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BENDING FATIGUE PROPERITIES RESEARCH OF POLYURETHANE CEMENT (PUC)

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ABSTRACT

In order to study the fatigue properties of polyurethane cement (PUC), the newly bridge reinforcement material, three different densities of PUC beams were tested. The studies indicate that the fatigue life of PUC material obeys two parameters Weibull distribution, and the double logarithm fatigue equation with different failure probability is established by this mathematical model. The fatigue life equations of the PUC with three different densities (PUC1500, PUC1200 and PUC800) were established when the failure rate was 0.5. The fatigue life of PUC1500 is the largest, and the fatigue life of PUC material decreases with the decrease of its density. Under the action of bending fatigue load, the fatigue strain of PUC material can be divided into three phases.

KEYWORDS

Polyurethane Cement (PUC), Fatigue, Bending, Four-point Loading, Weibull Distribution, Failure Probability

INTRODUCTION

The availability of many tests and the number of projects demonstrate that the use of polyurethane cement (PUC) materials to strengthen bridge structures is becoming a feasible technique [1-6]. PUC material can make the repair or retro-fitting of bridge elements more effective, easier to handle, and cheaper because of its very simple method of implementation and its excellent properties and flexural behaviour [1].

Usually polyurethane cement (PUC) material is a new type of composite material, with light weight, high strength, high toughness and good bonding performance [2-3]. In previous studies, ordinary Portland cement is used as filler and polyurethane raw material is used as cementing material. PUC has excellent bonding for the retrofitting of beams. Ten pieces of reinforced concrete beams were tested and studied by Haleem [1]. The external strengthened beams with PUC material showed an increase in the ultimate load. The maximum load capacity of retrofitted specimens reached values of about 170% comparing with control beam. Moreover, cracks were reduced around 58% comparing with control beam at the maximum applied load stage of control beam. To investigate the feasibility of the PUC-strengthened bridge, load tests were conducted before and after strengthening. The results of concrete strain and deflection show that the capacity of the repaired bridge, including the bending strength and stiffness, is enhanced [2]. The crack width measurement also indicates that this technique could increase the durability of the bridge. The PUC material is used as the embedded material of steel wire ropes in reinforcement [5], and the results showed significantly enhanced strength, stiffness, and ability to constrain cracks. The PUC also increases the durability of the steel wire ropes and promotes secure anchoring.

Nevertheless, a majority of previous studies were focused on the static performance between strength and density of the PUC material. In recent literatures, no studies were reported with respect to the flexural fatigue behaviour of PUC material. Actually, the fatigue behaviour of PUC material is an important design parameter for the strengthened structures, which have to be subjected to repetitive fatigue load. The PUC material in structural reinforcement is subjected to the repeated action of vehicle load. It is of great interest for both researchers and engineers to investigate the fatigue behaviour of PUC material.

The primary goal of this study is to investigate the flexural fatigue behaviour of PUC as strengthening material. The effective density and static flexural strength of PUC were detected prior to fatigue test. A laboratory testing program was applied to collect the fatigue lives of PUC at various stress levels. To incorporate the effects of stress level S and survival probability, equivalent fatigue-life was employed to study the fatigue equation of PUC. The fatigue prediction models for the PUC and the flexural fatigue behaviour of PUC800, PUC1200 and PUC1500 was compared.

EXPERIMENTAL PROGRAM AND TESTING METHODS

The main components of PUC are polyurethane and cement, mixed together [3-6]. The hardness range of this material is 10-100 (IRHD), and it possesses good chemical resistance, flexibility, adhesion and film-forming properties. The cement used in this study was produced under Chinese specifications. Ordinary Portland cement was used. The type of polyol used was polyether polyol. The acid value of the polyether polyol was ≤5 mg KOH/g, and the hydroxyl value of the polyether polyol was 350±10 mg KOH/g. The density of the polyether polyol was 1.13 g/cm^3. The mixing containers used are plastic buckets. Firstly, the weighed polyether polyol and the silicone oil with different water content were poured into the container. Secondly, the Portland cement is poured into the mixture after being weighed and dried. Finally, the isocyanate was poured into the container. The raw materials for the polyurethane and cement were mixed for 3 min in a mixing container. The mixture was electrically stirred at a rate of 1500 revolutions per minute, seeFigure1.

Polyurethane is a high performance polymer elastic material, polyols and the polyisocyanate, are the main chemical components forming the polyurethane segment block, and the ether linkages. Small quantity of water can play very important role in forming the polyurethane densities due to the chemical reaction of water with polyol and polyisocyanate which produced foam composite with an air bubbles which affect the density of final product. All components of the polyurethane are liquid material and were used in this research mixed with cement powder.

Three kinds of polyurethane cement materials with different densities (800 kg/m^3, 1200 kg/m^3 and 1500kg/m^3) were prepared in this experiment, which were respectively represented by PUC800, PUC1200 and PUC1500. The distribution of materials with different densities is shown in Table 1.

Pour the mixed polyurethane cement material into the sample mould of 100×100×400mm^3 [7], as Figure 2. The specimens were demoulded the next day. Thereafter, they were transferred into the curing room and stored at 20 ± 2℃ until preparation for testing. The specimens were removed from the curing room after 28 days. Sensors were pasted onto the prism specimens to measure the strain during loading, as Figure3.

Fig. 1 - Polyurethane cement （PUC） mixing diagram

Tab. 1 - Mixing ratio PUC materials for all cases

component	Ratio of PUC		
	PUC800 (800 kg/m³)	PUC1200 (1200 kg/m³)	PUC1500 (1500 kg/m³)
Cement	50.00	50.00	50.00
Polyisocyanate	24.64	24.87	25.00
polyether polyol	25.13	25.12	25.00
silicone oil	0.20	0.00	0.00
Water	0.03	0.01	0.00

Fig. 2 - Casting drawing of specimens

Fig. 3 - Fatigue test

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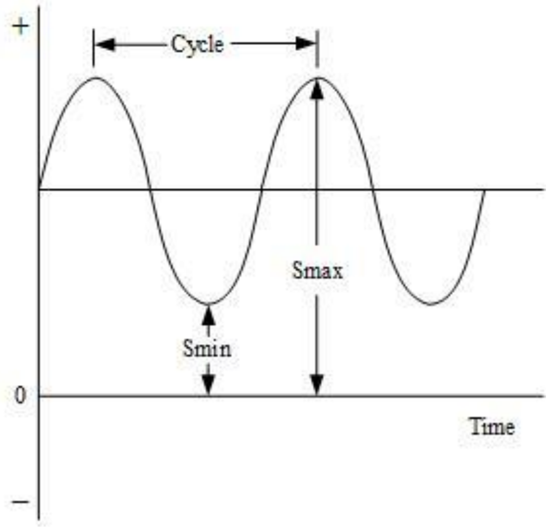

Fig. 4 - Fatigue test loading system

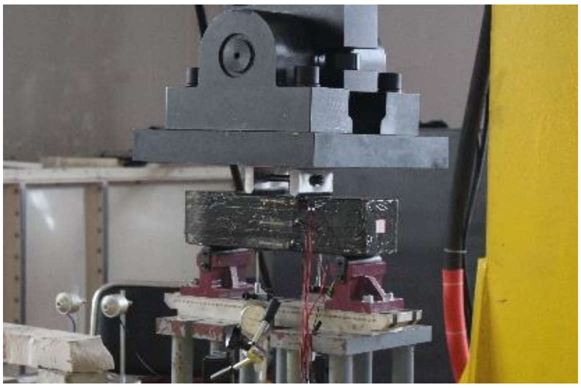

Fig. 5 - Fatigue test details

Strengthening analysis

In the static load test, there are three specimens for each density polyurethane cement composite, and the average value of ultimate flexural strength is shown in Table 2. It was found in the test that the flexural strength of PUC specimens increased with the increase of material density. The average flexural strength of high density polyurethane cement materials is 38.4MPa, which is far higher than that of ordinary Portland cement concrete and higher than that of general resin concrete [8-9].

Tab.2 - Average flexural strength of PUC for all cases

All case	PUC800	PUC1200	PUC1500
Flexural Strength（Mpa）	12.8	27.1	38.4

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Tab 3 - Fatigue life of the specimen (PUC1500)

Fatigue life				survival rate L_R	$\ln\ln\left(1/L_R\right)$
S=0.90	S=0.85	S=0.75	S=0.65		
270	1526	4489	14810	0.8571	-1.8698
528	3944	8342	28210	0.7143	-1.0892
1934	6934	16365	59290	0.5714	-0.5805
5066	11484	48521	139140	0.4286	-0.1657
6512	81804	197512	349968	0.2857	0.2254
9867	164322	293698	886523	0.1429	0.6657

Fatigue strength results

Fatigue life statistical analysis

The fatigue life of PUC1500 specimens with different stress levels is shown in Table 3. It can be seen from Table 3 that the fatigue life test of PUC is discrete to a certain extent. Only by adopting reasonable and scientific methods for analysis can the reliable results be obtained with a small sample. There are many mathematical probability models used in the statistical description of fatigue data, among which the most commonly used are logarithmic normal distribution and Weibull distribution. As the logarithmic normal distribution function decreases with the increase of fatigue life, it is obvious that this violates the physical phenomenon of gradual deterioration caused by the fatigue process of materials. However, the risk function of Weibull's probability density function gradually increases with the increase of time, which can more accurately describe the fatigue data and conform to the actual situation of fatigue test. Therefore, it is commonly used to describe fatigue data with Weibull distribution in recent years [10-11]. In this paper, the fatigue properties of PUC are studied by means of Weibull distribution. The probability density function $f\left(n\right)$ and cumulative distribution function $F_N\left(n\right)$ of the Weibull probability distribution can be expressed by the following Equations (1) and (2), respectively, under the conditions $n \geqslant n_0$, $\alpha > 0$, and $u > n_0$:

$$f\left(n\right)=\frac{\alpha}{u-n_0}\left(\frac{n-n_0}{u-n_0}\right)^{\alpha-1}\exp\left[-\left(\frac{n-n_0}{u-n_0}\right)^{\alpha}\right] \tag{1}$$

$$F_N\left(n\right)=1-\exp\left[-\left(\frac{n-n_0}{u-n_0}\right)^{\alpha}\right] \tag{2}$$

Where n is the specific value of the random variable N; α is the shape parameter; u is the scale parameter; and n_0 is the location parameter.

The survivorship function $L_R\left(n\right)$ may be given as:

$$L_R\left(n\right)=\exp\left[-\left(\frac{n-n_0}{u-n_0}\right)^{\alpha}\right] \tag{3}$$

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Considering the dispersion of materials, the minimum life parameter n_0 is 0, then Equation (3) can be rewritten as:

$$L_R(n) = \exp\left[-\left(\frac{n}{u}\right)^{\alpha}\right] \tag{4}$$

Take the logarithms twice on both sides of Equation (4), it holds Equation (5):

$$\ln\left[\ln\frac{1}{L_R}\right] = \alpha\ln(N) - \alpha\ln(u) \tag{5}$$

Equation (5) can be expressed as a simple linear relationship $Y = \alpha X - b$, where $Y = \ln\left[\ln\frac{1}{L_R}\right]$ and $X = \ln(N)$.

Under the given stress level S, the K fatigue test data obtained from the test were arranged from small to large in ascending order (the serial number is I), and the reliability L_R can be calculated as follows:

$$L_R = 1 - \frac{i}{k+1} \tag{6}$$

The survival rate and $\ln\ln(1/L_R)$ calculated by Eq. (6) are shown in Table 3, and the results of regression according to Equation (5) are shown in Table 4. It can be seen from Table 4 that $\ln\ln(1/L_R)$ has a good statistical linear relationship with $\ln(N)$. The correlation coefficients were 0.961, 0.918, 0.937 and 0.961, respectively. The results show that the fatigue life of PUC can obey the two-parameter Weibull distribution well.

Tab. 4- Regression coefficients at different stress levels (PUC1500)

stress level	regression coefficient a	regression coefficient b	u=exp（b/a）	correlation index R^2
0.90	0.6194	5.2121	4513	0.961
0.85	0.4886	5.1211	35638	0.918
0.75	0.5226	5.9312	84915	0.937
0.65	0.5823	7.179	226092	0.961

Tab. 5 - Fatigue life under different survival rates (PUC1500)

stress level	u	a	L_R					
			0.95	0.9	0.8	0.7	0.6	0.5
0.90	4513	0.6194	37	119	400	854	1526	2497
0.85	35638	0.4886	82	356	1654	4321	9013	16832
0.75	84915	0.5226	289	1145	4813	11810	23483	42111
0.65	226092	0.5823	1378	4741	17202	38494	71333	120484

Establishment of fatigue equation

The fatigue life is calculated by Equation (3) :

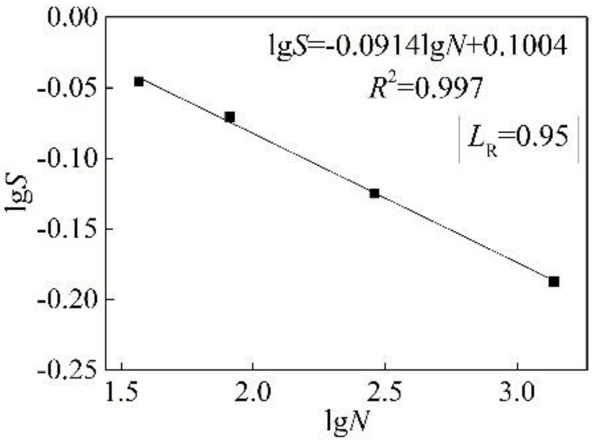
$$N = u\left|\ln\left(L_R\right)\right|^{1/\alpha} \tag{7}$$

The fatigue life under different survival probability was calculated by using Weibull function fitting results and Equation (7), as shown in Table 5.

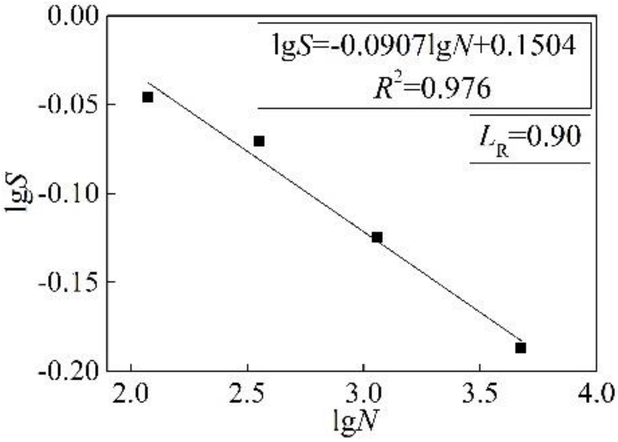
In engineering, the dual logarithmic fatigue equation is generally adopted for fatigue analysis:

$$\lg S = \lg\alpha - b\lg N \tag{8}$$

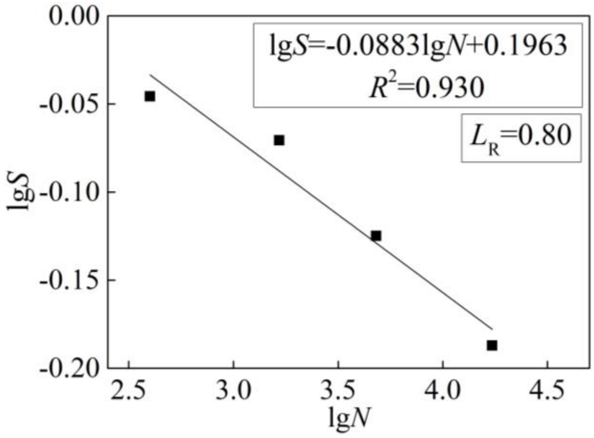
The relation curve and regression equation of *S-N* are shown in Figure 6.



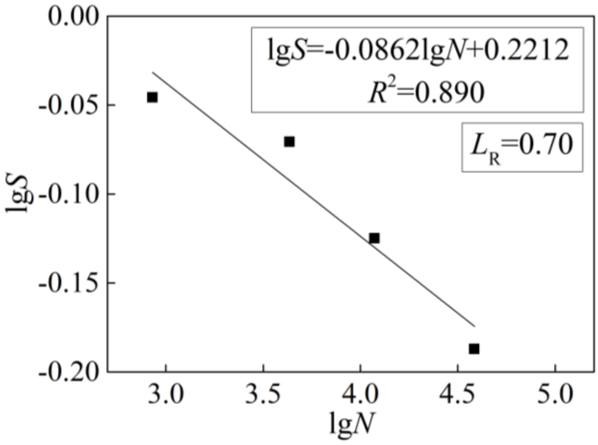
(a) L_R=0.95



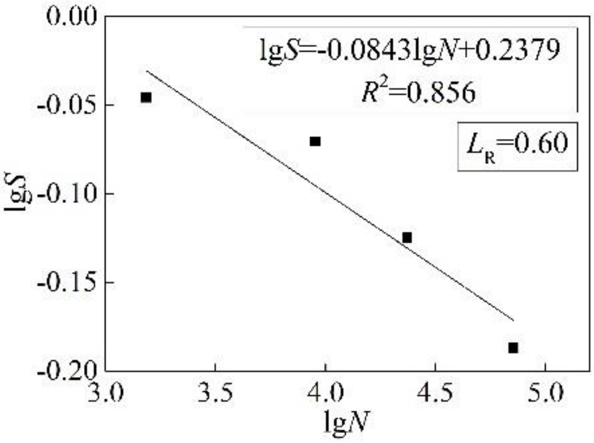
(b) L_R=0.90



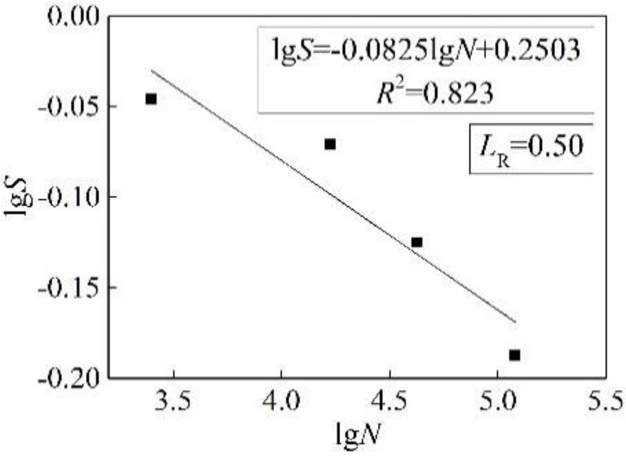
(c) L_R=0.80



(d) L_R=0.70



(e) L_R=0.60



(f) L_R=0.50

Fig. 6 - S-N regression curve and PUC fatigue equation （PUC1500）

The *S-N* fitting line equation with a survival rate of 0.5 in PUC1500 is shown in Equation (9) :

$$\lg S = -0.08820\lg N+0.2910 \qquad R^2 = 0.991 \tag{9}$$

The failure probability of PUC1200 and PUC800 specimens was analysed. The results show that the fatigue life of PUC1200 and PUC800 also conforms to Weibull distribution, and the S-N relation curve with the survival rate of 0.5 is as follows:

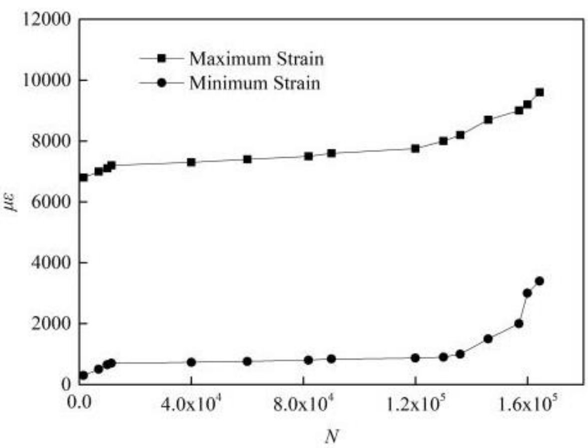
$$\lg S = -0.08430\lg N+0.2754 \qquad R^2 = 0.982 \tag{10}$$

$$\lg S = -0.09329\lg N+0.3248 \qquad R^2 = 0.992 \tag{11}$$

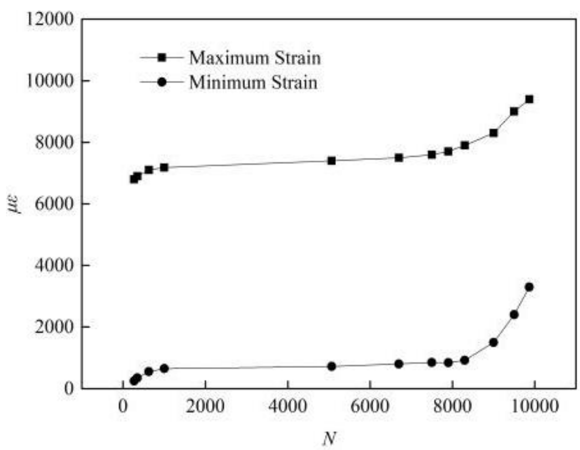
According to the S-N curve, the lgN and lgS of PUC1500, PUC1200 and PUC800 at the survival rate of 0.5 all conform to the linear relationship and fit well. According to the fatigue curves of PUC materials at different densities, the fatigue life of PUC1500 is the largest.

Strain analysis

Based on the dynamic strain acquisition instrument, PUC1500 samples were tested for the relationship between longitudinal maximum and minimum strain and fatigue life under flexural fatigue load. The resulting PUC1500 ε-N curve is shown in Figure 7.



(a) L_R=0.90



(b) L_R=0.85

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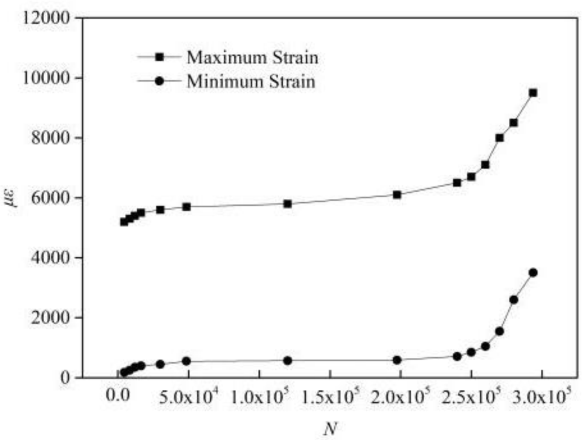
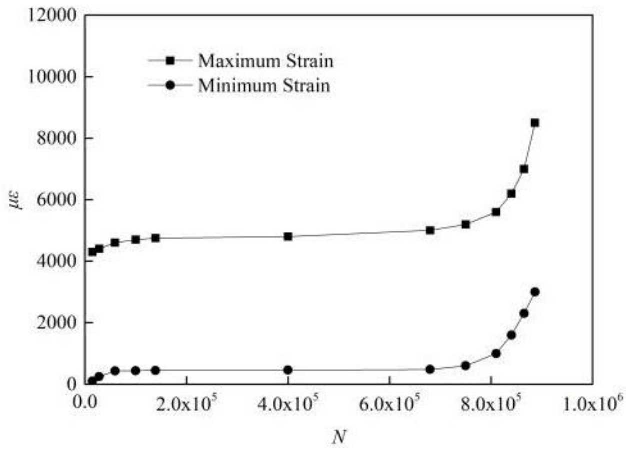


(c) L_R=0.75



(d) L_R=0.65

Fig. 7 - Curve of PUC1500 strain - fatigue life under different stress levels

As shown in Figure 7, under bending fatigue load, the variation rule of PUC1500 fatigue strain can be roughly divided into three stages: In the first stage, the fatigue strain increases rapidly. In the second stage, the fatigue strain increases linearly with the increase of fatigue times. In the third stage, the fatigue strain increases rapidly, which eventually leads to instability and failure.

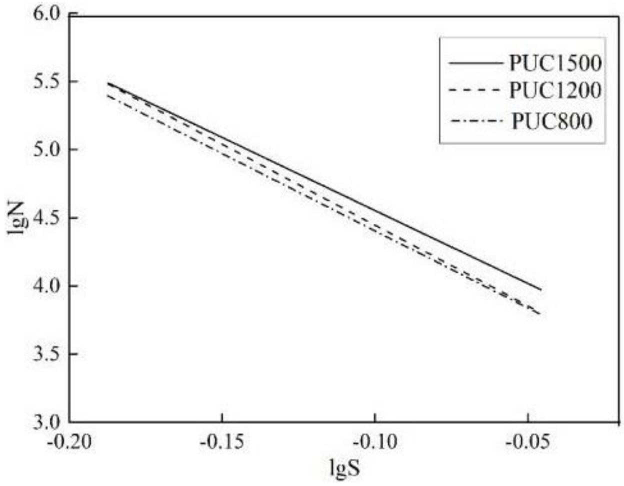


Fig. 8- Comparison of fatigue performance of PUC for all cases

The fatigue life equations for a survival probability of 0.5 were presented in Figure 8. Result indicates that PUC1500 has the maximum fatigue life among all the mixtures investigated. The fatigue life in descending order is PUC1500, PUC1200, and PUC800. Therefore, using the high density could enhance the flexural fatigue strength of PUC.

CONCLUSION

Through trabecular flexural fatigue tests, PUC material fatigue life basic obeys two parameter Weibull distribution, and through the mathematical model established the double logarithm fatigue equation under different failure probability.

According to the fatigue performance of PUC with three densities, the fatigue life equation of PUC1500, PUC1200 and PUC800 with a failure probability of 0.5 was obtained. PUC1500 has the highest fatigue life, and the fatigue life of PUC material decreases with the decrease of material density.

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Under flexural fatigue load, the variation rule of the fatigue strain of PUC can be roughly divided into three stages.

The fatigue life equations of PUC with different density for a survival probability of 0.5 were compared. The result indicates that PUC1500 has the maximum fatigue life among all the mixtures investigated. The fatigue life in descending order is PUC1500, PUC1200, and PUC800.

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