Compressive Properties and Anti-Erosion Characteristics of Foam Concrete in Road Engineering

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Abstract. To analyse the compression properties and anti-erosion characteristics of foam concrete, one-dimensional compression tests were carried out using ring specimens of foam concrete, and unconfined compression tests were carried out using foam concrete specimens cured in different conditions. The results of one-dimensional compression tests show that the compression curve of foam concrete has two critical points and three stages, which has significant difference with ordinary geotechnical materials such as soil. Based on the compression curve the compression modulus of each stage were determined. The results of erosion tests show that sea water has a slight influence on the long-term strength of foam concrete, while the sulphate solution has a significant influence on the long-term strength of foam concrete, which needs to pay more attention.

1. Introduction

Foam concrete is a lightweight material consisting of Portland cement paste or cement filler matrix (mortar) with a homogenous void or pore structure by introducing air in the form of small bubbles. As an excellent building material, foamed concrete has been widely used for decades in building insulation, fire prevention, noise reduction and other fields. Researchers have paid a lot of attention on its above related properties, and achieved a number of useful results, such as the influence of coarse aggregate and foaming agent (Nambiar et al. 2006a; Ramamurthy 2009; Lee et al. 2014; Pan et al. 2014), microstructure properties (Nambiar et al. 2007; Just et al. 2009; Hilal et al. 2015), thermal properties (Mydin et al. 2012a, 2012b), compressive strength (Nambiar 2006b, 2008), and so on. Recent years in China, foamed concrete has been used in the field of geotechnical engineering (Tian 2009; Chen 2011; Zhao 2013; Ma 2015), for example as seismic-isolation materials of tunnels, and as artificial crust layer in costal soft soil subgrade (Fig.1), and as the filler layer replacing part of the embankment (especially in the transition section of bridge and embankment). As a new geotechnical material, the compression properties of foam concrete need to be further studied; and in the costal environment, the erosion resistance properties of foam concrete need to pay more attention, too. However, limited studies have been reported on the compression properties and erosion resistance properties of foam concrete in costal geotechnical engineering, which has limited the further application of foam concrete in geotechnical engineering. This paper tries to discuss on this topic based on laboratory tests.
The tested foam concrete specimens were taken from a highway construction site of Hangzhou, Zhejiang Province, China, which is constructed by Zhejiang Hongtu Company. The foam was produced by animal protein foaming agent, and the foam concrete was produced at a target dry density of 600kg/m$^3$. According to the method of one dimensional compression test of soil, the compression properties of foam concrete were tested and analyzed. Then the unconfined compression test was carried out using foam concrete specimens of different curing conditions. Referring to the existing study (Ranjani 2012), the erosion influence of two kind of sulfate solution was also studied.

Fig. 1 Design section of backfill foamed concrete in a coastal soft soil subgrade

2. Compression properties

2.1. Test program
The foam concrete specimens were pouring into two kinds of cutting rings with the diameter of 7.98cm and 6.18cm, and the height of 2.0cm. The specimens were placed in the standard curing room until the test ages.

The compression tests of 28d and 120d specimens were carried out respectively, in each group of experiments three parallel tests were carried out. GDG series high pressure consolidation apparatus produced by Nanjing Soil Instrument Factory were used. The loading schedule of the tests was listed in Table.1. During the compression process, the deformation was considered as stable if it’s less than 0.01mm per hour in each load stage.

Table 1. Loading schedule

| Specimen No. | Age/d | Area/cm$^2$ | Loading stages/kPa |
|--------------|-------|-------------|-------------------|
| 1#, 2#, 3#   | 28    | 30          | 25-50-100-150-200-300-400-800-1200-1600-3200 |
| 4#, 5#, 6#   | 28    | 50          | 50-100-200-300-400-800-1200-1600-2000 |
| 7#, 8#, 9#   | 120   | 30          | 400-800-1200-1400-1600-1800-2000-2200-2600-3000-3400 |
| 10#, 11#, 12#| 120   | 50          | 400-800-1200-1400-1600-1800-2000 |

2.2. Test results
The final deformation under each load level was measured, and the compressive strain was figured out, the results were showed as the Fig.2~Fig.5. From Fig.2 and Fig.4 we can find that the total deformation of most specimens had exceeded 10mm, which is a value much larger than that of soft soil under the same load (usually about 3~5mm). We also can find that the relationship curves of all specimens have a same law as follow: the relationship curve between the pressure and the total deformation is a typical reverse “S” shape, which has two critical points and three stages. The deformation was small when the pressure is less than the first critical point; and the deformation increases significantly when the pressure exceeds the first critical point; then the deformation trends to be gentle when the pressure exceeds the second critical point. From Fig.3 and Fig.5, we can find that the compressive strains shows great differences under different pressures, at a certain pressure the strain may be dozens of times that of other pressure.
2.3. Discussion
On the base of the test results and the curves in Fig.2–Fig.5, the average values of two critical points of the specimens were determined by curve fit, as show in the following Table.2. From the table we found that the values of the critical points increased with the age and decreased with the area of the specimens. From 28d to 120d, for the 30cm\(^2\) specimens, the average value of first critical point increased by 17.9\%, and the average value of second critical point increases by 8.4\%; for the 50cm\(^2\) specimens, the average value of two critical points increased by 56.9\% and 36.9\% respectively. At the age of 28d, the average value of first critical point of the 30cm\(^2\) specimens is 1.76 times that of the 50cm\(^2\) specimens, while the ratio of second critical point is 1.42; at the age of 120d, the ratios were 1.32 and 1.12 respectively.

Table.3 shows the average deformation and proportion in each stage of all the specimens, from which we found that the main deformation occurs in the second stage, which may account for 70\%–80\% of the total deformation.

Since the three stages of the compressive curves are approximately linear, we can draw the stress-strain curves and define the slope of each line section as the compression modulus of corresponding stage, so the compression modulus of all the specimens can be figured out as following Table.4. For some special cases, the corresponding compression modulus cannot be calculated, for example the third stage of specimen 10#, 11# and 12#, because they were not fully deformed limited to the pressure. From Table.4, we can get the size relationship of the compression modulus of each stage and their change law with age: the compression modulus of first stage is large, and the compression modulus of third stage is slightly smaller, while the compression modulus of second stage is very small. The compression modulus of first stage obviously increases with age, but the change of second and third stage is not obvious.

Previous studies showed that the pores of foam concrete is composed of the gel pores, the capillary pores and air voids (Just 2009), combining analysing with the three stages of deformation of foam concrete, we can make a assumption that the three stages of deformation corresponds to the compression of three kinds of pores, which means that in the first stage, the deformation may mainly cause by the compression of the gel pores, and in the second stage the deformation mainly caused by the compression of the air voids, and in the third stage the deformation mainly caused by the capillary pores. The assume maybe need further mechanical and microstructure research to prove, which will be the next work of us.

![Fig. 2](image)

**Fig. 2** Relationship between pressure and total deformation (28d)
Fig. 3 Compressive strain of each load level (28d)

Fig. 4 Relationship between pressure and total deformation (120d)

Fig. 5 Compressive strain of each load level (120d)
Table 2. Average value of critical points of foam concrete specimens

| Age (d) | Area (cm²) | Critical point 1 (kPa) | Critical point 2 (kPa) |
|---------|------------|------------------------|------------------------|
| 28      | 30         | 1266                   | 1820                   |
|         | 50         | 720                    | 1283                   |
| 120     | 30         | 1493                   | 1973                   |
|         | 50         | 1130                   | 1757                   |

Table 3. Average deformation (mm) and proportion in each stage

| Age (d) | Area (cm²) | Stage 1 Deformation | Stage 1 Proportion | Stage 2 Deformation | Stage 2 Proportion | Stage 3 Deformation | Stage 3 Proportion |
|---------|------------|---------------------|--------------------|---------------------|--------------------|---------------------|--------------------|
| 28      | 30         | 1.04                | 9.7%               | 7.71                | 72.3%              | 1.91                | 18.0%              |
|         | 50         | 0.96                | 9.7%               | 8.33                | 83.9%              | 0.64                | 6.4%               |
| 120     | 30         | 0.97                | 9.8%               | 6.87                | 69.7%              | 2.02                | 20.5%              |
|         | 50         | 1.35                | 15.5%              | 7.05                | 80.2%              | 0.38                | 4.3%               |

Table 4. Average compression modulus of each stage (MPa)

| Age (d) | Area (cm²) | Stage 1 | Stage 2 | Stage 3 |
|---------|------------|---------|---------|---------|
| 28      | 30         | 18.5    | 1.2     | 12.4    |
|         | 50         | 22.2    | 1.2     | 12.6    |
| 120     | 30         | 28.2    | 1.4     | 12.3    |
|         | 50         | 18.9    | 1.5     | Not available |

3. Erosion resistance properties

3.1. Test program

In the geotechnical engineering of coastal areas, the working environment of foam concrete is usually complicated, especially the groundwater environment, which may be fresh water or salt water, or contains a variety of corrosive ions. In order to analyze the erosion resistance properties of foamed concrete under different erosion conditions, this paper has set up five kinds of different curing conditions, and cured to 28d, 120d, 60d, 210d. The curing conditions are as follows:

1. Standard curing: the specimens were placed in the standard curing room, under the humidity of 95% and the temperature of 20±2 centigrade.

2. Fresh water curing: the specimens were cured in fresh water, and then placed in the standard curing room.

3. Sea water curing: the specimens were cured in sea water, and then placed in ordinary indoor environment. The sea water was taken from the East Sea of China near Ningbo, Zhejiang Province.

4. Na₂SO₄ solution erosion: referring to the ion concentration of offshore seawater near Ningbo and the corrosion grades of water and soil to concrete structures specified in <Code for Highway Engineering Geological Investigation> (JTG C20-2011), the used Na₂SO₄ solution was divided into three grades, in which the concentration of SO₄²⁻ were 1500mg/L, 4500mg/L and 13500mg/L respectively. The erosion grades of the three kinds of Na₂SO₄ solution were weak, medium and strong in turn.

5. MgSO₄ solution erosion: in order to get a comparative analysis on the double erosion effect of Mg²⁺ and SO₄²⁻, the concentrations of SO₄²⁻ in used MgSO₄ solution were as the same as above Na₂SO₄ solution, that were 1500mg/L, 4500mg/L and 13500mg/L respectively. The corresponding concentrations of Mg²⁺ were 375mg/L, 1125mg/L and 3375mg/L, which were weak, weak and
medium respectively according to <Code for Highway Engineering Geological Investigation> (JTG C20-2011).

The specimens were cast into 100mm×100mm×100mm and cured under the five conditions. When reached the above ages, unconfined compression test was carried out to test the strength of the specimens.

3.2. Test results
The test results were showed in Fig.6~Fig.11. In order to analyze the influence of groundwater on foamed concrete, Fig.6 shows the change of the strength of foamed concrete with age in standard curing condition, fresh water curing condition, and sea water curing condition. Fig.7 and Fig.8 shows the influence of Na$_2$SO$_4$ solution of different concentration; Fig.9 and Fig.10 shows the influence of MgSO$_4$ solution of different concentration; Fig.11 shows the difference between Na$_2$SO$_4$ solution and MgSO$_4$ solution at the same concentration of SO$_4^{2-}$. In Fig.7, Fig.9 and Fig.11, the latter part of some curves was indicated by dotted line, which means that the specimens have been destroyed so that their strength cannot be tested.

3.3. Discussion
(1) Influence of curing conditions and age
Before the age of 210d, the compressive strength of foamed concrete increased under all the three curing conditions, and their strength of 28d have reached 78.3%, 66.5% and 80.0% of the strength of 210d, respectively.

Compared with standard cured specimens, at the age of 28d and 60d, the strength of fresh water cured specimens is larger by 4.3% and 7.9%, which indicated that the important promotion of water in the process of the formation of strength of the foam concrete, in other words is the process of the hydration and hardening of cement. However, at the age of 120d and 210d, the strength of fresh water cured specimens is smaller than that of standard cured specimens by 12.3% and 11.4%, which may be related to the softening of foam concrete.

Compared with standard cured specimens, the sea water cured specimens have a slightly larger strength at 28d and 60d. But at 120d and 210d, the strength of sea water cured specimens became significantly lower than that of standard cured specimens, accurately speaking the decrease magnitudes were about 17.4% and 13.9% respectively. And compared with fresh water cured specimens, the sea water cured specimens have a smaller strength, the largest decrease was 5.8%, which shows sea water has some influence on the strength of foam concrete, but the influence is not significant.

![Fig. 6 Change of strength of foamed concrete in different curing conditions and age](image_url)
**Fig. 7** Influence of the concentration of $SO_4^{2-}$ on the strength of foam concrete (Na2SO4 solution)

**Fig. 8** Relationship between $SO_4^{2-}$ concentration and strength at different ages (Na2SO4 solution)

**Fig. 9** Influence of the concentration of $SO_4^{2-}$ on the strength of foam concrete (MgSO4 solution)
Fig. 10 Relationship between $SO_4^{2-}$ concentration and strength at different ages (MgSO4 solution)

(a) $SO_4^{2-}$ concentration 1500mg/L  
(b) $SO_4^{2-}$ concentration 4500mg/L  
(c) $SO_4^{2-}$ concentration 13500mg/L

Fig. 11 Comparison of two kinds of sulfate on the strength of foamed concrete

(2) Erosion of Na$_2$SO$_4$ solution

Generally speaking, the strength of Na$_2$SO$_4$ eroded specimens increased before 60d and then decreased in all three concentrations of $SO_4^{2-}$, from which we can conclude that at earlier stage the promotion of water in the strength formation process is larger than the erosion of $SO_4^{2-}$, while in the later stage it is just the opposite. Compared with the fresh water cured specimens (concentration of $SO_4^{2-}$ is 0mg/L) of the same age, almost all the $SO_4^{2-}$ eroded specimens have a obvious lower strength, which shows that the strength of foam concrete has been eroded by different degrees whether the erosive environment is weak, medium or strong. Specifically, the strength of foam concrete decreased 0.6%~25.7% at the age of 28d, and decreased 22.1%~100% at the age of 210d. F the view of age, the decrease of strength was much more obvious after 60d, which shows that the erosive environment of $SO_4^{2-}$ has a larger influence on the long-term strength of foam concrete.
At the same age, the strength of the foam concrete decrease with the increase of concentration of \( \text{SO}_4^{2-} \), but there were a few exceptions and the change law is not obvious.

(3) Erosion of \( \text{MgSO}_4 \) solution

Similar to \( \text{Na}_2\text{SO}_4 \) erosion, the strength of \( \text{MgSO}_4 \) eroded specimens increased first and then decreased in all three concentrations of \( \text{SO}_4^{2-} \), the difference is that when the concentration of \( \text{SO}_4^{2-} \) is 1500mg/L, it happened after 120d, while when the concentration is large it happened after 28d.

Compared with the fresh water cured specimens at the same age, all the \( \text{MgSO}_4 \) eroded specimens have a obvious lower strength, especially when the concentration is large. The decrease magnitude of strength was showed as following Table 5. It can be seen that, with the increase of age and the concentration of \( \text{SO}_4^{2-} \), the decrease magnitude of the foam concrete strength is increasing, which indicates that the greater the concentration and the longer the age, then the larger influence on the strength of foamed concrete.

**Table. 5 Decrease magnitude of strength in different concentrations**

| Age/d  | \( \text{1500mg/L} \) | \( \text{4500mg/L} \) | \( \text{13500mg/L} \) |
|--------|------------------------|----------------------|------------------------|
| 28     | 3.5%                   | 10.6%                | 16.5%                  |
| 60     | 13.2%                  | 30.7%                | 33.7%                  |
| 120    | 9.2%                   | 30.9%                | 37.2%                  |
| 210    | 21.7%                  | almost 100%          | almost 100%            |

(4) Comparison of \( \text{Na}_2\text{SO}_4 \) and \( \text{MgSO}_4 \)

Compared with the specimens eroded by \( \text{Na}_2\text{SO}_4 \) solution of the same concentration, the specimens eroded by \( \text{MgSO}_4 \) solution have a smaller strength at lower concentration but have a larger strength at higher concentration, which shows that the \( \text{Mg}^{2+} \) has a complicated influence on the strength except of \( \text{SO}_4^{2-} \), the influence needs further studied.

4. Conclusion

(1) The compression properties of foam concrete are very different from ordinary geotechnical materials such as soil. The compressive curve of foamed concrete has two critical points and three stages, which is a typical reverse “S” shape. The deformation of first stage and third stage is relatively small, while the deformation of second stage is very large.

(2) The compression properties of foam concrete can be expressed by compression modulus of each stage of compressive curve. The compression modulus of first stage is large, and the compression modulus of third stage is slightly smaller, while the compression modulus of second stage is very small. The compression modulus of first stage obviously increases with age, but the change of second and third stage is not obvious.

(3) The existence of water has an important influence on the development of the strength of the foam concrete: in the earlier stage (less than 60d), water has a significant promotion effect on the hydration and hardening of cement water, which made the water cured specimens a higher strength than that of standard cured specimens; while in the later stage (more than 60d), the softening effect of water on foamed concrete is greater than its promotion effect on strength, which made the water cured specimens a lower strength than that of standard cured specimens. Compared with fresh water, the influence of sea water on the strength of foamed concrete is small.

(4) In strong, medium and weak erosion environment of \( \text{Na}_2\text{SO}_4 \) solution and \( \text{MgSO}_4 \) solution, the long-term strength of foam concrete will significantly decrease or even completely lost, which shows that sulfate has an important influence on the long-term strength of foamed concrete. In addition, \( \text{Mg}^{2+} \)
also has a obvious influence on the strength of the foam concrete, while the degree of its influence needs to be further studied.

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