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Research Article

Experimental Study on the Effect of Water on the Properties of Cast In Situ Foamed Concrete

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This study aims to investigate the effect of water on the properties of cast in situ foamed concrete with a dry density of 300–800 kg/m^3 (100 kg/m^3 is a gradient). Firstly, the shrinkage deformation with the curing time and the volumetric moisture content is studied by the drying shrinkage test and improved drying shrinkage test. Secondly, the influence of volumetric moisture content on mechanical properties is assessed. At last, the effects of immersion time and immersion type on the mechanical properties of foamed concrete are studied by considering the water-level conditions. The achieved results show that the shrinkage deformations increase with the curing time for the drying shrinkage test and the improved drying shrinkage test, while the variations are different. The shrinkage deformation increases with the decrease of volumetric moisture content for six dry densities of foamed concrete. Besides, it gradually changes in the early stage, while it changes fast in the later stage. The compressive strength and elastic modulus decrease with the increase of volumetric moisture content for each density. For the water-level unchanged condition, the compressive strength and elastic modulus initially decrease and then slowly increase with the increase of the immersion time. For the water-level changed condition, the compressive strength and elastic modulus of foamed concrete decrease with the increase of immersion time for each dry density, and the rate of early attenuation is high, whereas the rate of later attenuation is limited.

1. Introduction

Cast in situ foamed concrete is a new kind of geotechnical materials developed in recent years, mainly composed of cement, an admixture, and a proportion of stable tiny bubbles [1–3]. The foamed concrete is cast, molded, and cured at the construction site and possesses great advantages, involving low weight, convenient construction, stable performance, appropriate vertical stability, etc. [4–7]. The statistical results compiled by the China Concrete and Cement Products Association (CCPA) indicate that the annual production volume of foamed concrete was over 40 million m^3 in China in 2017. With the large-scale and extensive construction of structural and infrastructural systems, the industry has achieved annual growth of about 15%. Because the application time of foamed concrete is short, there are no corresponding technical specifications regarding the effect of water on the physical properties of cast in situ foamed concrete. As in the "Technical Specification for Foamed Concrete Application on Highway" (DB33T 996-2015) and "Specifications for Design of Highway Subgrades" (JTG D30-2015), the casting density is increased by 1.1–1.3 times when it is used under the water line.

When the "Test Methods of Autoclaved Aerated Concrete" (GBT 11969-2008) was revised by China Aerated Concrete Association (CACA), it was expressed that the linear deformation from casting state to natural dry state by the drying shrinkage test cannot be as the drying shrinkage value in the design. The actual drying shrinkage value is only part of it. Thus, the value of the drying shrinkage test cannot properly reflect the deformation of aerated concrete in practical engineering application, and it only expresses the material drying shrinkage performance. Combined with the working conditions of foamed concrete engineering, the working stage is between the natural dry state and immersion saturated state. When foamed concrete is used as filler, its deformation is the co-coupling function of multiple deformations. Combined with water absorption characteristics of the material itself and its application environment, foamed concrete material may be affected by underground and external water. The deformation characteristics and mechanical properties of foamed concrete will be affected by the content of water. When the material is repeatedly immersed and evaporated by the underground and the external water, the internal cracks of foamed concrete will increase by deformation. The durability of foamed concrete structure will be influenced by the repeated immersion and evaporation of moisture taking away gelling substance soluble in water, and thus lack of knowledge on the effect of water on the properties of foamed concrete is a major obstacle to its development.

As to the effect of water on the properties of cast in situ foamed concrete, the drying shrinkage experiment, the adsorption coefficient and the permeability coefficient test are mainly used in the related literatures. Drying shrinkage is one of main drawbacks of foamed concrete that occurs during the first month of casting time. The range of foamed concrete is between 0.1% and 0.35% [8]. Amran et al. [9] reported that the drying shrinkage decreased with the increase of aggregate and moisture contents. However, Jones and McCarthy [10] demonstrated that the foamed concrete with fine aggregate exhibited the largest shrinkage deformation due to higher mix water quantities (at equal w/c ratio), and this was expected to be smaller than that of 1400 kg/m^3 mixes, as reported in the literatures [11, 12]. Ramamurthy et al. [13] and Chindaprasirt et al. [14] recommended that the drying shrinkage could be maintained by minimizing the addition of the water to binder ratio, substituting Portland cement with other supplementary materials (fly ash, silica fume, and lime), and selecting a proper foam agent type at an appropriate volume.

The migration characteristics on behalf of the ability of gas and liquid go through foamed concrete. The adsorption coefficient and permeability coefficient can be used to evaluate the migration of water within the material. The permeability coefficient reflects the permeability of materials when the material is saturated, demonstrating the migration of water within the material. The adsorption coefficient reflects the internal moisture migration under the action of pressure in the direction of water seepage. However, the adsorption coefficient based on the unsaturated flow theory only is able to evaluate the moisture migration in unsaturated material. The adsorption coefficient and permeability coefficient mainly depended on the foam agent, type of mineral admixtures, density, and curing conditions [15]. Narayanan and Ramamurthy [16] reported that properties of foamed concrete (e.g., permeability, diffusivity, and shrinkage) were intimately related to its porosity and pore-size distribution. The critical pore diameter (from the MIP test) and the pore diameter size (>200 nm) were found to be closely correlated with the permeability of foamed concrete [17]. The effects of water on the deformation and mechanics performance of foamed concrete have not been mentioned.

In this study, firstly, the deformation characteristics are studied. The drying shrinkage test and improved drying shrinkage test are carried out to study the deformation with the variation of curing time and curing rule. The variation of the deformation with volumetric moisture content is studied when it is from the immersed saturated state to the natural dry state. Secondly, the influence of volumetric moisture content on mechanical properties is explored. At last, the effects of immersion time and immersion type on the mechanical properties of foamed concrete are studied by considering the water-level conditions.

2. Materials and Method

2.1. Materials. The foamed concrete is mainly made from ordinary Portland cement, water, and bubbles. The cement is Type I Portland cement conforming to GB 175-2007, and the water is tap water as well. The bubbles are made from a synthetic type of a foaming agent, which is highly eco-friendly and its air bubbles are enough strong [18, 19].

2.2. Mix Procedure of Foamed Concrete. For the preparation of foamed concrete slurry, the mix proportions and major parameters of foamed concrete are listed in Table 1. The mix procedure of foamed concrete is shown in Figure 1. Firstly, the bubbles were prepared, for which the density was controlled at $35 \pm 5\,kg/m^3$ [20]. Secondly, the cement and water were weighted and mixed according to Table 1. After this, the prepared bubbles were stirred with the cement slurry. Thirdly, qualified foamed concrete slurry was casted into the molds. Fourthly, the samples were demolded after 24 h to ensure that they were sufficiently hard for further handling. At the end, the samples were subjected to standard curing. There was a difference between theoretical dry density and measured dry density for each density of foamed concrete; however, that difference is small. For the convenience of analysis, the dry density is the theoretical dry density in the results and discussions.

2.3. Testing Method

2.3.1. Deformation Characteristics. At the beginning of practical engineering, the foamed concrete is at a fully closed state because the upper part of foamed concrete is covered with a plastic film. As the cement is hydrated, the foamed concrete comes under the composite effect of the rise of temperature and the shrinkage of chemical reaction, with the decrease of water content. With the increase of time, the plastic film will be removed or the adjacent structure is constructed. The temperature of the foamed concrete is converted to natural temperature by conduction. The water content of the foamed concrete is maintained at the constant value by conduction and volatilization.

For the test, the sample size is 400 mm long × 100 mm wide × 100 mm high. For the drying shrinkage test, the operation method is referred to the "Test Method of Autoclaved Aerated Concrete" (GBT 11969-2008). For the improved drying shrinkage test, the device was used as illustrated in Figure 2.

Before the pouring of the sample, a layer of oiled film was covered around the device to ensure that the sample deforms freely. When the sample was hardened, a hard

Table 1: Mix proportions and major parameters of foamed concrete.

Theoretical dry density (kg/m^3)	Water/binder	Water (kg/m^3)	Cement (kg/m^3)	Air bubbles (L/m^3)	Measured dry density (kg/m^3)	Flow value (cm)
300	0.75	180.0	240	762.5	300.10	16.5
400	0.68	217.6	320	685.2	398.72	16.7
500	0.61	253.2	415	625.5	496.76	17.2
600	0.56	271.6	485	581.5	596.55	17.5
700	0.53	302.1	570	525.5	694.26	16.4
800	0.52	353.6	680	437.6	793.56	17.7

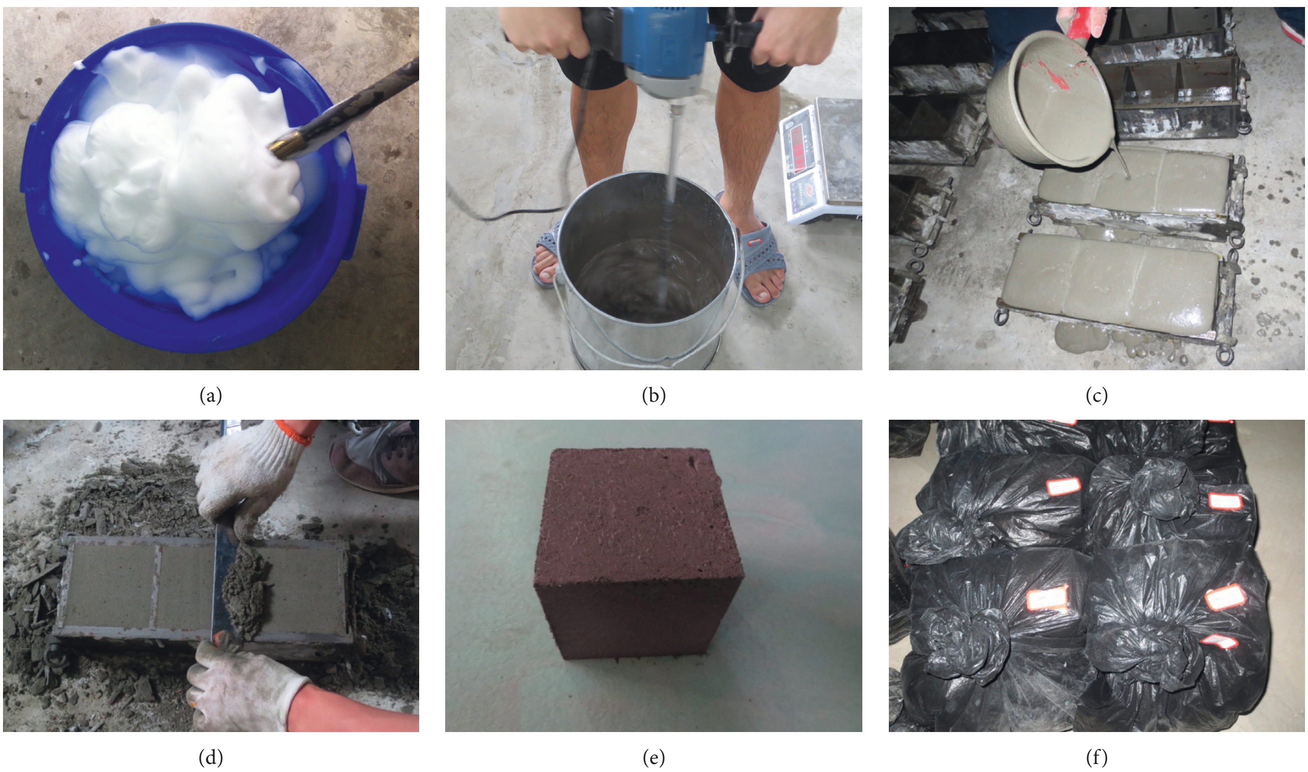


Figure 1: The process of the specimen preparation.

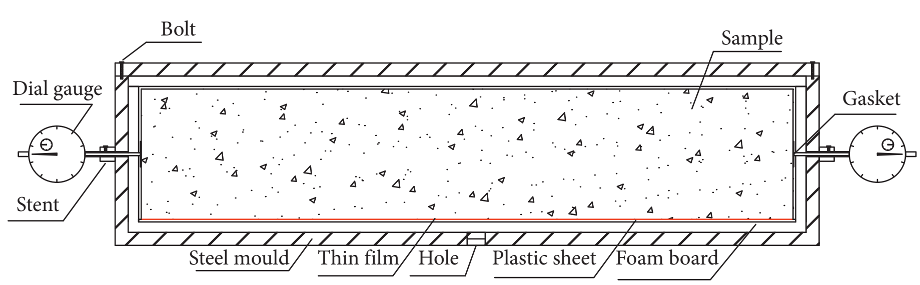


Figure 2: Expansion and contraction coupling device.

plastic gasket was installed on both ends of the sample center. After this, the testing was started. The test is divided into three steps. Firstly, the deformation was tested until 28 days after the casting when the sample was sealed. Secondly, the upper cover of the device was opened and the insulation foam boards on both sides of the device were removed. The deformation was tested until 90 days after the casting. Lastly, the sample was placed in a sink until the immersed saturation state is reached. The bottom hole of the device was opened, and the sample was placed in the device. The quality and the deformation of the sample were tested at different time. The variation of the deformation with volumetric moisture content can be conversed by the test results.

The volumetric moisture content was calculated using the following formula:

$$W_v = \frac{M_g - M_o}{V_o} \times \frac{1}{\rho_w} \times 100\%, \quad (1)$$

where W_v = volumetric moisture content (%); M_g = weight of the sample when tested (g); M_o = weight of the oven-dried sample (g), the value is four times the mass of the cube sample of the same mix; V_o = volume of the sample (cm^3); ρ_w = density of water (g/cm^3).

2.3.2. Moisture Content Influence Test. Eighteen identical samples (100 mm long × 100 mm wide × 100 mm high) were prepared for the dry weight test, casting with the drying shrinkage test and the improved drying shrinkage test at the same time. The test was divided into three parts, namely, dry quality test, quality test before compression test, and compression test. When the water content was between the standard curing state and immersed saturation state, the samples were immersed in the sink, as shown in Figure 3, by controlling the time to get different volumetric moisture contents. When the water content was between the standard curing state and the natural dry state, the samples were placed in dry air, by controlling the time to get different volumetric moisture contents.

When the quality test after absorbing water was conducted, in order to solve the outflow of water for the low density of foamed concrete causing the result to be smaller, the weight of the samples was measured suspending in water. For the water suspending weight test, the samples firstly were dried. After that, the dried samples were put in the sink. Adding water was slowly carried out until the surface of the water was above the samples surface within 30 mm. When the test time was reached, the total quality of tank and samples was tested. When a sample was removed, the total quality loss was M_1, and the added quality of the towel wiping the sample was M_2. The quality of the sample was $M_1 - M_2$.

2.3.3. Water Immersion Test. Sixty identical samples (100 mm long × 100 mm wide × 100 mm high) were casted for each mix proportion, and the fresh foamed concrete was prepared at a time. When the samples were cured for 28 days, half of the samples were used for the water-level unchanged condition and the other half were used for the water-level changed condition. For the water-level unchanged condition, the samples were put in the sink, keeping the surface of the water above the sample surface 30 mm until finishing the test. For the water-level changed condition, firstly, the samples were put in the sink for 6 hours, then the samples were put in the air for 12 hours, and lastly the samples were put in the sink for another 6 hours; thus, one cycle was completed.

For the three tests, the main test parameters are shown in Table 2.

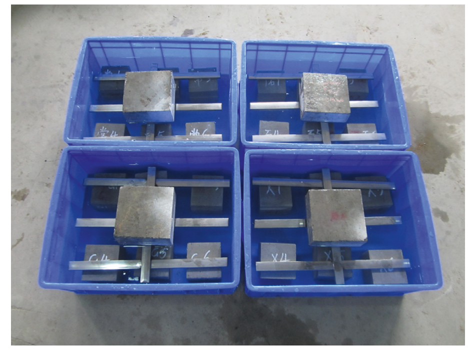


Figure 3: The samples immersed in the sink.

Table 2: The main test parameters for different tests.

Test types	The main test parameters
Deformation characteristics	The deformation value; curing time
Moisture content influence test	The volumetric moisture content; deformation value; compressive strength; elastic modulus
Water immersion test	Immersion time; compressive strength; elastic modulus

3. Results and Discussion

For the normal concrete, the mass moisture content is usually used as the parameter indicating the moisture content. The mass moisture content is calculated using the following formula:

$$W_m = \frac{M_g - M_o}{M_o} \times 100\%, \quad (2)$$

where W_m = mass moisture content (%).

The moisture contents of foamed concrete in different moisture states are shown in Table 3. It can be seen that the mass moisture contents of foamed concrete decrease with the increase of dry density for three moisture states. However, the volumetric moisture content increases with the increase of dry density in natural and standard states. The volumetric moisture content decreases with the increase of dry density in the immersed state. Compared with normal concrete, the densities of foamed concrete change largely by adding different volumes of air bubbles. Figure 4 shows a relationship between permeability and adsorption coefficients with dry density. The permeability coefficient decreases with the increase of dry density, indicating that the connecting holes reduce with the increase of dry density (Figure 5). The adsorption coefficient increases with the increase of dry density and with the increase of solids. For the natural dry state, the moisture content of foamed concrete stands for the ability of absorption, and thus the volumetric moisture content increases with the increase of dry density. For standard curing state, the volumetric moisture content was decided by the water/binder ratio and the consumption water of hydration reaction. For the low density of foamed concrete, the water/binder ratio is high and the consumption water of hydration reaction is low, while the volumetric moisture content is low. For the low density of foamed concrete in the immersion saturation state, the permeability coefficient and the pore content are both high, and the volumetric moisture content is high as well.

Table 3: The moisture contents of foamed concrete in different moisture states.

Dry density (kg/m^3)	Natural dry state		Standard curing state		Immersed saturated state	
	M content (%)	*V* content (%)	*M* content (%)	*V* content (%)	*M* content (%)	*V* content (%)
300	22.673	6.804	40.237	12.075	182.402	54.738
400	18.602	7.417	36.524	14.563	131.674	52.501
500	17.773	8.829	34.317	17.047	98.266	48.814
600	17.222	10.274	33.925	20.238	68.435	40.825
700	17.829	12.378	29.701	20.620	47.394	32.904
800	16.891	13.404	28.578	22.678	39.144	31.063

Note: *M* content denotes the mass moisture content; *V* content denotes the volumetric moisture content.

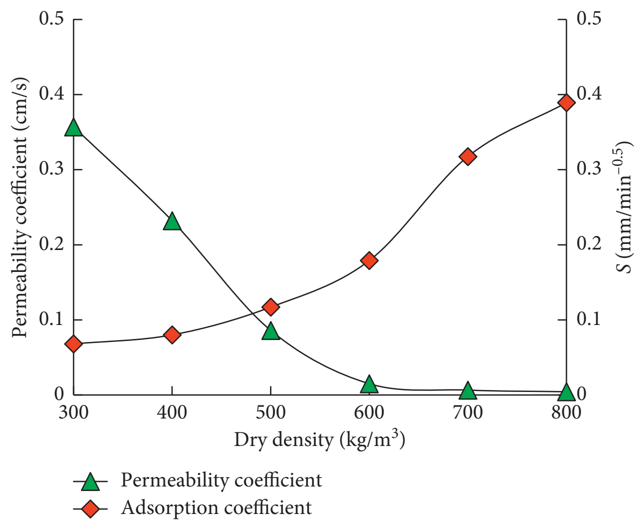
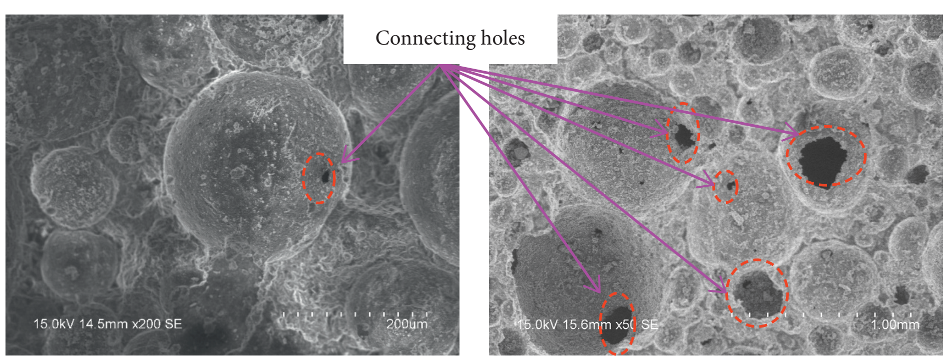


Figure 4: Relationship between permeability coefficient and adsorption coefficient with dry density.



(a) (b)

Figure 5: Comparative connecting holes in (a) high and (b) low casting density foamed concrete.

On the whole, the rate of mass water absorption cannot accurately reflect the degree of water absorption, while the volumetric moisture content precisely reflects the degree of water absorption accurately.

3.1. Variation of Shrinkage Deformation with Curing Time. The relationship between shrinkage deformation and curing time of six densities of foamed concrete is depicted in Figure 6. The results demonstrate that the shrinkage deformation value increases with the growth of the curing time for every dry density. The early growth is fast, and the growth of shrinkage deformation gradually decreases. The shrinkage deformation value is stable at the end. The final shrinkage deformation of foamed concrete decreases with the increase of dry density. The development of speed of shrinkage deformation and the time of development are correlated with the dry density of foamed concrete. With the increase of dry density, the shrinkage development speed decreases and the time to reach the stable state becomes longer. For the dry density of 300 kg/m^3, the stable shrinkage deformation is 3.502 mm/mm and the time is 45 days. However, for the dry

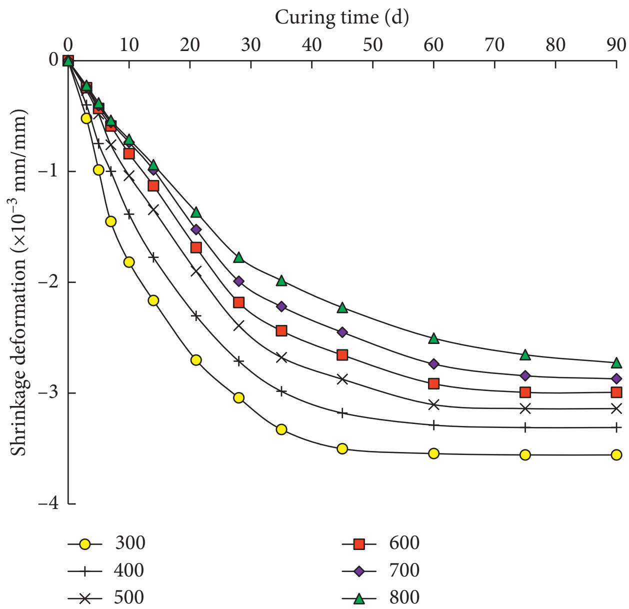


Figure 6: Relationship between shrinkage deformation and curing time.

density of 800 kg/m^3, the stable shrinkage deformation is 2.654 mm/mm, and the time is 75 days. For the reason, on the one hand, the hydration of foamed concrete generally requires water. The hydration speed is fast at the early stage, while the hydration is slow in the later stage. On the other hand, in the early stage, the hydration products are small, the structure is loose, and the water is more easily evaporated. With the increase of time, the degree of hydration reaction is completed. The structure is accordingly more compact. The strength of the hole wall and the ability of resistance to deformation both increase. The moisture content of the sample is in balance with the external environment, and the shrinkage deformation is stable as well.

For the improved drying shrinkage test, the relationship between shrinkage deformation and curing time is plotted in Figure 7.

As shown in Figure 7, it can be seen that the shrinkage deformation of stages 1 and 2 rapidly increases in the early stage and then tends to be stable. With the increase of dry density, the stable shrinkage deformation increases and the time to reach a stable state becomes shorter in stage 1. While in stage 2, with the increase of dry density, the stable shrinkage deformation decreases and the time to reach a stable condition becomes longer. The reason is that the maximum temperature of the hydration heat increases and the rate of hydration reaction increases with the increase of dry density. When the sample is completely sealed, the shrinkage deformation of the sample is mainly controlled by chemical shrinkage. In addition, with the increase of dry density, the time to reach a stable condition becomes shorter. Simultaneously, with the increase of the dry density, the cement content and the deformation of chemical shrinkage both increased. For stage 2, the shrinkage deformation is mainly controlled by dry shrinkage deformation. With the increase of dry density, the ability of water vapor to pass decreases, and the time of stable shrinkage deformation increases. At the same time, with the increase of the dry density, the water-cement ratio used in the mixing of foamed concrete slurry decreases, and the amount of water evaporation reduces as well, when the dry shrinkage deformation is stable. As the water in the foamed concrete pores escapes, the radius of meniscus in the pores becomes smaller. The surface tension of the liquid surface in the pore increases, leading to the compression stress pointing to the center. When the stress is generated, the deformation is reduced with the increase of dry density and the increase of the elastic modulus.

Compared with Figure 6, the pattern of variation of the shrinkage deformation and the curing time is different; however, the final value is very close for the same density. Besides, it can be seen that the shrinkage deformation of stage 1 accounted for only 20.7% to 46.0% in the dry shrinkage test, when the moisturizing measures are perfect. Hence, it is shown that retaining the moisture content of the foamed concrete is one of the key techniques to deal with the shrinkage deformation of foamed concrete in the working condition.

3.2. Variation of Deformation with Volumetric Moisture Content. The relationship between deformation and volumetric moisture content is obtained by conversing as depicted in Figure 8. It is assumed that the sample is always sealed after pouring, and the state is defined as a sealed state. The relationship between dry density and volumetric moisture content at sealed and immersed saturation states is shown in Figure 9.

In combination with Figures 8 and 9, it can be seen that the deformation increases with the decrease of volumetric moisture content for six dry densities of foamed concrete. For each density, it slowly changes in the early stage, while it rapidly varies in the next stage. For the early stage, the time is short and the deformation is small as well. The deformation is mainly caused by the decrease of the water inside the connecting hole. While for the late stage, the deformation is caused by the decrease of the water inside the capillary hole. The time is long and the deformation is large. Thus, the mechanism of controlling the change of water inside the capillary hole is a major issue to control the shrinkage deformation of foamed concrete structure. With the increase of dry density, the volumetric moisture content corresponding to the deformation jump increases because the amount of the capillary hole for the low dry density of foamed concrete is less than that of the high dry density. Thus, for the stable condition of foamed concrete, the volumetric moisture content for high dry density is higher than that for the low dry density. For the sealed state, the corresponding volumetric moisture contents are 12.08%, 14.56%, 17.05%, 20.24%, 20.62%, and 22.68% for the dry densities of 300, 400, 500, 600, 700, and 800 kg/m^3. When these data correspond to the relationship between deformation and volumetric moisture content, it was revealed that they are all in the slow phase of deformation. Therefore, regarding the deformation index for foamed concrete,

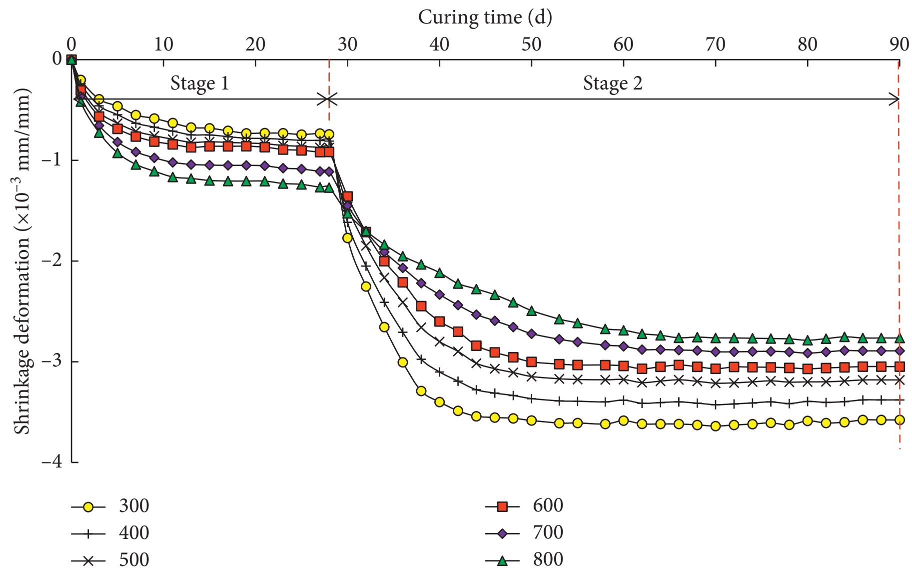


Figure 7: Relationship between shrinkage deformation and curing time (the improved drying shrinkage test).

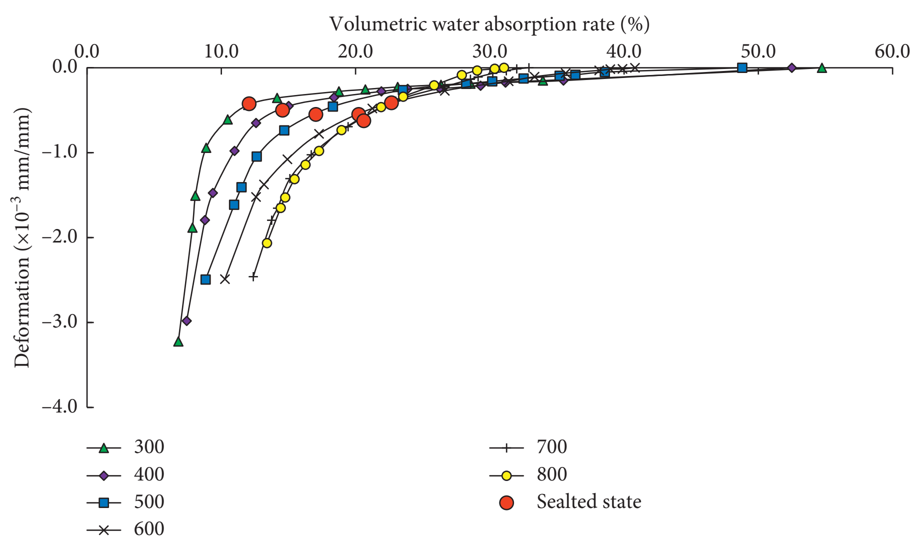


Figure 8: Relationship between deformation and volumetric moisture content.

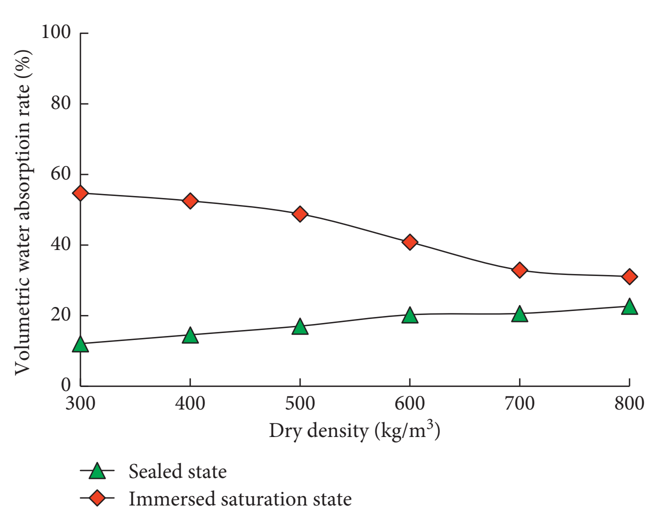


Figure 9: Relationship between dry density and volumetric moisture content at different water contents.

microexpansion will appear when the humidity increases. Moreover, large shrinkage appears without perfect protection measures, when it is in the dry state for a long time.

3.3. Effect of Volumetric Moisture Content on Mechanical Properties. The mechanical properties of foamed material mainly depend on the types of holes: open hole or closed hole. When the density is low, the deformation of open foam material is mainly caused by the bending of the hole wall. With the increase of density, the axial tension and compression of the pore wall play a significant role [21]. When the foam material contains liquid, for the open cell foam material, the elastic modulus of the material increases based on the fluid rheology when the fluid viscosity is high or the deformation rate is enough large. For the close cell foam material, the elastic modulus of the material increases by the deformation mechanism, the extension of the empty mask, and fluid compression inside the cavity [22].

For different densities and moisture states of foamed concrete, the compression test is conducted to study the effect of volumetric moisture content on compressive strength and elastic modulus, as shown in Figure 10. For each curve, the first point stands for the natural dry state, the third point stands for the standard curing state, and the last point stands for the immersed saturated state.

As illustrated in Figure 10(a), the achieved results show that the compressive strength decreases with the increase of volumetric moisture content for every density. The compressive strength clearly decreases when the moisture state changes from the natural dry state to the standard curing state. In addition, the compressive strength gradually decreases when the moisture state varies from the standard curing state to the immersed saturated state. For the same dry density of foamed concrete, the compressive strength in the immersed saturation state is about 0.86–0.89 times of that in the standard curing state. However, the compressive strength in the natural dry state is about 1.27–1.40 times of that in the standard curing state. Thus, the moisture content of the foamed concrete has an obvious effect on the compressive strength, which reduces or increases the compressive strength coefficient in combination with the practical environmental application.

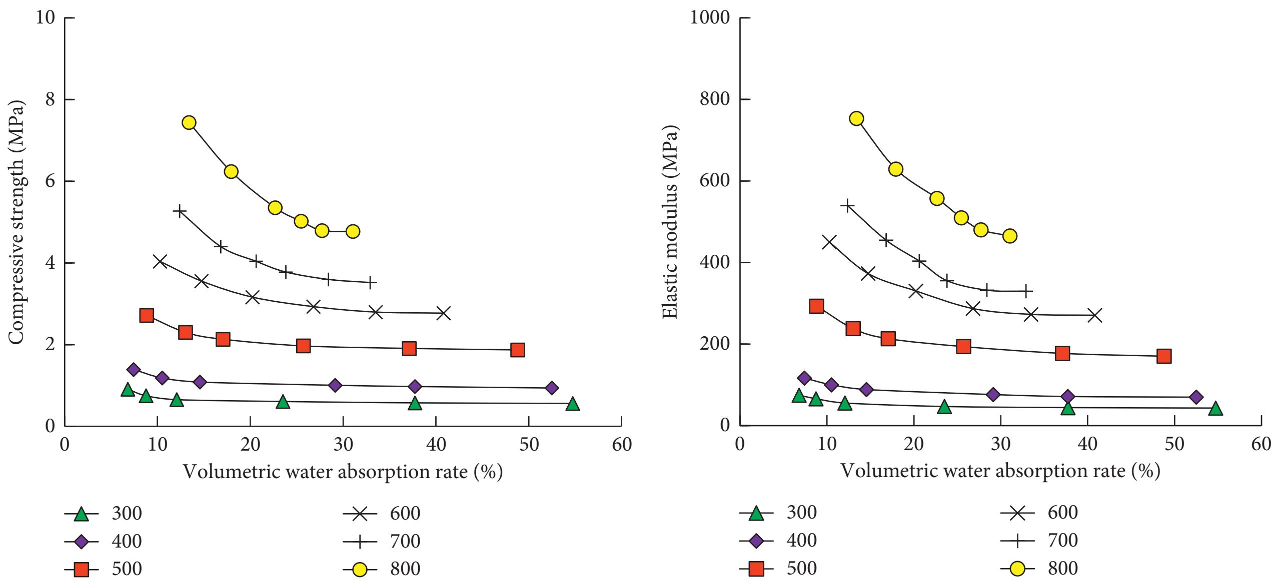
As depicted in Figure 10(b), it can be seen that the elastic modulus decreases with the increase of the volumetric moisture content for every density. For the same dry density of the foamed concrete, the elastic modulus in the natural dry state is roughly 1.32 to 1.38 times of that in the standard curing state and the elastic modulus in the immersed saturation state is about 0.78 to 0.84 times of that in the standard curing state.

The reason is that the applied rate of load is slow in the compression test. The water can pass through the gel pores. The effect of water reduces the Van der Waals force between particles. The particles of the foamed concrete are separated in different directions by the forces, and thus the cohesion between particles reduces, leading to the decrease of the compressive strength [23]. Simultaneously, the water pressure in the foamed concrete pore is equal to the wedge under the static load, resulting in reducing the strength of the material [24]. Therefore, the compressive strength and the elastic modulus decrease with increase of the volumetric moisture content for the same dry density of the foamed concrete under the compound actions. Combined with the deformation mechanism of foam material, the elastic modulus should increase with the volumetric moisture content. While in the test results, that phenomenon did not appear for every density. As the applied rate of the load is slow, the adverse effect of water on the mechanical parameters plays a major role. As a result, the elastic modulus gradually decreases with increase of the volumetric moisture content.

3.4. Effects of Immersion Time and Immersion Type on Mechanical Properties. In combination with foamed concrete in the actual working condition, long-term immersion tests were conducted including the water-level changed condition and the water-level unchanged condition.

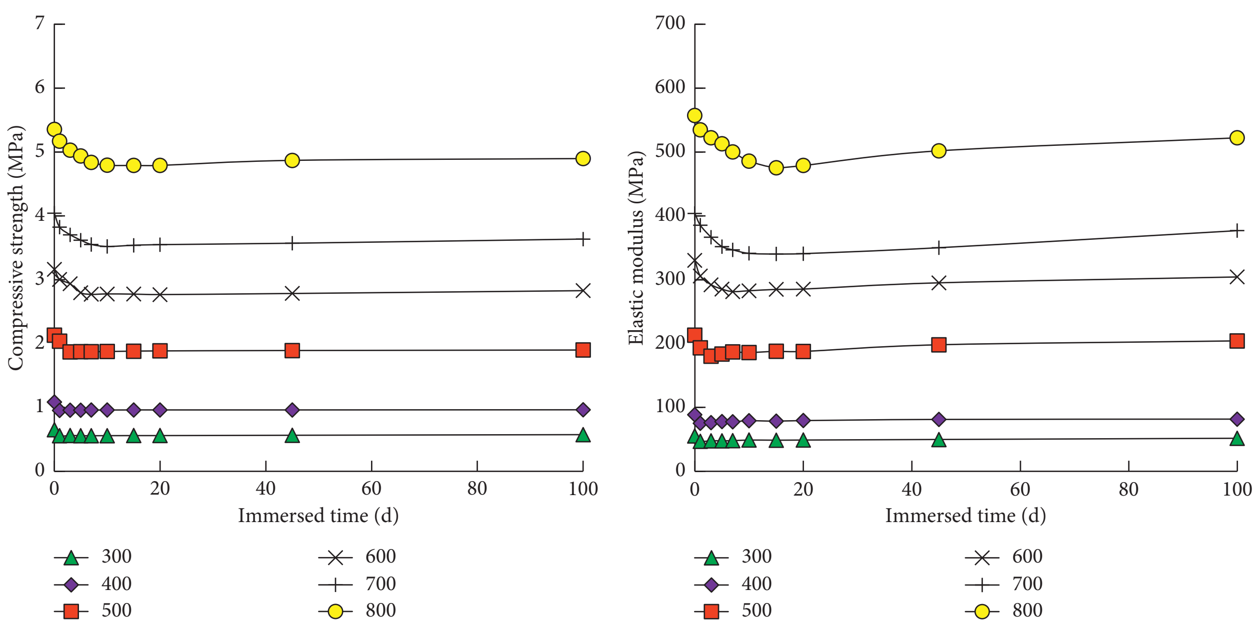
Figure 11 shows the effect of immersion time on the compressive strength and the elastic modulus in the water-level unchanged condition. The results demonstrate that the compressive strength and the elastic modulus initially decrease and then slowly increase with the increase of the immersion time. There is a turning point for the dry density of 300–800 kg/m^3 (100 kg/m^3 is the gradient), the corresponding time is 1, 3, 5, 7, and 15 day(s), and the corresponding time of the turning point increases with the increase of dry density. For the turning point of every density of foamed concrete, the corresponding compressive strength is 0.556, 0.953, 1.870, 2.796, 3.552, and 2.788 MPa, respectively, which is 85.3%, 88.0%, 87.7%, 88.4%, 87.9%, and 89.4% of that in the standard curing state, respectively. For the elastic modulus, the corresponding values are 47.1, 75.2, 180.1, 285.2, 346.7, and 475.3 MPa, respectively, which are 85.0%, 85.0%, 84.5%, 86.4%, 85.9%, and 85.3% of that in the standard curing state, respectively. In the water-level unchanged condition, the compressive strength and the elastic modulus are more than 80% of that in the standard curing state, reflecting that the foamed concrete possesses a satisfactory durability.

Figure 12 shows the effect of immersion time on the compressive strength and the elastic modulus in the water-level changed condition. The compressive strength and the elastic modulus of foamed concrete decrease with the increase of immersion time for each dry density, and the rate of the early attenuation rate is high, while the rate of the later attenuation is low. After 100 cycles of immersion, for the dry density of 300–800 kg/m^3 (100 kg/m^3 is the gradient), the corresponding compressive strength is 0.336, 0.616, 1.421, 2.567, 3.366, and 4.525 MPa, respectively, which is 51.5%, 56.9%, 66.7%, 81.2%, 83.3%, and 84.5% of that in the standard curing state, respectively. For the elastic modulus, the corresponding values are 35.2, 59.1, 147.5, 265.1, 329.5, and 458.2 MPa, respectively, which are 63.5%, 66.8%, 69.2%, 80.3%, 81.5%, and 82.2% of that in the standard curing state, respectively. The strength ratio and the elastic modulus ratio



(a) (b)

Figure 10: Effect of volumetric moisture content on (a) compressive strength and (b) elastic modulus.



(a) (b)

Figure 11: Effect of immersion time on (a) compressive strength and (b) elastic modulus (the water-level unchanged condition).

of foamed concrete increase with the increase of dry density in the water-level changed condition, and the compressive strength ratio is more than 80% when the dry density is more than 600 kg/m^3.

Compared with Figure 11(a), for the same dry density of foamed concrete, the compressive strength and the elastic modulus in water-level unchanged condition decrease faster than those in the water-level changed condition. Besides, the phenomenon remarkably decreases when the dry density is more than 600 kg/m^3. The reason is that the hydration product $Ca(OH)_2$ can be dissolved in water for the long-term water immersed test (Figure 13), compared with the moisture content influence test, leading to the decrease of the mechanical parameters of foamed concrete. For the water-level unchanged condition, the dissolution rate would reduce or stop with the increase of the concentration of $Ca(OH)_2$ in water. The dissolution phenomenon will go on decreasing forever in the water-level changed condition. Foamed concrete has not been fully hydrated when the curing time is 28 days. The mechanical parameters increase with the increase of immersion time. Simultaneously, the change of the volumetric moisture

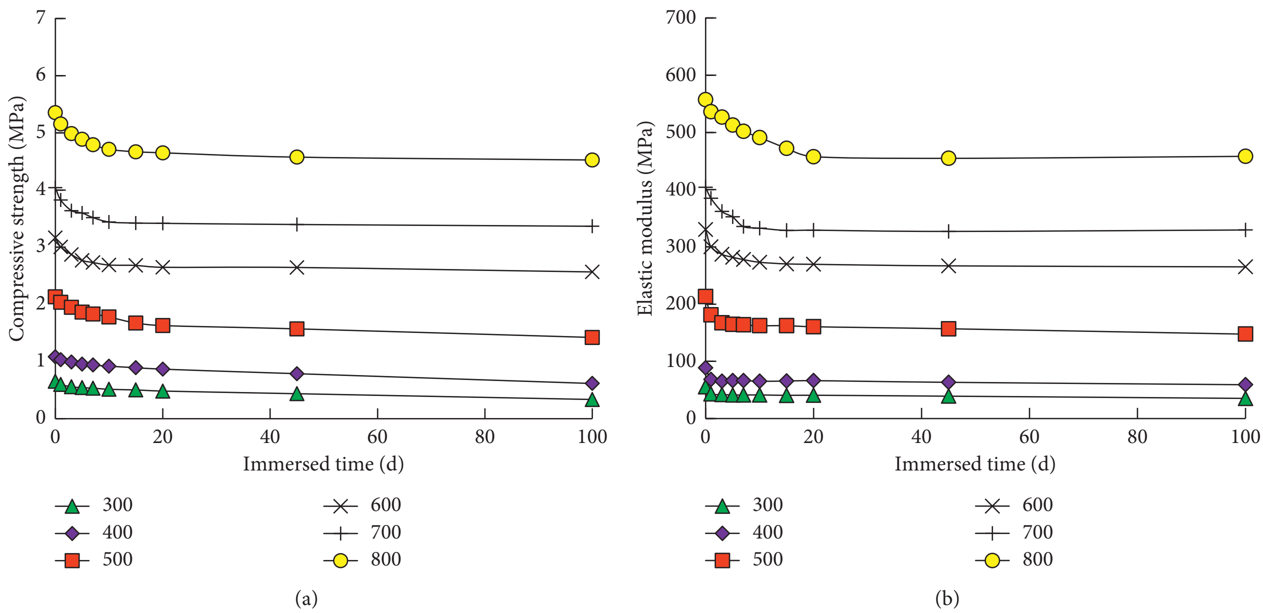


FIGURE 12: Effect of immersion time on (a) compressive strength and (b) elastic modulus (the water-level changed condition).

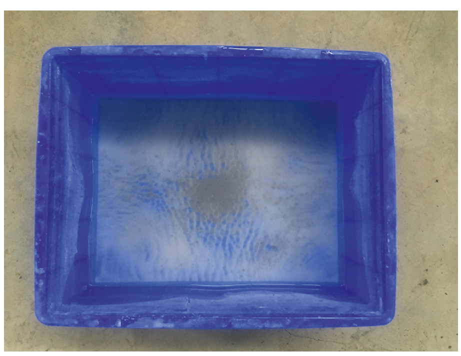


FIGURE 13: The phenomenon of $Ca(OH)_2$ dissolving in water.

content could affect the mechanical parameters of the foamed concrete in combination with analyses of the effect of volumetric moisture content on mechanical properties of foamed concrete.

Under the coupling action of various factors, for the water-level unchanged condition, the mechanical parameters of the foamed concrete rapidly decrease with the immersion time in the early stage. This is because the effect of the moisture content on foamed concrete plays a crucial role. When the foamed concrete is in the immersion saturation state, the moisture content cannot increase as the internal gas cannot be discharged with the increase of the viscous forces. Then, the dissolution of $Ca(OH)_2$ and the further hydration are the main factors influencing the mechanical parameters. When $Ca(OH)_2$ is saturated, further hydration is dominant, and the mechanical parameters increase slightly in the later stage.

For the water-level changed condition, the mechanical parameters decrease more rapidly than those for the water-level unchanged condition in the early stage of the water immersion test, due to the role of circulating water, accelerating the saturation of water and reducing the saturation time. The mechanical parameters also decrease with the immersion time in the later stage with the dissolution of $Ca(OH)_2$. When the dry density of foamed concrete is between 300 and 500 kg/m^3 with the high permeability coefficient, the mechanical parameters are apparently reduced due to the variation of water and the water inside the sample discharges, accelerating the dissolution of $Ca(OH)_2$. When the dry density is more than 600 kg/m^3, the phenomenon of water discharging occurs. The attenuation of mechanical parameters was not very tangible because the dissolution of $Ca(OH)_2$ just appears at the surface of the samples.

4. Conclusions

The following conclusions are drawn based on the experimental and comparative results:

(1) For the drying shrinkage test, the final shrinkage deformation of the foamed concrete decreases with the increase of dry density. The range of stable shrinkage deformation is 2.726 to 3.558 mm/mm for the dry density of 300 to 800 kg/m^3.

(2) For the improved drying shrinkage test, the shrinkage deformation in stage 1 varies between 20.7% and 46.0% of the total shrinkage deformation, and the other is mainly caused by the change of moisture content.

(3) The deformation increases with the decrease of volumetric moisture content for six dry densities of foamed concrete. In addition, its variation is slow in the early stage and is fast in the later stage. For the sealed state, the volumetric moisture contents for six densities of foamed concrete are all in the slow phase of deformation.

(4) For the same dry density of the foamed concrete in the water-level unchanged condition, the compressive strength in the immersed saturation state is about 0.86 to 0.89 times of that in the standard curing state. Besides, the compressive strength in the natural dry state is about 1.27–1.40 times of that in the standard curing state.

(5) For the water-level changed condition, after 100 cycles of immersion, the compressive strength is about 51.5%–84.5% of that in the standard curing state and the elastic modulus is about 63.5%–82.2% of that in the standard curing state. Moreover, the strength ratio and the elastic modulus ratio increase with the increase of dry density.

Data Availability

For detailed data, refer to the doctoral thesis "Study on the Structure Performance and Construction Technology of New Foamed Concrete Subgrade for High-Speed Railway," which will be published in this year.

Conflicts of Interest

There are no conflicts of interest regarding the publication of this paper.

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