum. As shown in Figure 7, xanthan gum has basically no effect on the surface tension of this composite foaming agent solution. The reason is that the molecules form more hydrophilic bonds in the aqueous solution after the xanthan gum dissolves in water, which affects the movement speed of the surfactant in the solution. However, the concentration of the surfactant adsorbed on the surface of the solution changes little, resulting in a small change range of surface tension. In addition, it can also be seen from Figure 7 that the viscosity of the solution increases with the increase of xanthan gum concentration. When the concentration of xanthan gum is 1.1 g/L, the viscosity of the solution can reach 18.3 mP·s, and the viscosity value at this time is relatively large. Although the addition of xanthan gum can increase the viscosity of the mixed solution and delay the rupture time of the liquid film, the viscosity of the composite foaming agent solution is not as bigger as better. If the viscosity is too large, the foam surface is not easy to form the film, which weakens the self-repair ability of the foam liquid film. Therefore, the concentration of xanthan gum should not be too large. It is necessary to determine the optimal concentration of xanthan gum by measuring other performance indicators of the composite foaming agent.

After different concentrations of xanthan gum are added to the composite foaming agent solution, the foaming volume and half-life are measured, respectively, and the results are shown in Figure 8. As can be seen from Figure 8, with the increase of xanthan gum concentration, the foaming volume of this composite foaming agent decreases continuously, while the half-life of the foam prepared by this composite foaming agent increases continuously. The reason is that the addition of xanthan gum is beneficial to increase the viscosity of the composite foaming agent system, improve the strength of the film, and slow down the drainage rate of the liquid foam film so as to achieve the purpose of enhancing the stability of the foam. However, it also reduced the foaming volume of the composite foaming agent, which further verified that the concentration of xanthan gum should not be too large.

In order to further study the influence of xanthan gum concentration on the composite foaming agent system, the change curve of foam relative conductivity over time was measured under the condition of different xanthan gum concentrations, as shown in Figure 9. It can be seen from Figure 9 that the relative conductivity of foam firstly increases and then decreases with the increase of time. In addition, with the increase of xanthan gum concentration, the time when the relative conductivity of foam begins to decline is delayed, and the rate of decline also decreases with time. The reason is that the electrode has a certain measurement depth when the conductivity is measured. At first, the conductivity increases due to the flow of foam drainage above the measuring point. However, the drainage of the foam film gradually decreased with the acceleration of drainage speed, resulting in the continuous decline of the electrical conductivity.

This phenomenon can also be further verified from Table 5; the slope absolute value of the fitting linear equation about relative conductivity decreases continuously with the increase of xanthan gum concentration; that is, the stability of foam increases continuously. However, when the xanthan gum concentration is high, the fitting degree of the fitting linear equation is relatively low. The reason may be that when the xanthan gum concentration is high, the viscosity of the solution is too large, which leads to the poor uniformity of the solution so that the relative conductivity instability is also increased.

On the other hand, the influence of different xanthan gum concentrations on the particle size distribution of composite foaming agent from the microscopic point of view was analyzed in this paper, and the test results are shown in Figures 10 and 11. As can be seen from Figures 10 and 11, the particle size distribution of foam gradually narrowed with the increase of xanthan gum concentration. When xanthan gum concentration is 0.5 g/L, the particle size distribution is mainly in the range of $0 \sim 200\,\mu$m, indicating that the uniformity of particle size distribution at this time is good, which is conducive to the preparation of foamed concrete with low density and low connected porosity. Based on the above test results, it is reasonable to select the concentration of xanthan gum at 0.5 g/L, which is beneficial to further improve the stability of the self-made composite foaming agent system in this paper.

3.3. Performance Analysis of Foamed Concrete Prepared with the Composite Foaming Agent

3.3.1. Effect of Foam Volume on Properties of Foamed Concrete. In order to study the relationship between foam volume and performance of foamed concrete, based on the above self-made composite foaming agent system and the testing scheme in Table 3, multiple groups of foamed concrete specimens were prepared through adjusting the dosage of foaming agent solution to control the number of bubbles in the concrete. After standard curing for 28 d, corresponding performance indexes such as dry density, compressive strength, and water absorption were measured, respectively. The test results are shown in Figures 12 and 13.

It can be seen from Figures 12 and 13 that the volume of the composite foaming agent solution has a significant effect on the performance of the foamed concrete. The test results of Figures 12 and 13 show that as the volume of the foaming agent solution increases, the dry density and compressive strength of foamed concrete present the trend of decreasing gradually, while the water absorption of foamed concrete increases gradually. The reason can be explained from the scanning electron microscope (SEM) images in Figure 14. It is obvious from Figure 14 that, with the increase of volume of foaming agent solution, the diameter of pores in foamed concrete gradually increases, and the proportion of connected pores also increases, resulting in the continuous increase of water absorption rate of foamed concrete and the decrease of its compressive strength and dry density. In order to prepare high-quality foamed concrete with a density

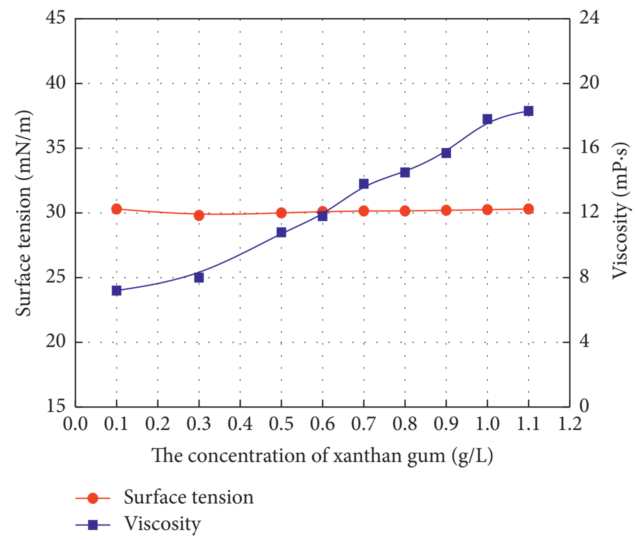


Figure 7: The curve of surface tension and viscosity under different concentrations of xanthan gum.

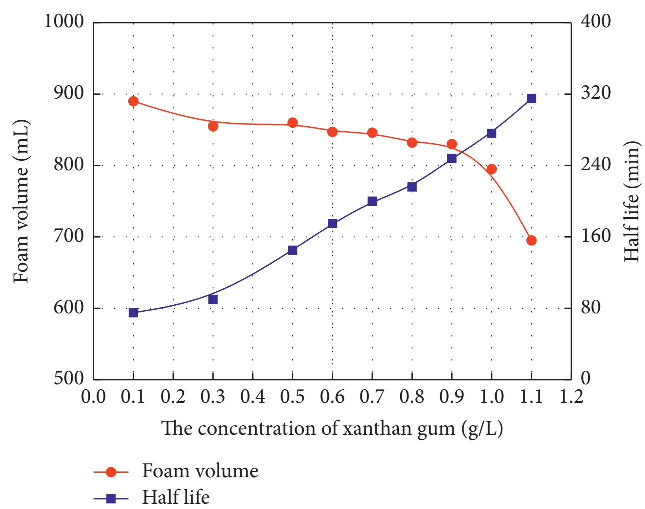


Figure 8: The curve of foaming volume and half-life under different concentrations of xanthan gum.

of $600 \pm 50\,kg/m^3$ and compressive strength of 3.0 MPa, it can be known from the above test results that the dosage of composite foaming agent solution should be 90 mL, the corresponding dry density of foamed concrete is $657\,kg/m^3$, its compressive strength is 3.21 MPa, and the water absorption is 25.21%.

3.3.2. Effect of Water-Cement Ratio on Properties of Foamed Concrete. Similarly, in order to compare and analyze the effect of different water-cement ratios on the performances of foamed concrete, based on the above self-made composite foaming agent system and the testing scheme in Table 3, several groups of foamed concrete specimens were prepared by adjusting water-cement ratio, and the corresponding dry density, compressive strength, and water absorption rate were measured, respectively, after standard curing for 28 d. The test results are shown in Figures 15 and 16.

As can be seen from Figure 15, when the water-cement ratio is in the range of 0.54 ~ 0.66, the dry density and compressive strength of foamed concrete decrease with the increase of the water-cement ratio. The reason is that the increase of the water-cement ratio can improve the compatibility of foam and concrete slurry and reduce the competition effect between foam and cement particles so that the utilization rate of foam increases, which leads to the dry density and compressive strength of foamed concrete both decrease. In addition, similar to the influence of foam volume on the water absorption rate of foamed concrete, it can be seen from Figure 16 that the water absorption rate of foamed concrete increases gradually with the increase of the water-cement ratio. The reason can be seen from SEM images of the foamed concrete in Figure 17; the density of internal holes and the ratio of connected holes in foamed concrete both increase gradually with the increase of the water-cement ratio, resulting in the increase in water

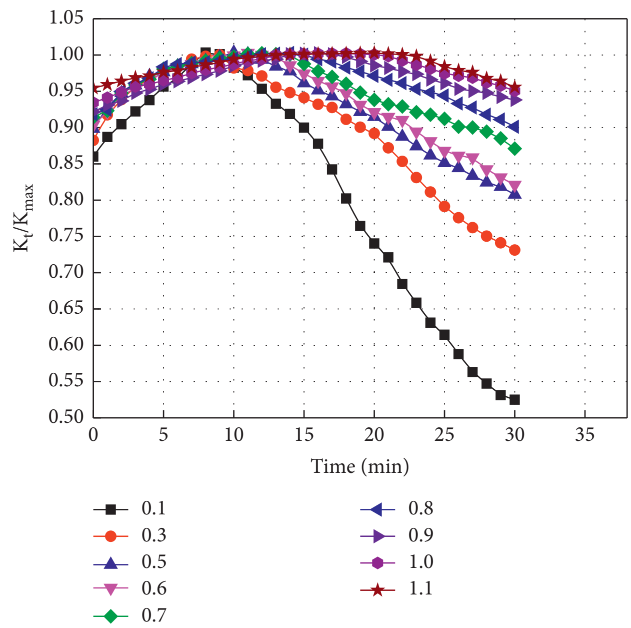
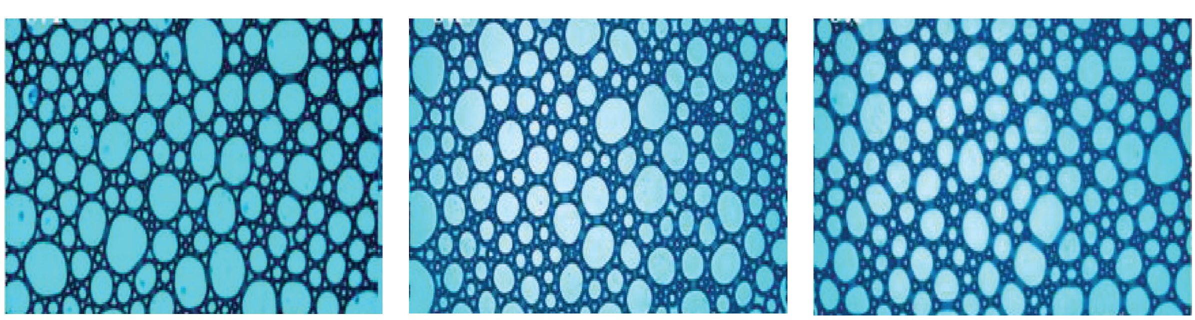


Figure 9: The curve of foam relative conductivity with time under different concentrations of xanthan gum.

Table 5: The fitting linear equations of foam relative conductivity with time under different concentrations of xanthan gum.

Surfactant mass ratio	Xanthan gum concentration (g/L)	Fitting linear equations	Fitting degree
m_{APG}: $m_{SCA} = 2:1$	0.1	$y = -0.0241x + 1.2387$	0.9783
	0.3	$y = -0.0137x + 1.1493$	0.9767
	0.5	$y = -0.0101x + 1.1353$	0.9625
	0.6	$y = -0.0104x + 1.1956$	0.9814
	0.7	$y = -0.0063x + 1.0750$	0.9659
	0.8	$y = -0.0052x + 1.0605$	0.9693
	0.9	$y = -0.0035x + 1.0537$	0.9686
	1.0	$y = -0.0029x + 1.0393$	0.9184
	1.1	$y = -0.0028x + 1.0363$	0.8882

x is the time (min); y is the relative conductivity of the foam.



(a) (b) (c)

Figure 10: Continued.

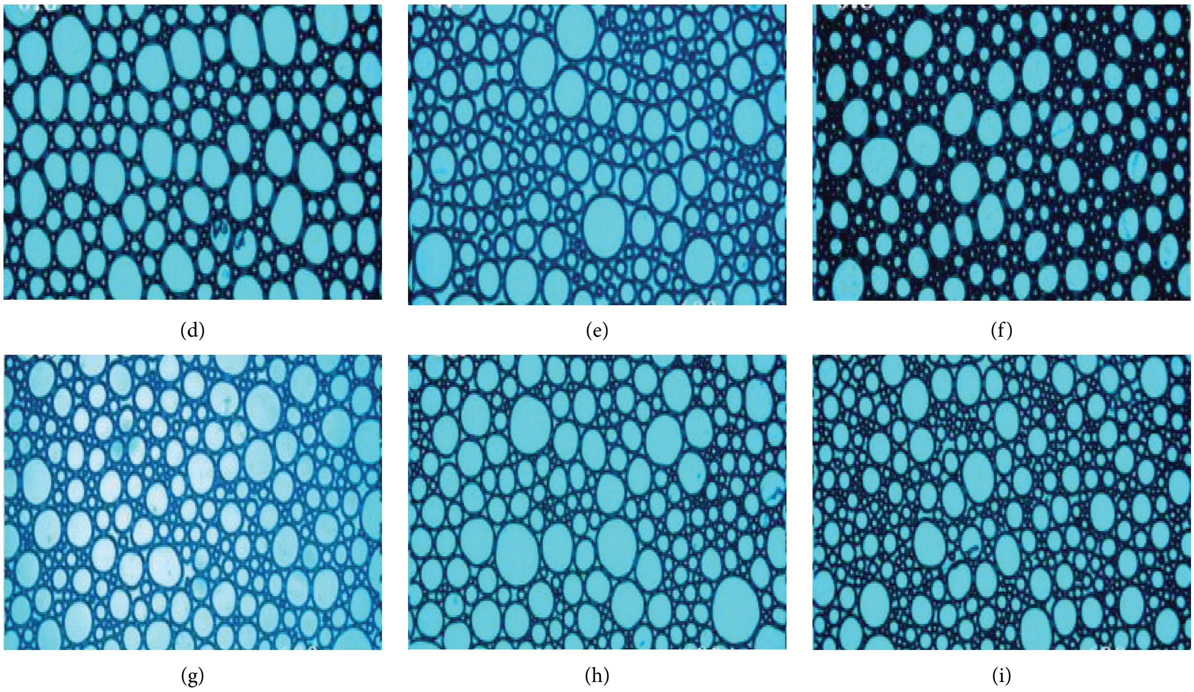


Figure 10: Microstructure of the foam under different xanthan gum concentrations: (a) 0.1; (b) 0.3; (c) 0.5; (d) 0.6; (e) 0.7; (f) 0.8; (g) 0.9; (h) 1.0; (i) 1.1.

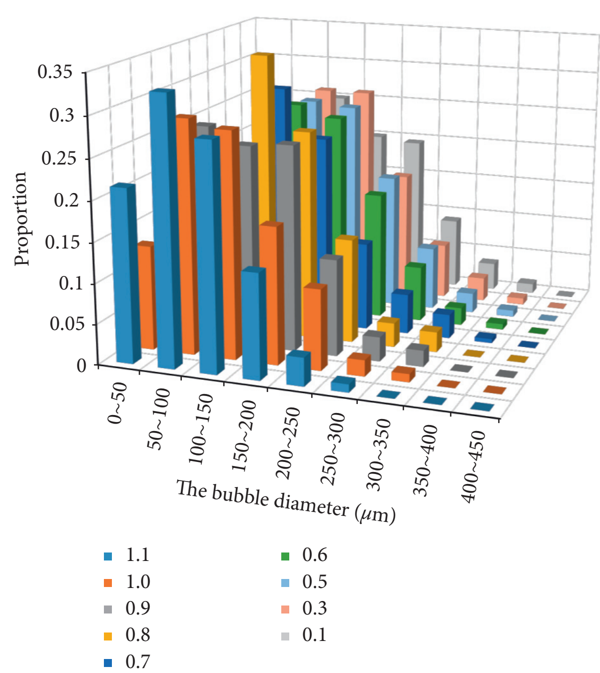


Figure 11: Particle size distribution of foam under different xanthan gum concentrations.

absorption rate of foamed concrete. This shows that the water-cement ratio is an important factor affecting the performance of foamed concrete. Therefore, in order to prepare high-quality foamed concrete with a density of $600 \pm 50\,kg/m^3$ and compressive strength of 3.0 MPa, the water-cement ratio should be 0.60 based on the above test results.

3.3.3. Effect of Diatomite Content on Properties of Foamed Concrete. Diatomite is a porous material rich in silicon dioxide, with a large specific surface area and many hydroxyl groups on its surface, which also has good activity and can react with calcium hydroxide in a concrete slurry to promote secondary hydration in the later stage. Therefore, it is beneficial to improve the performance of the foamed

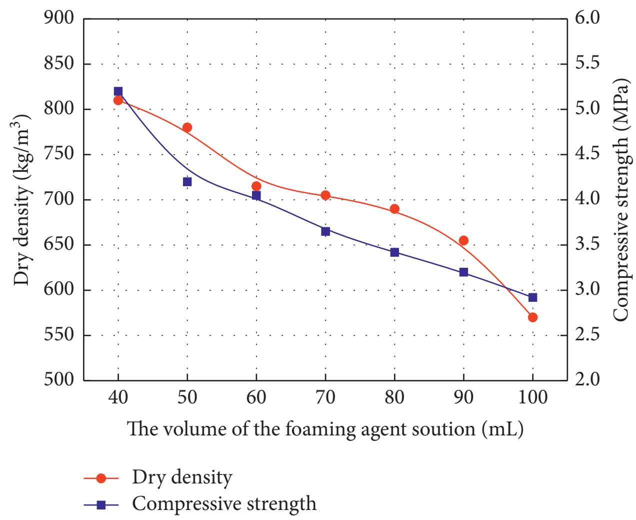


FIGURE 12: Dry density and compressive strength of foamed concrete prepared with different volumes of foaming agent solution.

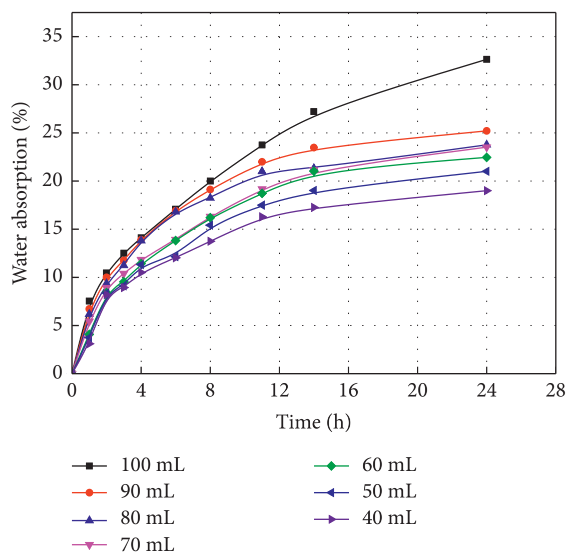
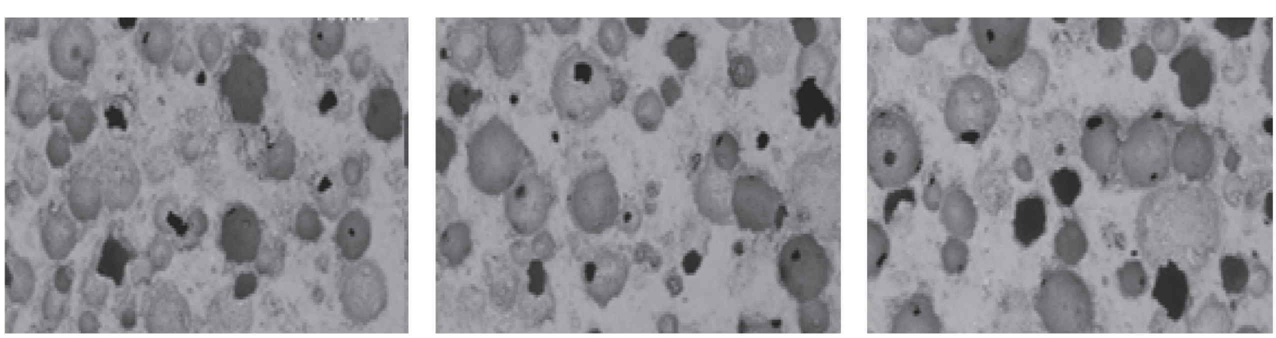


FIGURE 13: Water absorption of foamed concrete prepared with different volumes of foaming agent solution.



(a) (b) (c)

FIGURE 14: Continued.

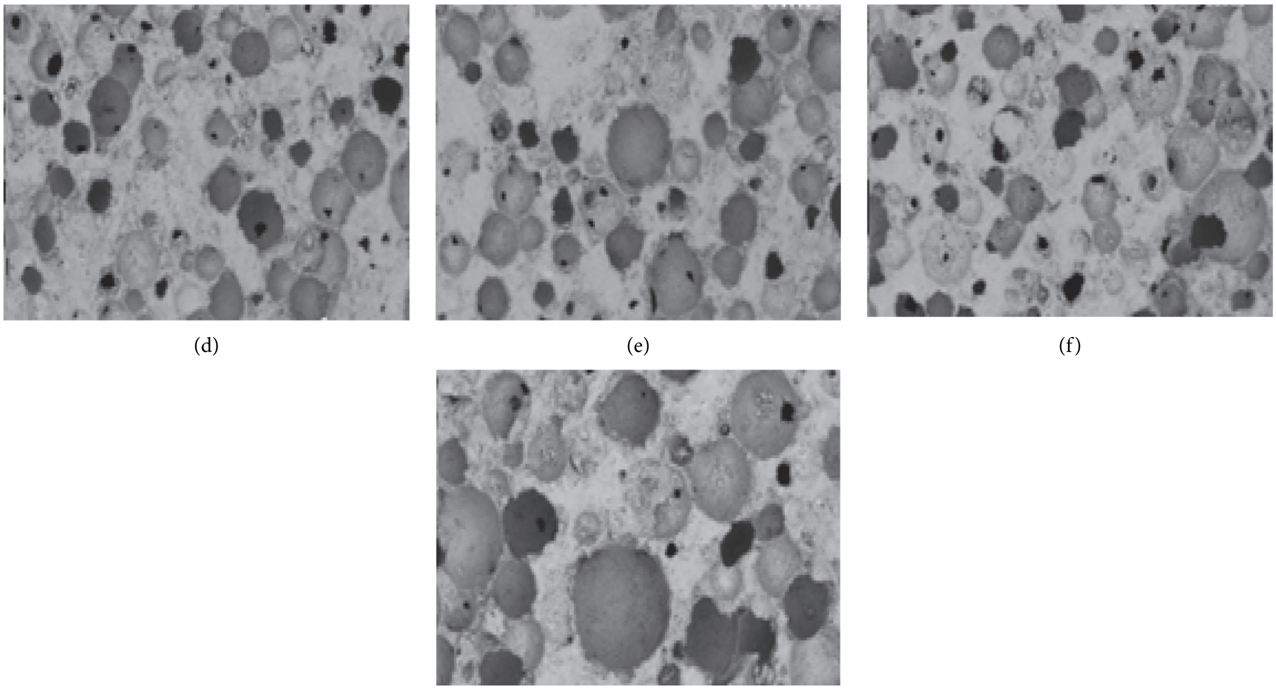


Figure 14: SEM images of foamed concrete prepared with different volumes of foaming agent solution: (a) 40 mL; (b) 50 mL; (c) 60 mL; (d) 70 mL; (e) 80 mL; (f) 90 mL; (g) 100 mL.

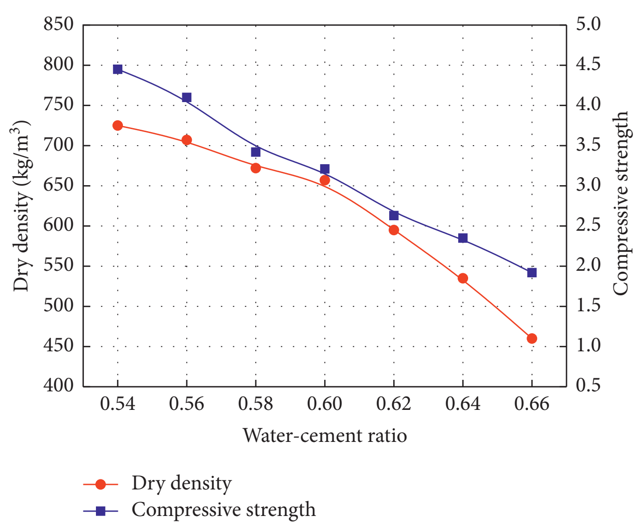


Figure 15: Dry density and compressive strength of foamed concrete under different water-cement ratios.

concrete by adding diatomite instead of cement in foamed concrete. In order to further reveal the diatomite content on the properties of foam concrete, a series of performance indexes of foamed concrete under different diatomite content were measured by using the same method above. The test results are shown in Figures 18 and 19.

It can be seen from Figures 18 and 19 that, with the increase of the diatomite content, the dry density and compressive strength of the foamed concrete firstly increase and then decrease on the whole, while its water absorption keeps increasing. The reason for this change can be seen from SEM images of the foamed concrete in Figure 20, when the diatomite content is small, the number of pores in foamed concrete is small, and the shape of pores is relatively complete, so the dry density and compressive strength of foamed concrete show the trend of gradually increasing first. However, when the diatomite content is large, the amount and density of pores inside the foamed concrete are both large, which leads to the decrease of dry density and compressive strength of foamed concrete and the increase of water absorption. This indicated that the dosage of diatomite should not be too large, and the diatomite in a certain dosage range

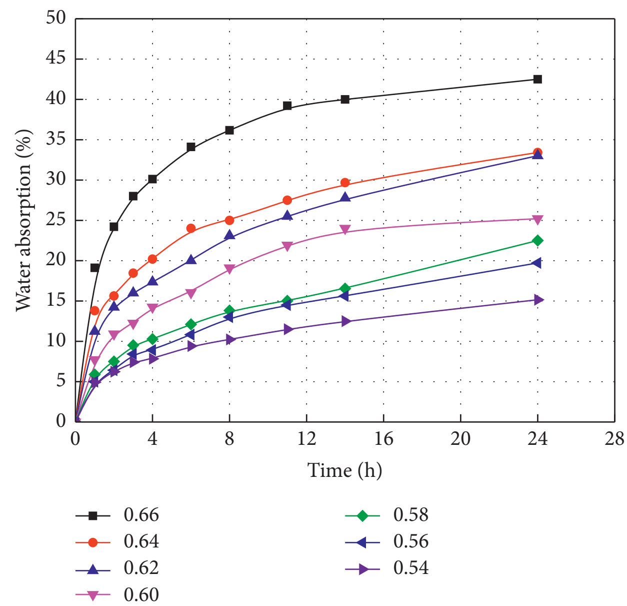


Figure 16: Water absorption of foamed concrete under different water-cement ratios.

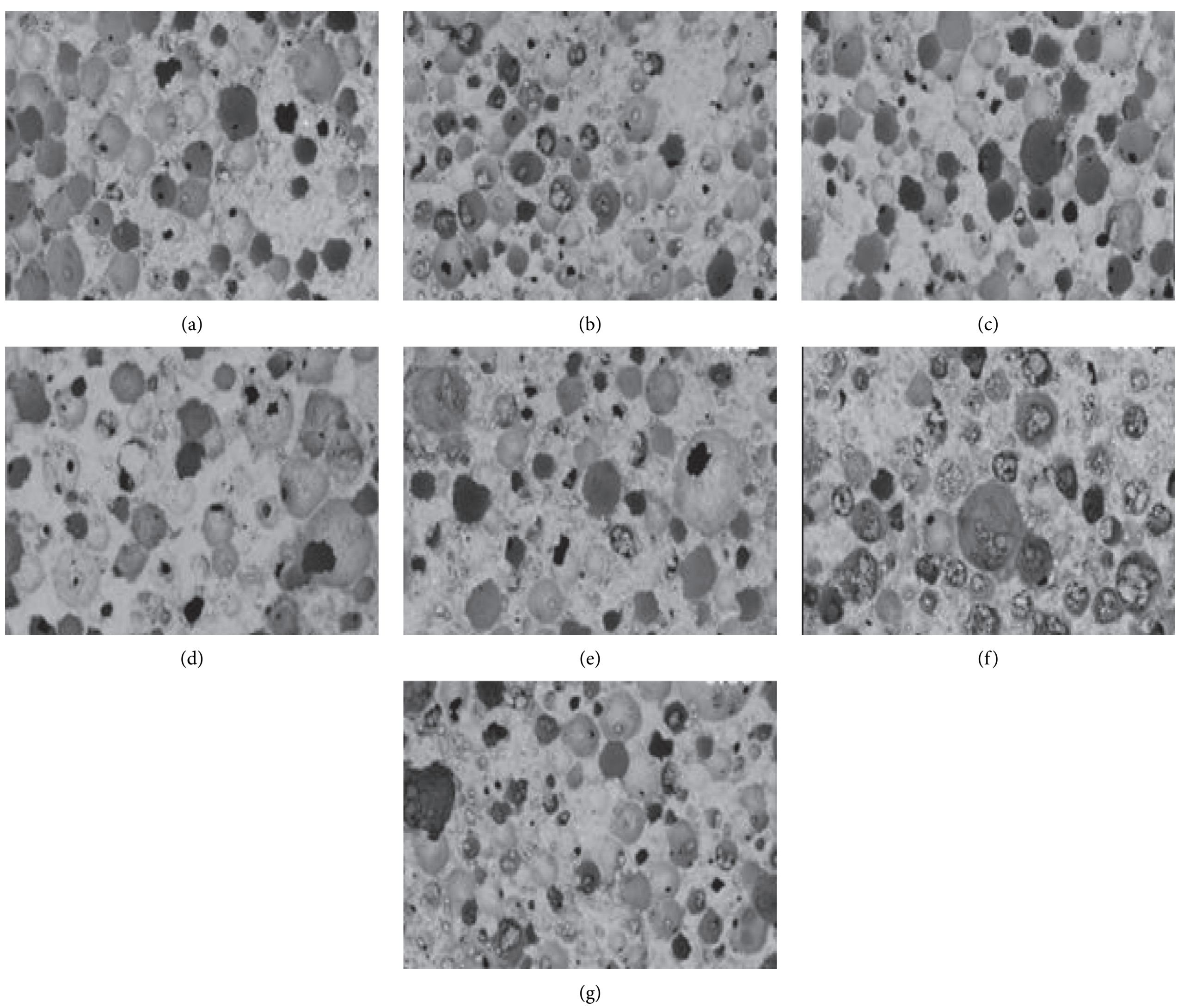


Figure 17: SEM images of foamed concrete under different water-cement ratios: (a) 0.54; (b) 0.56; (c) 0.58; (d) 0.60; (e) 0.62; (f) 0.64; (g) 0.66.

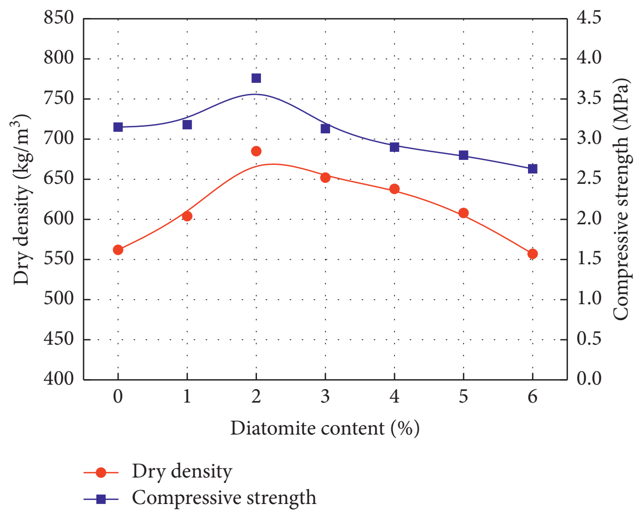


FIGURE 18: Dry density and compressive strength of foamed concrete under different diatomite contents.

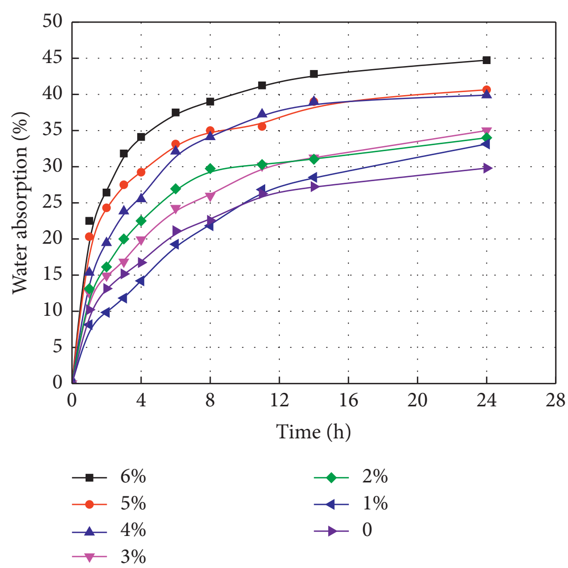


FIGURE 19: Water absorption of foamed concrete under different diatomite contents.

may have the effect of foam stabilization, which can improve the compatibility between the foam and the concrete slurry and increase the utilization rate of the foam. Therefore, it can be known from the above test results that the dosage of diatomite should be 3%, which is conducive to the preparation of high-quality foamed concrete with a density of $600 \pm 50\ kg/m^3$ and compressive strength of 3.0 MPa.

3.3.4. Response Surface Analysis of Compressive Strength. The above test results show that the volume of foaming agent solution (V), water-cement ratio (W/C), and diatomite content (R_D) have a great influence on the performance of foamed concrete. In order to further analyze the interaction of different factors on the compressive strength of foamed concrete, the response surface analysis was conducted on the basis of these three influencing factors, and the optimal ratio of these three factors was obtained with the experimental model, which further optimized the composition system of foamed concrete prepared with this new composite foaming agent. The test results are shown in Tables 6 and 7. As can be seen from Table 7, in addition to the single factor having a relatively large impact on the performance of foamed concrete, the interaction of AB, AC, and BC is also remarkable. Thus, the following regression equation can be obtained:

$$P = 3.97 - 1.11A + 0.63B - 0.50C - 0.41A \times B + 0.29A \times C + 0.42B \times C + 0.38A^2, \tag{1}$$

where P represents the compressive strength; A represents the water-cement ratio; B represents the diatomite dosage; and C represents the volume of foaming agent solution.

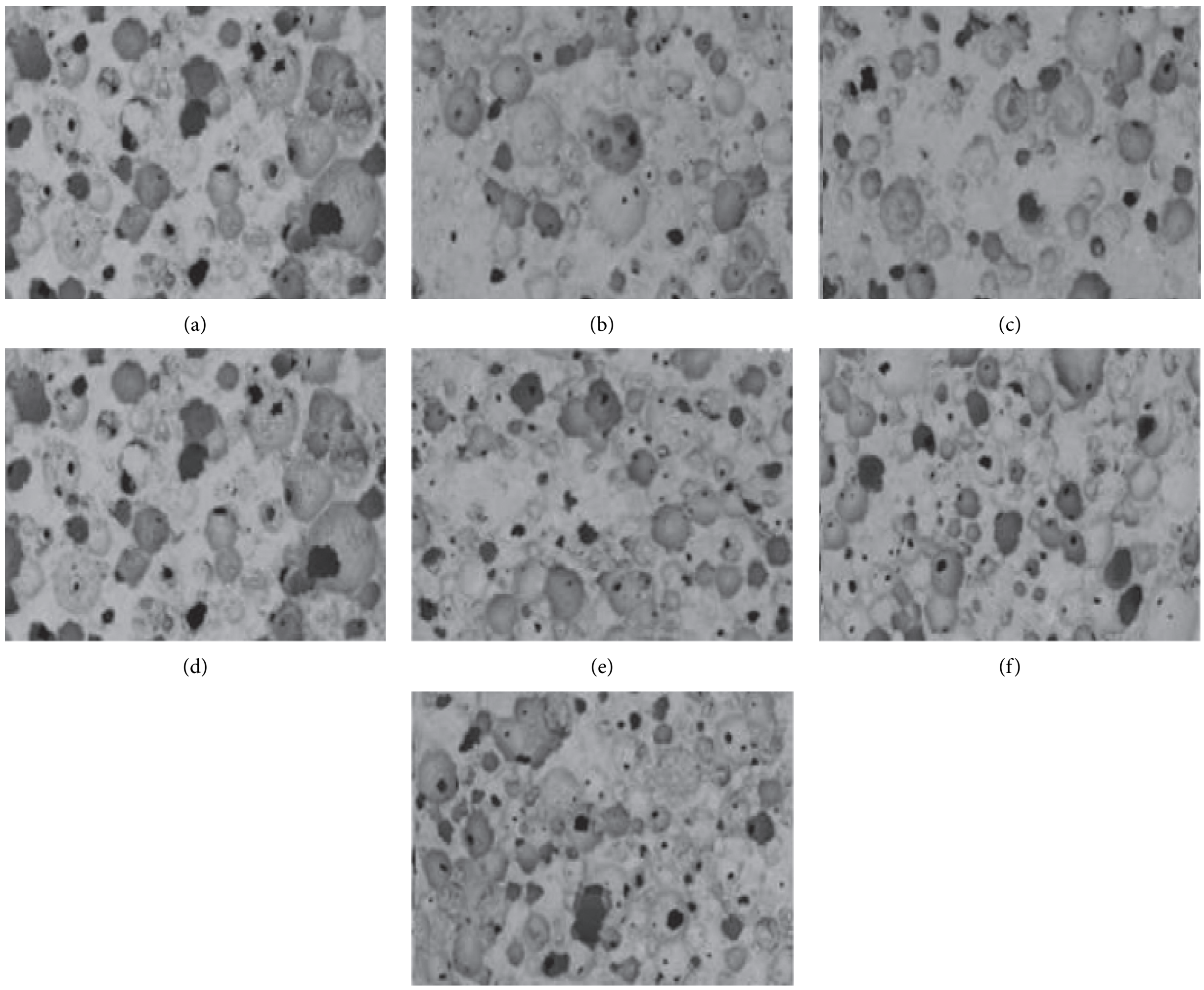


Figure 20: SEM images of foamed concrete under different diatomite contents: (a) 0; (b) 1%; (c) 2%; (d) 3%; (e) 4%; (f) 5%; (g) 6%.

Table 6: The response surface analysis of compressive strength.

Number	W/C	R_D (%)	V (mL)	P (MPa)	ρ_d (kg/m^3)	Absorption (%)
1	0.58	2.00	90	3.19	615.72	21.18
2	0.62	2.00	90	3.47	624.12	27.56
3	0.58	4.00	90	4.62	713.33	15.49
4	0.62	4.00	90	3.26	635.46	19.49
5	0.58	3.00	80	4.65	736.54	13.78
6	0.62	3.00	80	3.22	626.62	24.89
7	0.58	3.00	100	3.36	594.17	32.12
8	0.62	3.00	100	3.08	608.53	23.63
9	0.60	2.00	80	3.57	658.31	18.08
10	0.60	4.00	80	2.99	643.27	18.21
11	0.60	2.00	100	2.58	518.96	36.51
12	0.60	4.00	100	3.69	603.41	24.16
13	0.60	3.00	90	3.18	630.62	19.10
14	0.60	3.00	90	3.16	625.83	19.32
15	0.60	3.00	90	3.51	631.51	19.27
16	0.60	3.00	90	3.26	645.66	16.31
17	0.60	3.00	90	3.10	638.09	17.51

Table 7: The variance analysis.

Source	Sum of squares	df	*MS*	*F*-value	*P* value	Significance
Model	4.05	7	0.58	13.58	0.0004	Significant
A	1.15	1	1.15	26.92	0.0006	
B	1.05	1	1.05	24.73	0.0008	
C	0.67	1	0.67	15.79	0.0032	
AB	0.67	1	0.67	15.77	0.0032	
AC	0.33	1	0.33	7.75	0.0212	
BC	0.71	1	0.71	16.75	0.0027	
A^2	0.61	1	0.61	14.31	0.0043	
Residual	0.38	9	0.043			
Lack of fit	0.28	5	0.056	2.18	0.2346	Not significant
Pure error	0.10	4	0.026			
Total	4.44	16				

As can be seen from the results of the analysis, the significance of the regression model obtained from the response surface test is relatively good, while the lack of fit is not significant, indicating that the regression equation obtained is consistent with the actual situation, and can reflect the relationship between various factors and the compressive strength of foamed concrete. To sum up, through the test model in this paper, the composition ratio of foamed concrete is further optimized as follows: water-cement ratio is 0.60, diatomite content is 2.96%, and volume of foaming agent solution is 99.40 mL, which is conducive to the preparation of high-quality foamed concrete with a density of $600 \pm 50\,kg/m^3$ and compressive strength of 3.0 MPa. Combined with the actual application, it is finally determined that the water-cement ratio in the target foamed concrete is 0.60, the diatomite content is 3.00%, and the volume of the foaming agent solution is 100 mL.

4. Conclusion

In this paper, a new protein composite foaming agent was prepared by using the mixture of anionic surfactant (SCA), nonionic surfactant (APG), and foam stabilizer (AR). Through a series of tests and calculation analysis, the effects of different surfactant mass ratios and foam stabilizer concentrations on the properties of the composite foaming agent were studied, and high-quality foamed concrete was prepared on the basis of an optimized composite foaming agent system. The main conclusions are as follows:

(1) There is a reasonable critical value of SCA content for the composite foaming agent. The appropriate increase of SCA content is beneficial to enhance the stability of foam, ensure the number of bubbles generated by the composite foaming agent, and improve the uniformity of the foam particle size. However, when SCA content is too large, the foaming volume of the composite foaming agent would be greatly reduced.

(2) Based on the analysis of the foaming volume and foam stability, the optimal mass ratio of surfactants is determined as m_{SCA}: $m_{APG} = 1:2$, so that the composite foaming agent prepared in this paper has both excellent foaming ability and foam stability.

(3) As a foam stabilizer, xanthan gum concentration is closely related to the performance of the composite foaming agent. The stability of foam and the strength of foam film can be improved with the appropriate increase of the xanthan gum concentration, but the viscosity of the foaming agent solution would increase when the concentration of xanthan gum is too large, which affects the foaming difficulty of the composite foaming agent. The optimal dosage of xanthan gum is determined to be 0.5 g/L for this composite foaming agent.

(4) The volume of foaming agent solution, water-cement ratio, and diatomite content all have significant effects on the performance of foamed concrete. In a certain range, with the increase of foaming agent solution volume, water-cement ratio, and diatomite content, the dry density and compressive strength of foamed concrete both reduce in various degrees, while the water absorption rate of foamed concrete gradually increases. Among them, the proper increase of water-cement ratio is beneficial to improve the compatibility of foam and concrete slurry, and the proper increase of diatomite content can achieve the effect of stabilizing the foam. However, adding too much foam would increase the proportion of harmful holes, which is not conducive to the preparation of foamed concrete with excellent performance.

(5) Through the response surface analysis of compressive strength, the optimal proportion of three influencing factors is further determined: the volume of foaming agent solution should be 100 mL, the water-cement ratio should be 0.60, and the dosage of diatomite should be 3.00%, which provided a beneficial reference for the preparation of high-quality foamed concrete.

Abbreviations

APG: Alkyl glycoside
AR: Xanthan gum
df: Degree of freedom
K_t: Conductivity of the foam at that time

K_{max}: Maximum conductivity of foam
K_t/K_{max}: Relative conductivity of foam
m_{APG}: The mass of alkyl glycoside
m_{SCA}: The mass of sodium caseinate
m_1: The mass of cement
m_2: The mass of fly ash and diatomite
m_3: The mass of water
MS: Mean square
ρ_d: The dry density
P: The compressive strength
R_D: Diatomite content
RSA: Response surface analysis
SEM: Scanning electron microscope
SCA: Sodium caseinate
V: The volume of foaming agent solution
W/C: Water-cement ratio.

Data Availability

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

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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