Experimental Study on Fatigue Performance of Foamed Lightweight Soil

Youqiang Qiu 1,4, Ping Yang 2, Yongliang Li 3, Liujun Zhang 1,4,*

1School of Highway, Chang’an University, Xi’an 710064, Shaanxi, China
2China Railway Pearl River Delta Investment Development Co., Ltd., Foshan 528300, Guangdong, China
3Shanghai Civil Engineering Co., Ltd. of CREC, Hefei 200436, Anhui, China
4CCCC First Highway Consultants Co., Ltd., Xi’an 710075, Shaanxi, China

*Corresponding author e-mail: 1450312182@qq.com

Abstract. In order to study fatigue performance of foamed lightweight soil and forecast its fatigue life in the supporting project, on the base of preliminary tests, beam fatigue tests on foamed lightweight soil is conducted by using UTM-100 test system. Based on Weibull distribution and lognormal distribution, using the mathematical statistics method, fatigue equations of foamed lightweight soil are obtained. At the same time, according to the traffic load on real road surface of the supporting project, fatigue life of formed lightweight soil is analyzed and compared with the cumulative equivalent axle loads during the design period of the pavement. The results show that even the fatigue life of foamed lightweight soil has discrete property, the linear relationship between logarithmic fatigue life and stress ratio still performs well. Especially, the fatigue life of Weibull distribution is more close to that derived from the lognormal distribution, in the instance of 50% guarantee ratio. In addition, the results demonstrated that foamed lightweight soil as subgrade filler has good anti-fatigue performance, which can be further adopted by other projects in the similar research domain.

1. Introduction

By the end of 2016, the highway total mileages of China have reached 4696300 km, and the roads which applied foamed lightweight soil as roadbed filler have occupied a certain proportion in recent years. We can believe this proportion will gradual expand with the development and perfecting of foamed lightweight technology. When foamed lightweight soil is used as roadbed filler, its density is much lighter than the regular roadbed filler owing to too many independent closed gas holes in foamed lightweight soil. On the other hand, there is no doubt that its strength must decrease greatly because of these gas holes. In general, the strength of foamed lightweight soil is about 0.3~5.0MPa [1]. Therefore, the typical characteristics of foamed lightweight soil is light weight and low-strength.

The traffic loads would transfer loads to foamed lightweight soil roadbed through pavement structure layer, and pavement structure layer and foamed lightweight soil filler would gradually appear cracks after the traffic loads reach certain loading cycles. Furthermore, the destruction of foamed lightweight soil even appears earlier than pavement structure layer, we can call this the fatigue failure
Therefore, it is a very meaningful work to study the fatigue performance of foamed lightweight soil in order to ensure its fatigue life can meet the requirements of road design service life.

In this paper, we would systematically analyze the the fatigue performance of foamed lightweight soil and get fatigue equations by beam fatigue tests. At the same time, based on the traffic technological standards of the supporting project, we can calculate fatigue life to appraise its fatigue performance, which can provide helps and references to other similar projects.

2. Determination of the mix ratio
Based on some relevant experimental researches [5-7], the beam fatigue test is made up by the basic mix ratio in Table 1, and its physical and mechanical performance indicators as shown in the Table 2.

| Water-solid ratio | Fly ash accession (%) | Cement (kg/m³) | Fly ash (kg/m³) | Water (kg/m³) | Foam (kg/m³) |
|-------------------|------------------------|----------------|----------------|--------------|--------------|
| 1: 1.80           | 30                     | 258            | 110.7          | 204.8        | 26.5         |

Table 2. The physical and mechanical performance indicators of foamed lightweight soil.

| Pilot projects                  | Curing time                  | Test results |
|---------------------------------|------------------------------|--------------|
| Flow factor (mm)                 | Within 2min of a stir finishing | 189          |
| Moist unit weight (kJ/m³)        | Within 2min of a stir finishing | 5.56        |
| Unconfined compressive strength (MPa) | 7d                          | 0.343        |
|                                 | 28d                          | 0.621        |
|                                 | 90d                          | 1.332        |
| Flexural strength (MPa)          | 28d                          | 0.205        |
| Modulus of resilience (MPa)      | 28d                          | 225          |
| CBR (%)                          | 28d                          | 12.2         |

It can be seen from Table 2, the basic mix ratio in Table 1 can meet basic mechanical properties of foamed lightweight soil according to relative regulations. Therefore, it is reasonable to adopt this mix ratio to beam fatigue tests.

3. Test scheme

3.1. Test Method
The test equipment is UTM-100 test system produced by Australian IPC, including a loading equipment, a control and data acquisition system and an environmental cabinet. Furthermore, the load strength of this loading equipment is 4.5kN ± 4N while the load frequency is 5~10Hz. In the beam fatigue test, the fatigue life can be automatically collected by computer data acquisition system.

3.2. The shaping method of specimen
According to the test requirements of relevant standard [7], the size of the test piece is 380mm×63mm×50mm. In this paper, we use the mix ratio to make test pieces, and form stripping after specimen shaping for 24h. What’s more, beams should have a standard curing for 28d.

3.3. Parameter design of the test
There are two kinds of load controlling mode for fatigue test: stress controlling mode and strain controlling mode. For foamed lightweight soil, it is shown that stress controlling mode is adequate because it being mainly in a brittle failure state and its ultimate strain is small. In the stress controlling
mode for beam fatigue test, the sign of fatigue failure is that beams have been tally destroyed. When the beam is tally broken, the number of load applications is fatigue life of foamed lightweight soil.

The load frequency and load wave in the fatigue test should be decided on the basis of the mechanics characteristic of the pavement. Various tests [8-12] have indicated that, the load time is 0.016s when load frequency is 10HZ, while it amounts to 60~65km/h for running speed. There is no doubt that it can meet the requirement of the specifications, so this test adopts 10HZ of load frequency. Under the function of driving load, it is generally believed that sine wave is closely related to the load wave produced by actual road surface, so this test adopts sine wave to load.

In order to improve the accuracy of beam fatigue test, the stress ratio should be representatively selected. In this paper, 0.5, 0.6, 0.7 and 0.8 are separately chosen as the stress ratio. By the comprehensive analysis above, parameter design in this beam fatigue test as shown in Table 3.

| Test Parameters | Parameter values |
|-----------------|------------------|
| Load controlling mode | Stress controlling mode |
| Load wave | Sine wave |
| Load frequency | 10Hz |
| Stress ratio | 0.5, 0.6, 0.7, 0.8 |
| Damage standard | Beams have been tally destroyed. |
| Test temperature | 25℃ |

4. Test results and Analysis

Based on the mix ratio and test scheme, the fatigue life is obtained by fatigue test under the different stress ratio, and results are presented in Table 4.

| Stress ratio | Test results | The first test | The second test | The third test | The fourth test | The fifth test | Average |
|--------------|--------------|----------------|----------------|--------------|----------------|---------------|--------|
| 0.5          | Fatigue life | 193490         | 114810         | 68650        | 332400         | 253120        | 192494 |
|              | Logarithmic fatigue life | 5.2867        | 5.0600         | 4.8366       | 5.5217         | 5.4033        | 5.2844 |
| 0.6          | Fatigue life | 44090          | 16800          | 26700        | 130310         | 69180         | 57416  |
|              | Logarithmic fatigue life | 4.6443        | 4.2253         | 4.4265       | 5.1150         | 4.8400        | 4.7590 |
| 0.7          | Fatigue life | 4240           | 2290           | 1121         | 15840          | 8120          | 6322   |
|              | Logarithmic fatigue life | 3.6274        | 3.3598         | 3.0496       | 4.1998         | 3.9096        | 3.8009 |
| 0.8          | Fatigue life | 410            | 210            | 112          | 1640           | 830           | 640    |
|              | Logarithmic fatigue life | 2.6128        | 2.3222         | 2.0492       | 3.2148         | 2.9191        | 2.8062 |

It can be deduced from these results in Table 4, stress ratio has a prominent influence of fatigue life, and fatigue life would gradually decrease with the increase of stress ratio. Besides, the fatigue life of foamed lightweight soil has a great dispersion even under the same stress ratio. Through the comparison of test results, the dispersion of fatigue life would be more obvious with the increase of stress ratio.
In general, the fatigue life can be expressed by lognormal distribution. However, it is believed that Weibull distribution would express fatigue life better in recent years [13]. Therefore, this paper adopts respectively lognormal distribution and Weibull distribution to analyze the fatigue life of foamed lightweight soil. At the same time, it obtains S-N curves and fatigue equations by the comparison of two methods.

4.1. The analysis of Weibull distribution

According to Weibull distribution theory, when fatigue life obeys the Weibull distribution, the reliability functional calculation formula is as follows (1).

\[-\ln \ln (1/p) = -2.303b l\lg N_p + 2.303b l\lg N_a \]  

(1)

According to the formula above, the fatigue life will obey the Weibull distribution if the linear relation between \(-\ln \ln (1/p)\) and \(\lg N_p\) appears good. Furthermore, the specific calculation formula about guarantee rate is as follows (2).

\[ p = 1 - i/(n+1) \]  

(2)

In this paper, five groups of fatigue tests were carried out, and fatigue lives should be arranged from smallest to largest. The results about guarantee rate to count that is following in Table 5.

| Test serial number | 1   | 2   | 3   | 4   | 5   |
|-------------------|-----|-----|-----|-----|-----|
| Guarantee rate    | 0.833 | 0.667 | 0.5  | 0.333 | 0.167 |
| \(-\ln \ln (1/p)\) | 1.702 | 0.903 | 0.365 | -0.094 | -0.583 |

Depending upon the data in Table 4 and Table 5, taking the logarithmic fatigue life as the X-axis, \(-\ln \ln (1/p)\) as the Y-axis to draw the standard curve in order to verify the fatigue life obeys or disobeys Weibull distribution, and the result is shown in Figure 1.

**Figure 1.** Weibull distribution fitting-figures under different stress ratio.
Figure 1 shows a good linear relationship between \(-\ln \ln (1/p)\) and logarithmic fatigue life because correlations of these fitting equations all are close to 1. Therefore, the fatigue life of foamed lightweight soil obeys Weibull distribution. Combine with above fitting equations, when the guaranteed rate is 50% and 95%, it can be concluded that logarithm fatigue life under different stress ratio in Table 6, and the S-N curves as shown in Figure 2.

**Table 6.** Logarithm fatigue life with different guaranteed rates under different stress ratio.

| Stress ratio | 0.5     | 0.6     | 0.7     | 0.8     |
|--------------|---------|---------|---------|---------|
| 50% guaranteed rate | 5.2504  | 4.6869  | 3.6763  | 2.6723  |
| 95% guaranteed rate | 4.4404  | 3.6536  | 2.3452  | 1.2991  |

![Figure 2. S-N curve of Weibull distribution](image)

According fitting equations in Figure 2, the fatigue equations are obtained under the guaranteed rate is 50% and 95%.

1. The fatigue equation under 50% guaranteed rate:

\[
\lg N = 9.75572 - 8.74497(\sigma/S), \quad R^2 = 0.97729
\]

2. The fatigue equation under 95% guaranteed rate:

\[
\lg N = 9.9107 - 10.7325(\sigma/S), \quad R^2 = 0.98772
\]

4.2. *The analysis of lognormal distribution*

When fatigue life of foamed lightweight soil obeys the lognormal distribution, its logarithmic average is took as the logarithmic fatigue life. According to test results in Table 4, taking the stress ratio as the X-axis, logarithmic fatigue life as the Y-axis to draw the standard curve, which shown in Figure 3.
According to the fitting equation in Figure 3, the fatigue equation is obtained when fatigue life obeys the lognormal distribution.

\[ \lg N = 9.618 - 8.39289 \frac{\sigma}{S}, \quad R^2 = 0.97368 \]  

(5)

5. The estimation of fatigue life

5.1. The general situation about supporting project

The supporting project is located in the first segment of Guangzhou-Foshan-Jiangmen Freeway in Jiangmen city, which includes the north section of the tunnel in West Ring Road (K3+550–K18+143) and the connecting section of Heshan (LK0+000–LK5+853), a total length of 20.446 km, while the road length about the soft ground subgrade is 3.403 km. The subgrade is filled by cast-in-situ foamed lightweight soil due to its poor engineering duality and thick layer of soft soils.

This project adopts the first class highway technical standard to build. It has two-way six lanes with 3.75 m lane width. The pavement structure adopts the asphalt pavement, and its structure and thickness as follow: 16 cm of asphalt concrete coating +1 cm of sub-seal coat +40 cm 5% of cement stabilized graded broken stone base +20 cm 4% of cement stabilized graded broken stone subbase. Besides, there is 10 cm of C25 concrete slab under the subbase in order to protect the cast-in-situ foamed lightweight soil. Therefore, the aggregate thickness of pavement structure and C25 concrete slab is 0.87 m.

According to the prediction results analysis of traffic volume in the feasibility study report shows that the cumulative equivalent axle loads during the design period of the pavement is \(1.81 \times 10^7\) times.

5.2. The calculation of vehicles load stress

Formula (6) is used to calculate the compressive stress produced by the vehicle load on the roof of foamed lightweight soil roadbed.

\[ \sigma = \frac{p(1 + \xi)}{\frac{\pi}{4} (d + 2z \tan \theta)^2} \]  

(6)
Considering the most disadvantage condition, 550kN heavy axle load as the single-type is obtained [14], so the vehicle load is 35kN, the impacting factor is 0.3, diameter of equivalent circle is 0.213m, the radial angle is 30°. And then putting these parameters into the formula (6) for calculating.

\[
\sigma = \frac{p(1+\xi)}{\pi(d+2z\tan\theta)^2} = \frac{35(1+0.3)}{\pi\left(0.213+2\times0.87\times\tan30°\right)^2} = 39.1 \ (kPa)
\]

(7)

5.3. The comparison of fatigue life

In this supporting project, actual stress ratio is a calculation of the dynamic loads born by foamed lightweight to its flexural strength, and the calculation formula as follows (8).

\[
c(\sigma S) = 0.0391/0.205=0.191
\]

(8)

On the basis of fatigue equations, using the actual stress ratio to calculate the actual fatigue life of foamed lightweight soil, the calculation result is shown in Table 7.

Table 7. The comparison of fatigue life.

| Distribution of fatigue life | Fatigue equation | Fatigue life |
|------------------------------|-----------------|-------------|
| 50% guaranteed rate Weibull distribution | \(\lg N = 9.75572 - 8.74497\frac{\sigma}{\sigma_o}\) | 1.224\times10^8 |
| 95% guaranteed rate Weibull distribution | \(\lg N = 9.9107 - 10.732\frac{\sigma}{\sigma_o}\) | 7.304\times10^7 |
| Lognormal distribution | \(\lg N = 9.618 - 8.39289\frac{\sigma}{\sigma_o}\) | 1.040\times10^8 |

We can see from Table 7, whether the fatigue life of foamed lightweight soil obeys Weibull distribution or lognormal distribution, its fatigue life is greater than the cumulative equivalent axle loads during the design period of the pavement. This means the fatigue life of foamed lightweight soil must be enough to satisfy the request of the designed service life of a highway.

6. Conclusion

This paper mainly analyzes the fatigue performance of foamed lightweight soil by beam fatigue test, and reaches the following conclusions:

Foamed lightweight soil made from the basic mix ratio in Table 1 not only meets the physical mechanical performances but also has well performance in fatigue, which can provide references to other similar projects.

The fatigue test results show that larger discreteness in fatigue life of foamed lightweight soil, and its discreteness is more obvious with the increase of stress ratio.

The linear relation between logarithmic fatigue life and stress ratio appears good whether the fatigue life of foamed lightweight soil obeys Weibull distribution or lognormal distribution.

Compared with 95% of the guarantee rate, when the guarantee rate is 50%, the fatigue life of Weibull distribution is closer to that of the lognormal distribution.

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