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Study on Influence Factors of Compressive Strength of Low Density Backfill Foamed Concrete Used in Natural Gas Pipeline Tunnel

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Abstract: Foamed concrete is mostly used for backfilling of long-distance tunnels and compressive strength is an important technical index to control the quality of foamed concrete. The influence factors on compressive strength of low-density foamed concrete were obtained by the single factor test method based on the targeted dry density and compressive strength. The results show that the HT composed of pollution-free animal protein oil and vegetable oil is an efficient foaming agent and can produce stable foams. The cementation ability of cement can be fully expressed when a water to cement ratio of 0.45~0.5 is employed, making foamed concrete have a compressive strength higher than 2 MPa. The foam content is inversely proportional to the compressive strength and dry density of foamed concrete, and the volume ratio of slurry to foam should be 2:1~3:1. The content of fly ash is also inversely proportional to the compressive strength but positively proportional to the dry density. When the content of admixture is 40~55%, the compressive strength of foamed concrete with low density is not less than 2 MPa. The mixing proportion can be changed in the reasonable range to meet the requirements of different projects.

Keywords: foamed concrete; low density; compressive strength; admixture; slurry–foam ratio; water–cement ratio

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1. Introduction

As a new kind of porous material, foamed concrete has a dry density of 200~1300 kg/m^3 which has the characteristics of low self-weight. Improved foamed concrete can be used in road construction [1], backfilling [2,3] and other aspects. In recent years, landslide disaster caused by explosion accident from gas pipeline cracking and leaking occurs frequently, so it is very valuable to find a suitable protective material for gas pipeline. The backfill method was widely used to protect pipelines in practical engineering projects. The main filling materials now used between pipes are water, air and foamed concrete. Compared with the other two materials, foamed concrete has the advantages of anti-corrosion and convenient excavation and maintenance. Because of the fluidity of foamed concrete, it can be used in long-distance tunnel filling engineering. Using foamed concrete to fill shield tunnels can avoid a lot of economic losses caused by disasters. Existing studies have shown that foamed concrete has excellent properties such as light weight, heat preservation [4], heat insulation, low elastic, seismic resistance [5], and fire prevention [6]. There are also studies on the microstructure of foamed concrete [7]. It has been revealed that the compressive strength of foamed concrete is correlated with multiple factors, including its size and shape [8–10]. Huang Haijian et al. [11] studied the response of foamed concrete under impact load and found that foamed concrete had significant strain hardening and strain rate hardening characteristics, indicating that foamed concrete can reduce the seismic impact on the structure during earthquakes and the propagation speed of seismic waves, with strong seismic performance. At present, foamed concrete is mainly studied in terms of strength. Through an orthogonal test of foamed concrete, Ma Yongjionget al. [12] found that the water–cement ratio, fly ash and the content of cement all had an impact on the strength and density of foamed concrete. Shi C. et al. [13] discussed the influence of fly ash content on the thickness of hole walls in foamed concrete and explained the influence of fly ash in foamed concrete. Liu et al. [14] studied the relationship between the density and compressive strength of foamed concrete and discovered that the compressive strength increases exponentially with density. However, there are few studies on the backfilling of natural gas pipeline tunnels with foamed concrete. Considering the complex and diverse topography of the natural gas pipeline [15,16] and based on the existing research on the mix ratio of foamed concrete [17–23], the factors affecting the compressive strength of foamed concrete and the reasonable proportion range were given through the test of backfilled foamed concrete under natural gas pipeline tunnel in this paper.

2. Analysis of Engineering Background and Difficulties

The China-Russia east route natural gas transmission project (Yongqing-Shanghai) starts from Yongqing contact compressor station and ends at Baihe Terminal Station on the first line of west–east gas transmission. The total length of the pipeline is 1503 km.

At present, there is no specification for the mix ratio of foamed concrete for its strength and dry density, but different design principles and mix ratios are varied in different projects. In practical engineering, foamed concrete has many internal holes that facilitate the loss of water in the surface layer of foamed concrete, resulting in insufficient hydration and hardening. The resultant defects will directly lead to the reduction of strength and the surface layer is easy to peel off. Therefore, the reasonable water–cement ratio should be used to make cement give full play to its cementation ability.

Furthermore, the stability of foamed concrete slurry is not good enough, with a maximum pouring height of 40 cm, and higher pouring heigh will induce the collapse of foams. It is, therefore, necessary to select a high-quality foam agent to improve the stability of foamed concrete slurry to ensure that the foam has enough stability and is not easy to destroy. Additionally, appropriate preparation technologies and an appropriate number of admixtures are also necessary for this purpose. The compressive strength of low-density foamed concrete is low, generally less than 2 MPa. In order to meet the actual working conditions, the design strength of foamed concrete should not be less than 2 MPa. The density of foamed concrete for natural gas pipeline tunnel backfilling should be less than 1100 kg/m^3 to prevent the floatation of pipes. Therefore, the foamed concrete for the backfilling construction of the Yangtze River shield tunnel in the southern section of the China-Russia East Line should be designed carefully to address construction difficulties as mentioned above. To this end, in this paper, the influences of cement, water, admixture and foam ratio on the compressive strength of foamed concrete are studied. Based on these results, an optimized mixture design is recommended for the foamed concrete. The cross-section of the filled tunnel is shown in Figure 1, below.

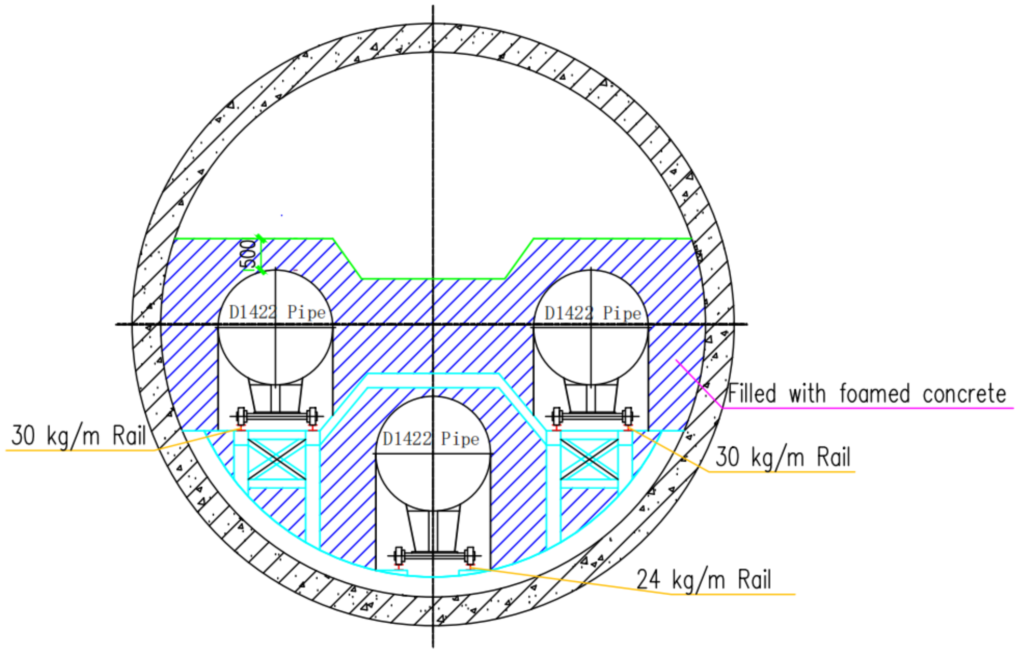


Figure 1. Layout in tunnel.

3. Experimental Section

3.1. Experimental Design

Using a single factor test, it is able to fine-tune the mixture's compressive strength, examine the results, and draw conclusions. The test scheme is as follows:

- The dry density of pre-designed foamed concrete is 1100 kg/m^3 and the compressive strength is greater than 2 MPa. By adjusting the mixing proportion of cement and admixture, the appropriate admixture content was determined;
- The foam content was determined by changing the mixing ratio of foam and cement slurry;
- The effect of different types of cement on compressive strength and dry density of foamed concrete was compared by changing the types of cement;
- The suitable foaming agent for foamed concrete was determined by changing the type of foaming agent and testing the compressive strength and dry density of foamed concrete.

3.2. Material

3.2.1. Cement

Cement is the main cementitious material in foamed concrete and also the main strength source of foamed concrete. If the hardened cement is not strong, the strength of foamed concrete cannot be guaranteed. P.O 42.5 (the compressive strength of standard maintaining for 28 d is 42.5 MPa) ordinary Portland cement and P.O 42.5 composite Portland cement were used in this test. Their basic properties are listed in Table 1.

Table 1. Physical properties of cements.

Number	Initial Setting Time /Min	Final Setting Time /Min	Bulk Density kg/m^3	Compressive Strength/MPa			Flexural Strength/MPa		
				3 d	7 d	28 d	3 d	7 d	28 d
Composite Portland cement	70	240	1175	19.2	29.2	48.2	3.5	5.0	7.2
Ordinary Portland cement	70	242	1137	18.5	28.0	47.0	3.6	5.1	7.3

3.2.2. Foaming Agent

Foam is the foundation of forming pores in foamed concrete. In order to obtain the stomatal structure that meets the technical requirements, the foam should be stable, uniform, with small diameter, low bleeding and inoffensive to the cementitious material. The foaming agent selected in this test included two types: foaming agent named HT and sodium dodecyl sulfate foaming agent. HT foaming agent is a compound foaming agent with high foaming rate and good mixing performance. Sodium dodecyl sulfate foaming agent is white and light-yellow powder. It has good foaming ability, but foam stabilizer is in need to overcome poor foam stability. The foam stabilizer used here is named FM-550 (a kind of modified silicone polyether microemulsion).

3.2.3. Fly Ash

Fly ash is a type of mineral admixture and can partially replace cement in concrete and improve the comprehensive properties of concrete. When a certain amount of fly ash is mixed into concrete, it will react slowly with $Ca(OH)_2$ precipitated in the hydration process of cement, and the particles between the filled aggregate will form a denser concrete structure as a result. It is more conducive to the formation of hydrated aluminum silicate which can make the later strength grow faster. The fine particles of fly ash are evenly distributed in cement slurry to fill the pores in the pore wall and improve the compactness, thus improving the strength and durability of foamed concrete. The fly ash selected in this test is class F fly ash from Nanjing Huaneng Power Plant which meets the requirements of "Technical specification for foamed mixing lightweight soil filling engineering" (CTJ/T177-2012) [24], and its chemical composition is as Table 2:

Table 2. Chemical compositions of fly ash.

Composition	ρ kg/m^3	SiO_2	Al_2O_3	CaO	Fe_2O_3
Content (%)	2400–2600	50.76	30.37	3.53	4.04

3.2.4. HTFC Admixture for Foamed Concrete

HTFC foamed concrete admixture used in this test was provided by Henan Huatai New Material Technology Co., LTD. It was the powders composed of two or more mineral admixtures in a certain proportion. When ordinary Portland cement is used and the water–cement ratio is greater than 0.4, the composite admixture accounts for 30% of the total amount of cementitious materials.

3.2.5. Addition Agent

The addition selected in this experiment is polycarboxylate superplasticizer owing to its advantage of small dosage, strong dispersion of cement particles, efficient water-reducing capabilities, and strong plasticity. It can effectively control the slump of concrete mixture to make the concrete have a better strengthening effect. However, the effect may vary in different types of cement, so compatibility tests should be performed prior to use. The information on polycarboxylate superplasticizer is summed up in Table 3.

Table 3. Technical index of polycarboxylate superplasticizer.

Appearance	Bulk Density/(g/L)	PH (20% Solution)	SO4^{2-} Content/%	Cl^- Content/%
White	500~600	6~8	2.6	0.01

3.2.6. Water for Mixing

In this test, the water used for mixing foamed concrete was Qingdao tap water which meets the requirements of the "Standard of water for concrete" (JGJ 63-2006) [25].

3.3. Preparation of Test Block

The procedures for preparation of the HT foam concrete are as follows:

- According to the predetermined mix ratio, dry mix cement, fly ash, and other dry materials were stirred for 1 min to make the dry materials evenly mixed;
- After mixing the dry ingredients evenly, water was added as the designed water–cement ratio and the mixture was then stirred for three minutes to form a uniform slurry (Figure 2);
- In the process of mixing cement slurry, foams were prepared. HT foam agent was firstly diluted by 20 times by adding water, and the foaming agent and water were evenly mixed. Then, the cement foaming machine was used to prepare the foam. Foam was used immediately after foaming;
- The foams were added to cement slurry, and the mixture was mixed evenly;
- The mixed foamed concrete was injected into the 100 mm × 100 mm × 100 mm triplet test mold, and the mold was removed 48 h later (Figure 3);
- The specimens were cured under 25 ± 2 °C and 70 ± 5% humidity. The compressive strengths were measured at 7 d, 14 d and 28 d, respectively.

(**a**) (**b**)

Figure 2. Cement mixing process: (**a**) cement net slurry mixing; (**b**) foamed concrete mixing.

(**a**) (**b**)

Figure 3. Cast in situ foamed concrete block: (**a**) pouring mold for concrete test block; (**b**) the test block is removed from the mold.

4. Test Implementation

The mixing proportion of foamed concrete was studied by the single factor analysis method. The foaming agent was HT foaming agent.

4.1. Mixing Proportion Design of Foamed Concrete

In the first group, the ratio of fly ash to cement was changed from 0.25 to 0.55. The appropriate fly ash to cement ratio was determined by the 28 d compressive strength and dry density of foamed concretes with different contents of admixture. Based on the dry density and 28 d compressive strength, the P1-2 was selected.

The ratio of slurry volume to foam volume (slurry foam ratio) was changed in the second group. The 28 d dry density and compressive strength of the second group of test blocks were measured, and the volume ratio of P2-4 slurry to foam was selected as 3:1.

In the third group, foamed concrete was used to change the water–cement ratio. The water–cement ratio of P3-3 was selected as 0.5 according to the measured 28 d compressive strength and dry density.

In the fourth group, the compressive strength and dry density of foamed concrete made of 42.5 ordinary Portland cement and 42.5 composite Portland cement were compared, so as to analyze the influence of cement varieties on foamed concrete.

Each group studies the effect of a specific variant on the properties of foamed concrete. In order to ensure a comprehensive analysis, two to four values were given to each variant.

The specific mixing proportion of foamed concrete (with a volume of 38 L) is shown in Table 4.

Table 4. Mixing proportion of foamed concrete (38L).

	Groups	Cement/kg	HTFC Amount/kg	Fly Ash/kg	Admixture Content	Water/kg	Water to Cement Ratio	Volume Ratio of Slurry to Foam
Change the amount of admixture	P1-1	27	8.1	0.9	0.25	16.2	0.45	1:1
	P1-2	21.6	6.48	7.92	0.4	16.2	0.45	1:1
	P1-3	16.2	4.86	14.9	0.55	16.2	0.45	1;1
Change the slurry–foam ratio	P2-1	21.6	6.48	7.92	0.4	16.2	0.45	1:2
	P2-2	21.6	6.48	7.92	0.4	16.2	0.45	1:1
	P2-3	21.6	6.48	7.92	0.4	16.2	0.45	2:1
	P2-4	21.6	6.48	7.92	0.4	16.2	0.45	3:1
Change the water–cement ratio	P3-1	21.6	6.48	7.92	0.4	14.4	0.4	3:1
	P3-2	21.6	6.48	7.92	0.4	16.2	0.45	3:1
	P3-3	21.6	6.48	7.92	0.4	18	0.5	3:1
Change cement type	P4-1	21.6	6.48	7.92	0.4	18	0.5	3:1
	P4-2	21.6	6.48	7.92	0.4	18	0.5	3:1

4.2. Test Results

The HT foaming agent was used to make 12 groups of specimens, with 12 test blocks for each group. These test blocks were used to test the compressive strength and dry density of the shield tunnel at 7 d, 14 d and 28 d under the simulated environment of the Yangtze River.

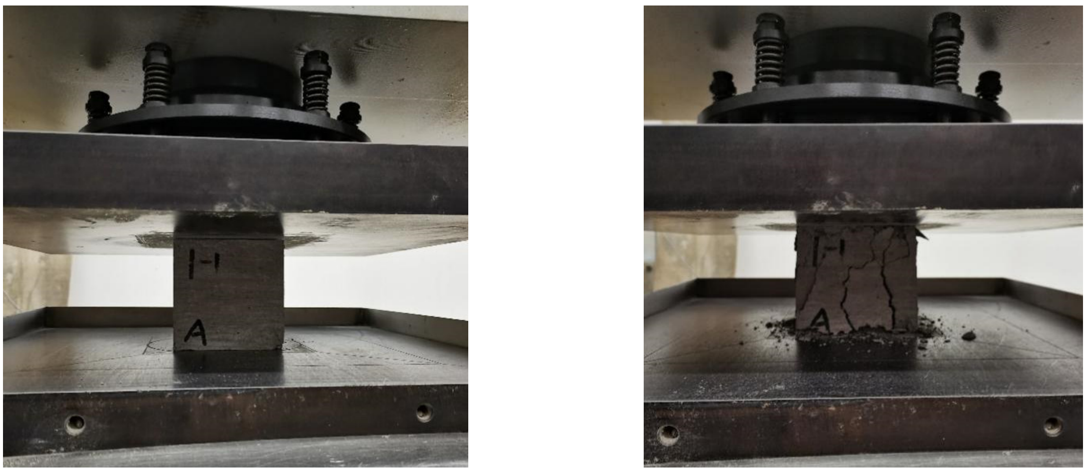
4.2.1. Measurement Steps

The specific measurement steps are as follows:

- The compressive strengths of the specimen at 3 d were not measured, because the early strengths of the test blocks were too small to be detected. At the age of 7 d, 14 d and 28 d, three test blocks in each group were taken out from the maintaining box, respectively, for the compressive strength test. The moisture on the surface was wiped dry, and the compression area of the test blocks was measured. At the same time, the dry densities of the 28 d foamed concrete test blocks were measured.

- The testing machine used in this compressive strength test was SANS microcomputer controlled electro-hydraulic testing machine (Figure 4). The foamed concrete test block was placed in the center of the downforce plate (the forming surface is not used as the force surface), and the test block was adjusted to remain in the center of the pressure plate. The height of the pressure plate was adjusted until it contacted the test block surface, and the lower plate was adjusted to ensure the test block was uniformly compressed.
- The compressive strengths of the test blocks were very small, so the load was applied continuously and uniformly at the speed of 2 kN/s (Figure 5). When the curve dropped rapidly, the loading was stopped, and the failure of the test block under pressure was observed. The loading force was then unloaded by controlling the displacement speed until the pressure value decreased to zero.

Figure 4. SANS microcomputer controlled universal testing machine, maximum load 30 T.



(**a**) (**b**)

Figure 5. Compressive strength test on blocks: (**a**) the test block before loading; (**b**) the test block after failure.

4.2.2. Test Details

Detailed test data are as follows in Table 5:

Table 5. Compressive strength and dry density in foamed concrete.

The Surrounding Environment of the Yangtze River Shield for Maintenance				
Num	**7 d Compressive Strength /MPa**	**14 d Compressive Strength /MPa**	**28 d Compressive Strength /MPa**	**Dry Density /kg/m^3**
P1-1	0.78	0.99	1.43	482
P1-2	0.65	0.87	1.25	540
P1-3	0.59	0.78	1.09	619
P2-1		collapse		
P2-2	0.65	0.98	1.28	551
P2-3	1.05	1.53	2.06	756
P2-4	1.23	1.67	2.56	953
P3-1	0.98	1.29	2.03	919
P3-2	1.22	1.48	2.59	1037
P3-3	1.29	1.57	2.71	1089
P4-1	1.42	1.61	2.82	1096
P4-2	1.44	1.65	2.86	1103

4.3. Analysis of Test Results

4.3.1. Influence of Fly Ash Content on Performance of Foamed Concrete

It is concluded that the dosage of cement is crucial to the strength of the foamed concrete by analyzing the 7 d, 14 d and 28 d compressive strengths of P1-1, P1-2, and P1-3 foam concretes that are cured under the simulated surrounding environment. The content of fly ash is negatively correlated to the compressive strength of foamed concrete. Because fly ash has a higher bulk density, the higher replacement of fly ash in foamed concrete makes the concrete denser, and the density of foamed concrete also increases with the increase in admixture content. When P1-2 is selected, the weight of fly ash accounts for 40% of the total dry material, the 28 d compressive strength is closer to the targeted compressive strength and dry density.

The relationship between compressive strength and dry density is shown in Figure 6.

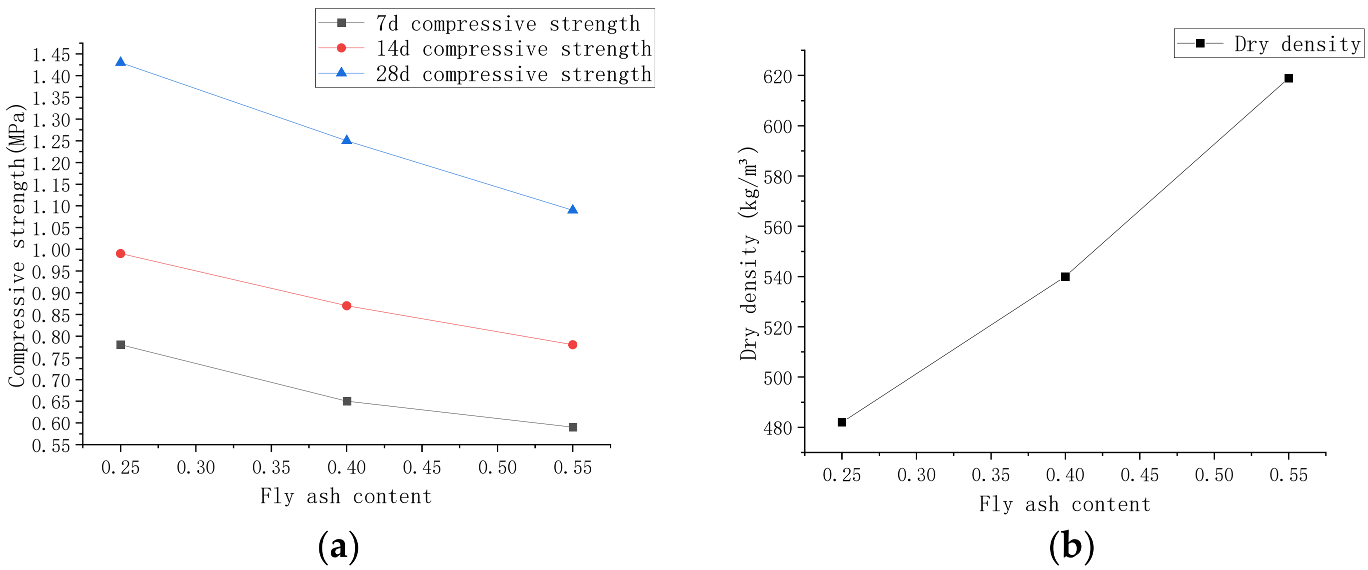


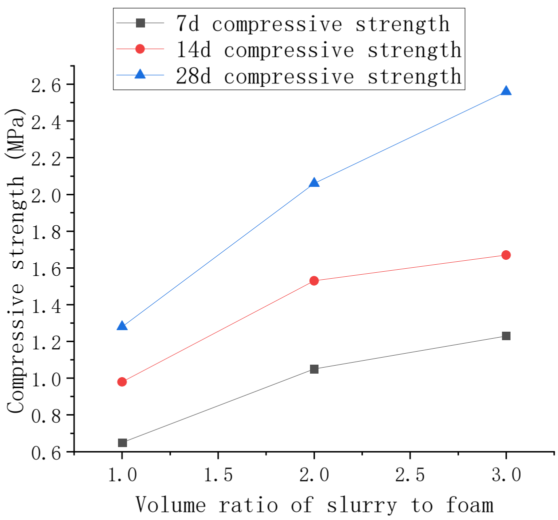
Figure 6. Effect of fly ash content: (**a**) effect of fly ash content on compressive strength; (**b**) effect of fly ash on dry density.

Based on the analysis of the experimental results, the reasons are as follows: when the proper amount of admixture is added into foamed concrete, the admixture plays its micro aggregate effect, form effect, pozzolanic effect and interface effect. When the admixture with a fineness less than that of cement is mixed into the slurry, it will be evenly dispersed in the slurry and fill the pores and capillary pores, which improves the structure of the pore wall, improves the strength of the pore wall and increases the density. The secondary hydration reaction makes the cementitious material and aggregate denser and improves the cohesion and compressive strength.

4.3.2. Effect of Volume Ratio of Slurry to Foam on Performance of Foamed Concrete

Through the experimental results of 28 d compressive strength of foamed concrete of P2-1, P2-2, P2-3 and P2-4 and the analysis of the compressive strength of foamed concrete of 7 d, 14 d and 28 d in the surrounding environment, it is concluded that the amount of foam has a great influence on the strength of foamed concrete. The greater the amount of foam, the denser the pores in the cement slurry, so that the compressive strength and density of foamed concrete decrease with the increase in foam content. The 28 d compressive strength of foamed concrete is closer to the designed compressive strength and dry density when P2-4 is selected, that is, the slurry–foam ratio is 3:1.

The relationship between compressive strength and dry density is shown in Figure 7.



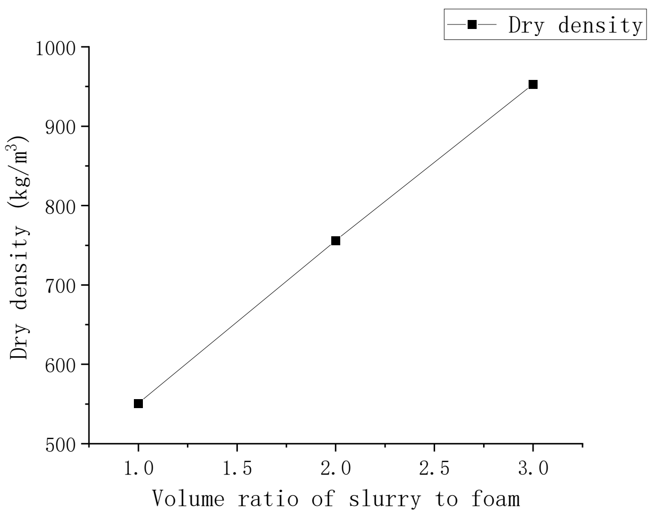


Figure 7. Effect of slurry–bubble ratio: (**a**) effect of slurry–bubble ratio on compressive strength; (**b**) effect of slurry–bubble ratio on dry density.

The introduced foams not only increase the dispersion of cement and avoids the cement agglomeration, but it also improves the fluidity of slurry, and therefore increases the workability of slurry. However, with the gradual increase in foam content, small foams connect to form larger foams, which hinders the gelation of slurry, impedes the development of compressive strength, and decreases the density of foamed concrete.

4.3.3. Influence of Water to Cement Ratio on Performance of Foamed Concrete

The effect of the water to cement ratio on compressive strength and dry density of foamed concrete is shown in Figure 8. It is concluded that the change of water to cement ratio has a great influence on the compressive strength of foamed concrete. When the water–cement ratio is low, cement cannot fully play its cementing role, resulting in the low strength of the test block. The dry density also increases with the increase in the water to cement ratio. When the water–cement ratio of P3-3 is 0.5, the 28 d compressive strength of foamed concrete is closer to the compressive strength and dry density of foamed concrete.

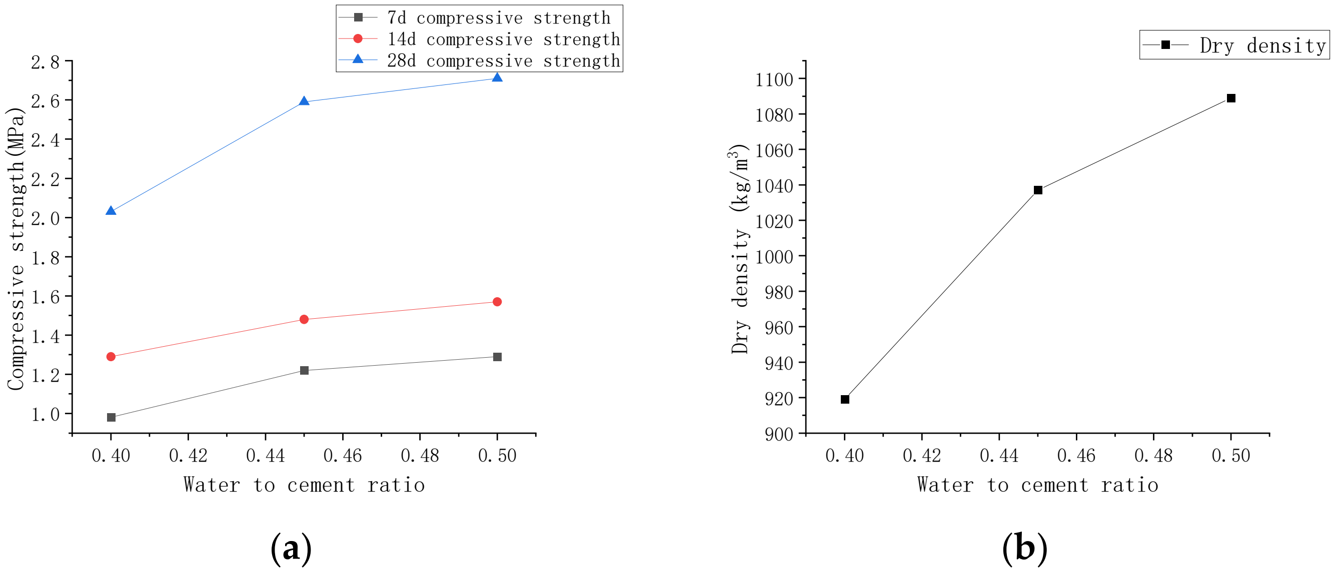


Figure 8. Effect of water to cement ratio: (**a**) effect of water to cement ratio on compressive strength; (**b**) effect of water to cement ratio on dry density.

Based on the analysis of experimental results, the reasons may be explained as follows. When a lower water–cement ratio is applied, the slurries composed of cement–fly ash–water become more viscous, and the introduced foams are very difficult to be dispersed homogenously in the slurries due to great friction to be overcome, and the foams are therefore deformed or even broken down, leading to uneven distribution of pore sizes. Cement skeletons, where large pores exist, are prone to collapse when subjected to an external load. As the water–cement ratio increases to 0.5, the viscosity of slurry decreases significantly and the fluidity of slurry improves. In the mixing process of slurry and foam, the foam is better dispersed into the slurry, and the foam is more easily to keep sphere shape in the slurry. Consequently, the test block has uniform pores, increased density and enhanced load-bearing capacity.

4.3.4. Influence of Cement Type on Performance of Foamed Concrete

It is found that ordinary Portland cement and composite Portland cement have little influence on the performance of foamed concrete. The compressive strength of the two kinds of cement decreases, respectively, by 1.38%, 2.48%, 1.42% and 0.63% in 7 d, 14 d, 28 d compressive strength and dry density which are within the standard deviation of 5% by analyzing the test results of foamed concrete of P3-3, P4-1 and P4-2 mix proportion.

4.3.5. Optimal Mixing Proportion

Through the tests on dry density and compressive strength of foamed concrete with varied contents of fly ash, cement type, foam proportion and water reducing agent dosage, the mixing proportion of P4-2 is finally selected. The recommended mixing proportion of 1 m^3 foamed concrete is shown in Table 6.

Table 6. Optimized mixing proportion of foamed concrete.

Dry Material /kg	Water–Cement Ratio	HTFC Content	Admixture Content	Volume Ratio of Slurry to Foam	Water Reducing Agent
948	0.45~0.6	30~40%	40~55%	2:1~3:1	0.05~1.5%

4.4. Foamed Concrete with Different Foaming Agents

4.4.1. Preparation and Maintenance of Test Blocks

The foamed concrete blocks are also prepared using sodium dodecyl sulfate as a foaming agent:

- According to the P4-2 mixing ratio, the dry material was mixed and the net cement slurry was prepared;
- The concentration of sodium dodecyl sulfate foam was 3 g/L, and the foaming factor was 20 times. The modified silicone polyether microemulsion was used as foam stabilizer to make the foam more compact and stable. The additional content of modified silicone polyether microemulsion was 2 g/L according to the instructions. The foams were prepared according to the above mixture ratio;
- The cement slurries and foams were mixed evenly according to the volume ratio of 1:1, and then the mixtures were injected into the 100 mm × 100 mm × 100 mm triplet test mold, and the mold was removed after 48 h. The specimens were cured under the same conditions as that of foamed concrete prepared with an HT foaming agent.

4.4.2. Test Data

The compressive strengths of foamed concrete test blocks with a foaming agent of sodium dodecyl sulfate were tested. The results were averaged and accurate to 0.01 MPa. The 28 d dry density of foamed concrete was measured. Table 7 shows the test results.

Table 7. Properties of foamed concrete block with twelve alkyl sulfate as foaming agent.

Number	7 d Compressive Strength/MPa	14 d Compressive Strength/MPa	28 d Compressive Strength/MPa	Dry Density kg/m^3
K12	0.7	1.08	1.59	509

4.4.3. Analysis of Test Results

The 28 d compressive strength of foamed concrete with sodium dodecyl sulfate as a foaming agent was rather low. The reason may be that the foams have poor stability and thus rupture before the cement slurry is hardened. In addition, the compatibility of foam and cement slurry is poor, and the foams cannot be well dispersed in the cement slurry. According to the damaged internal section of foamed concrete test block, the distribution of pores in K12 foamed concrete is sparse and uneven. In summary, sodium dodecyl sulfate is not recommended to be used as a foaming agent for foamed concrete.

5. Conclusions

The effects of two different foaming agents on the performance of low-density foamed concrete were tested. Compared with sodium dodecyl sulfate, the HT produces more stable foams that are more compatible with cement slurries, so it is suggested to use HT foamed concrete.

With the increase in foam content, the compressive strength and density of foamed concrete decrease gradually. The compressive strength of foamed concrete is higher than 2 MPa when the volume ratio of slurry to foam is controlled as 2:1 to 3:1.

The water–cement ratio is an important index in concrete mixing proportion. Reasonable water–cement can make cement fully hydrated so that foamed concrete can reach its designated compressive strengths. According to the test data analysis, the compressive strength of low-density foamed concrete can reach 2 MPa when the water–cement ratio is 0.45~0.5.

The main components of fly ash are SiO_2 and Al_2O_3, which will show cementitious activity under the action of strong alkali. In foamed concrete, $Ca(OH)_2$ continuously precipitates in the course of cement hydration and reacts with fly ash. When the admixture content is 40~55%, the compressive strength of low-density foamed concrete can reach 2 MPa.

In general, when the compressive strength of foamed concrete is higher than 2 MPa and the dry density is higher than 1100 kg/m^3, the pipes in the tunnel can be fully protected, which avoids a series of landslides caused by the leakage explosion of the gas pipeline.

Nevertheless, further research might be expected to be explored to optimize the mixing proportion of foamed concrete to deal with the difficulties in different engineering backgrounds. Because the raw materials of foamed concrete will have a direct impact on the performance of finished products, a reasonable change in the ratio of foamed concrete can make it have a wider range of performance to meet different engineering requirements. More attention can also be given to other ingredients in foamed concrete or the coupling effects of multiple factors.

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