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Research Article

Study on Fatigue Test and Life Prediction of Polyurethane Cement Composite (PUC) under High or Low Temperature Conditions

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There are many diseases in the deck pavement of long-span steel bridges under the action of vehicles, rainwater, and freezing. It is necessary to study a new type of pavement material with high waterproof property, light weight, and high bonding performance for steel deck pavement. Polyurethane cement composite (PUC) can be used for steel deck pavement. In order to find out the temperature effect on fatigue properties of PUC, the four-point bending fatigue test was carried out at different temperatures. In this paper, the optimum mix ratio of PUC was selected by compressive and flexural tests, and then the bending fatigue test was conducted under strain control mode. Under temperature and external force coupling condition, a method for predicting fatigue life of PUC is proposed by the combination of theoretical deduction and experimental research. The results show that the proposed formula can effectively describe the fatigue life and fatigue limit of PUC. Finally, compared with three different asphalt mixtures for steel deck pavement, it is found that the fatigue performance of polyurethane cement is better than that of asphalt mixture.

1. Introduction

Bridge deck pavement is an important part of the bridge. As an interface directly acting with the wheels, it bears various loads from traffic and environment and plays an important role [1, 2]. The performance of bridge deck pavement is directly related to the high-speed, safe, and comfortable operation of vehicles [3–5]. At present, asphalt mixture is most widely used in the pavement materials of existing steel bridges due its advantages of low cost, small weight, and convenient maintenance [6, 7]. A large number of diseases such as slippage, cracking, rutting, and bulging appeared in the steel bridge pavement, which can directly affect the comfort and safety of driving. After the bridge deck pavement was damaged, the steel deck would be exposed to the natural environment. Water and salt ions are more likely to contact the steel roof from the cracks in the pavement. The steel is corroded, and durability of the steel bridge is reduced [8, 9]. In terms of the diseases of asphalt mixture in steel bridge deck pavement, polyurethane cement composite (PUC) can eliminate the diseases in asphalt mixture. PUC has large tensile deformation capacity and good bonding with steel bridge deck. PUC is a new kind of material with excellent mechanical properties of high tensile strength, large ultimate deformation, high modulus of elasticity, and excellent bonding performance. Thus, PUC has great advantages in steel bridge deck pavement materials [10–12].

Polyurethane is widely used at present. Polyurethane is a kind of synthetic material with excellent properties such as wear resistance, temperature resistance, and good comprehensive mechanical strength. Many scholars have carried out a series of studies on its excellent performance in civil engineering materials. Wang et al. added ordinary Portland cement and ultrafine cement with different components to polyurethane, and the ripening time was observed, and bond strength, compressive strength, and flexural strength were tested. The polyurethane grouting material can be used to strengthen the coal mine rock mass, which meet the requirements of the industry, and the strengthening method was safe for the coal mine and other industries [13]. Li et al.

applied polyurethane to modify cement mortar and mixed it with river sand and ordinary Portland cement. The strength and durability of polyurethane modified cement mortar were studied experimentally. The permeability, frost resistance, and dry shrinkage resistance of polyurethane modified cement mortar were significantly better than those of ordinary cement mortar. The strength and fluidity of polyurethane modified cement mortar were significantly improved due to the addition of water reducing agent [14]. Wang et al. poured polyurethane foaming material to form polyurethane cured ballast bed. The freeze-thaw test and fatigue test showed that polyurethane ballast bed had small residual deformation, durable elasticity, and low maintenance cost [15].

PUC has the characteristics of light weight, high strength, good toughness, and strong bonding performance, and it also has good frost resistance, impermeability, and corrosion resistance. Hussain et al. obtained PUC composite by mixing polyurethane with fly ash. The flexural, compressive, and bonding tests of the composite were carried out. The stress-strain curves, elastic modulus, Poisson's ratio, and bonding strength with concrete under different densities were obtained. On the basis of material research, seven T-section beams were tested for flexural strengthening under different damage degrees. The results showed that the ultimate bearing capacity of beams strengthened with PUC can be significantly improved, and the crack width of strengthened beams can be significantly reduced [16]. Yang et al. studied the performance of hollow slab bridges strengthened with polyurethane concrete. The results showed that the influence line of transverse load distribution of hollow slab bridges strengthened with polyurethane concrete was gentler than that of original bridge and the transverse overall mechanical performance of the bridge was significantly improved [17]. Wang et al. have strengthened the Baixi Bridge with polyurethane concrete composite; the polyurethane concrete composite can improve the bearing capacity of the structure. The strengthening method can be carried out in construction without interruption of traffic [18].

However, when PUC is used in practical engineering structures, it will be in the actual working environment. Engineering structures are usually directly exposed to the natural environment, and they are affected by periodic changes in atmospheric temperature and bending fatigue loads caused by vehicle loads. The superstructure and pavement structure of bridge subjected to bending fatigue load are particularly critical. Fatigue is a phenomenon caused by the accumulation of irrecoverable strength attenuation under repeated loads. The more the repeated loads are, the more severe the strength damage is and the less stress or strain the material can bear. The bridge superstructure and pavement structure are the main components to bear live load, and their fatigue performance determines the safety and durability of the whole bridge [19, 20]. In order to ensure the fatigue performance and durability of bridge superstructure and pavement structure, the fatigue performance of PUC under actual working environment should be studied. Therefore, it is of great scientific significance to study the fatigue properties of PUC considering temperature effect.

2. Materials and Methods

Polyurethane is generally defined as a polymer containing a repetitive polyurethane bond unit -[-NH-CO-O-]- in the main chain of the polymer. The structure of polyurethane is -[-CO-NH-R-CO-O-R-O-]n-, which is usually synthesized by step-by-step polymerization of binary or polyisocyanates with two or more active hydroxides [21, 22]. Polyurethane materials are widely used in various fields because of their excellent properties. Polyurethane has low thermal conductivity, good bonding property, good waterproofing property, and good durability and protects the environment. It is used as a new type of environmental protection material. The polyurethane cement has fast setting speed and high early strength, which can be used for rapid repair of concrete and pavement structure.

Polyurethane cement is mixed with cement and polyurethane, and the properties of the composite can be obviously improved after solidification. It is a new kind of organic-inorganic composite material with high strength and toughness.

2.1. Materials

2.1.1. Cement. The cement uses 42.5R ordinary silicate cement. The physical and mechanical properties of the cement are shown in Table 1.

2.1.2. Polyurethane. Polyurethane (PU) is a general term for polymers containing urethane groups. The urethane groups are formed by chemical reactions of compounds containing active hydrogen, such as isocyanate group and hydroxyl group. The chemical reaction schematic diagram is shown in Figure 1. The polyurethane used in this study is made in the laboratory, including two components, which is mainly composed of polyaryl polymethylene isocyanate and polyether combinations.

Polyaryl polymethylene isocyanate is abbreviated as PAPI, or crude MDI, and it is commonly known as black material. It is a mixture of isocyanate and diphenylmethane diisocyanate containing a certain amount of higher functionality, which is a brown liquid at room temperature. The polyaryl polymethylene isocyanate type used in this experiment is WANNATE® PM-200. WANNATE® PM-200 has macromolecule to increase structural integrity and flexibility, while other polyurethane made from small molecule PAPI is fragile and brittle. PAPI liquid is viscous, and its consistency decreases with the increase of temperature [23]. The composition of the main substances is shown in Figure 2, and the physical and chemical properties are shown in Table 2.

The main components of polyether combinations (commonly known as white material) are polyether polyols, silicone oil, and epoxy catalyst EZ01, which is a colorless transparent liquid at room temperature. The type of polyether combinations used in this experiment is ES305. The composition of the main substances is shown in Figure 3, and the physical and chemical properties are shown in Table 3.

Table 1: Physical and mechanical properties of cement.

Flexural strength		Compressive strength		Setting time		Fineness
3 days	28 days	3 days	28 days	Initial setting time	Final setting time	
4.6 MPa	10.5 MPa	24.6 MPa	55.6 MPa	240 min	276 min	1.8%

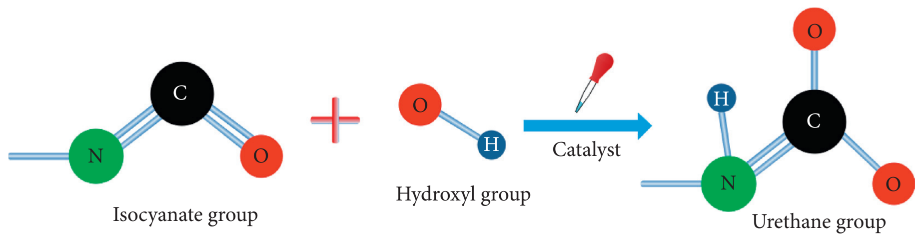


Figure 1: Schematic diagram of chemical reaction of urethane group.

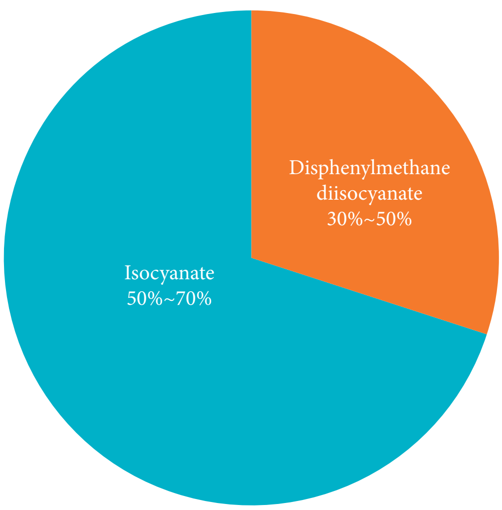


Figure 2: Material composition of WANNATE® PM-200.

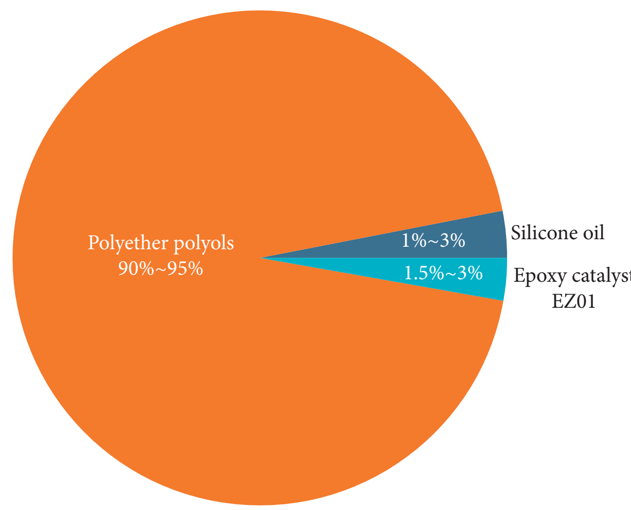


Figure 3: Material composition of polyether combinations.

Table 2: Physical and chemical properties of WANNATE® PM-200.

No.	Category	Index
1	Appearance	Brown liquid
2	Viscosity (25°C) (mPa·s)	150~250
3	Isocyanate content (-NCO) (%)	30.5~32.0
4	Density (25°C) (g/cm^3)	1.220~1.250
5	Acidity (%)	≤0.030
6	Hydrolyzed chlorine (%)	≤0.20

Table 3: Physical and chemical properties of polyether combinations.

No.	Category	Index
1	Appearance	Colorless transparent liquid
2	Viscosity (25°C) (mPa·s)	200~1500
3	Hydroxyl value (mg KOH/g)	30.5~32.0
4	Density (25°C) (g/cm^3)	1.11 ± 0.20

2.1.3. Catalyst. Dabco MixCO2 is used as catalyst of tertiary amine containing Dabco structure. The appearance of Dabco MixCO2 is colorless transparent liquid.

The composition of polyurethane prepared in this study is shown in Figure 4.

2.2. Preparation Process. The Preparation process of polyurethane cement is as follows:

(1) The cement is fried and dehydrated.

(2) Isocyanate and polyether combinations are mixed in the designed proportion. The mixing process is stirred for 2 minutes evenly.

(3) Cement and catalyst are added into polyurethane solution with stirring at high speed for 2 minutes.

(4) The polyurethane cement mixture is put into the mould after the mixture is more uniform. Then, the specimens are poured and cured for 24 hours.

The operation flow of preparation process is shown in Figure 5.

FIGURE 4: Composition of polyurethane. (a) Polyaryl polymethylene isocyanate WANNATE® PM-200. (b) Polyether combinations ES305. (c) Catalyst Dabco MixCO2.

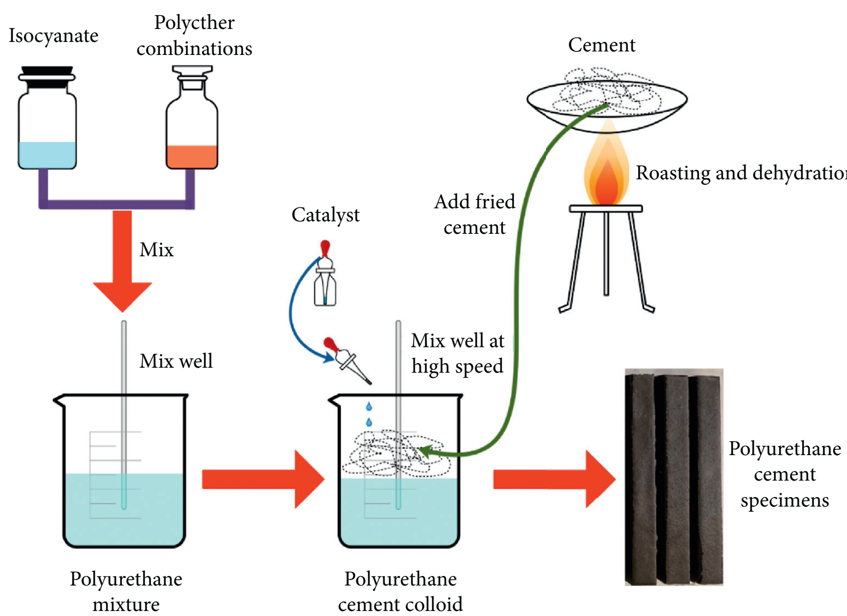


FIGURE 5: Preparation process of polyurethane cement.

3. Compressive and Flexural Tests of PUC

3.1. Mix Proportion of PUC. There are few studies on polyurethane cement. Different molecular chain structures of polyurethane can be designed by the ratio of isocyanate and polyether combinations. Different molecular chain structures determine the different properties of polyurethane cement composite. In this paper, four mix ratios were designed, which were divided into four groups: A, B, C, and D. The effects of different polyurethane and cement ratios ($P:C$) on the compressive and flexural properties of polyurethane cement composite were compared. The ratio of polyurethane and cement ($P:C$) of the four groups were 2:1, 1:1, 1:0.67, and 1:0.5, respectively. Table 4 lists the mix ratios used in this experiment.

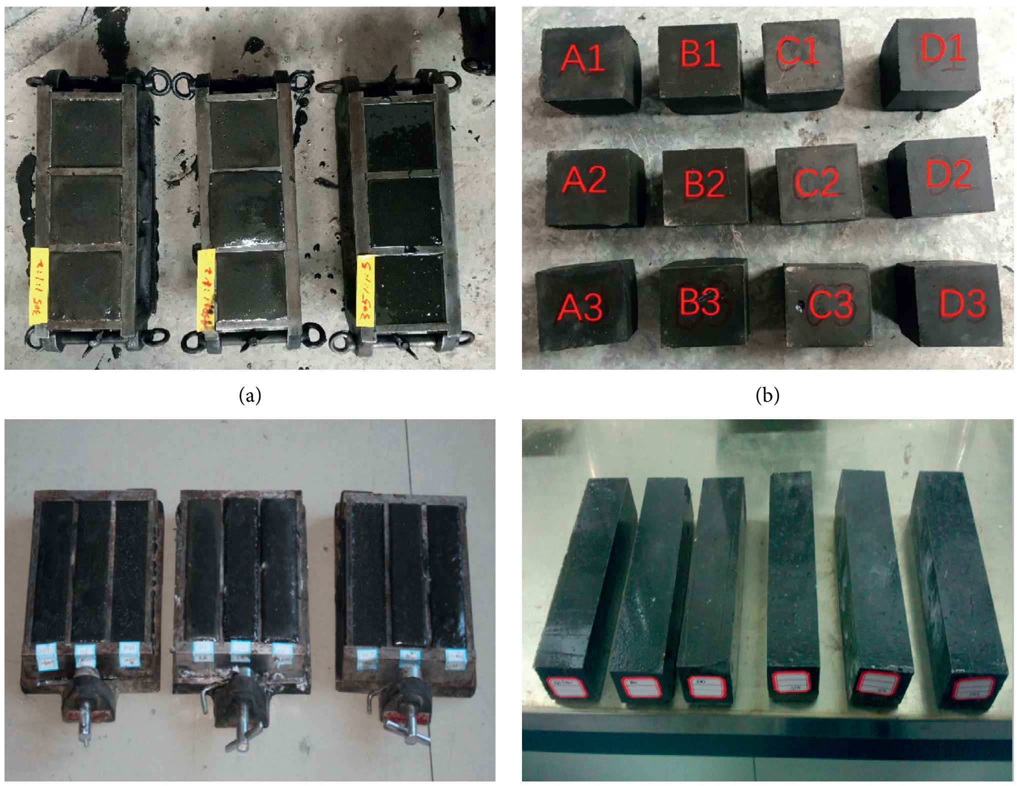
3.2. Specimen Preparation and Loading. Compressive strength specimens are made of cube with the size of 70 mm × 70 mm × 70 mm. Flexural strength specimens are made of cuboid with the size of 40 mm × 40 mm × 160 mm. The preparation process of the specimens is shown in Figure 6.

All specimens were taken out after solidification and then tested. The specimens were loaded by the TYA-2000 electro-hydraulic pressure testing machine. In order to obtain the complete load-displacement curves of the test specimens, the loading system adopted displacement control mode. The loading rate was 0.1 mm/s. Resistance strain gauges were pasted on the surface of cube blocks along the horizontal and vertical directions, respectively, which measured the strain changes of specimens during the compression process. Resistance strain gauges were pasted on the top, bottom, and middle of the cuboid specimens along the horizontal direction at the middle span, which measured the strain changes of the top and bottom edges of the specimens during the bending process.

3.3. Test Results and Analysis. The failure mode was toughness during polyurethane cement specimens during

Table 4: Mix proportion of PUC.

No.	Material composition (mass ratio)				
	Isocyanate WANNATE® PM-200	Polyether combinations ES305	Cement	$P:C$	Catalyst
A	1	1	1	2	0.02
B	1	1	2	1	0.02
C	1	1	3	0.67	0.02
D	1	1	4	0.5	0.02



(a) (b)

(c) (d)

Figure 6: Preparation of polyurethane cement specimens: (a) pouring and curing of compressive specimens, (b) demoulding and numbering of compressive specimens, (c) pouring and curing of flexural specimens, and (d) demoulding and numbering of flexural specimens.

the process of compression. The concrete on the surfaces of group C and D specimens peeled off slightly. With the increase of $P:C$, the surfaces of group A and group B specimens were basically complete with no obvious peeling phenomenon. The proportion of polyurethane with larger ductility increased with the increase of $P:C$ during the compression process, which made the specimens have greater ductility and toughness.

In the process of flexural test, the group C and D specimens ruptured immediately after loading to the peak load and showed typical brittle failure. The group A and B specimens appeared to have bottom-up irregular cracks along the lower edge of the middle span, which lasted a long time and showed strong toughness. The content of polyurethane in the specimens was large, which gave full play to the advantages of high ductility and toughness of polyurethane and played a role of toughening and anticracking.

The density, compressive strength, and flexural strength of each group PUC specimens are shown in Table 5. With the increase of $P:C$, the density of PUC decreased gradually from 1698 kg/m^3 in group D to 1552 kg/m^3 in group A, but the change range of compressive and flexural strength was very small. The change range of compressive strength was only 66.3 MPa to 67.7 MP and that of flexural strength was only 42.9 MPa to 43.9 MPa. The results showed that the change of $P:C$ ratio had little effect on the compressive and flexural strength of specimens, but it had great influence on the compressive and flexural modulus of elasticity. From group A to group D, the compressive and flexural modulus of elasticity for PUC increased by 76% and 235%, respectively. The phenomenon indicated that the deformation ability of PUC was decreasing.

The stress-strain curves of compressive and flexural strength of each group PUC specimens are shown in

Table 5: Test values of compressive and flexural strength for PUC.

No.	Density (kg/m^3)	Compressive strength (MPa)	Compressive modulus of elasticity (MPa)	Flexural strength (MPa)	Flexural modulus of elasticity (MPa)
A ($P:C=2$)	1552	66.3	2659	42.9	4748
B ($P:C=1$)	1602	66.6	3087	43.2	6470
C ($P:C=0.67$)	1648	67.5	3783	43.4	9990
D ($P:C=0.5$)	1698	67.7	4693	43.9	15914

Figures 7 and 8. It can be seen that the slopes of the stress-strain curves from group A to group D specimens were increasing, which coincided with the increasing elastic modulus of PUC. The ultimate strains of group A and B were much larger than that of group C and D. According to the above analysis, the performance of group A and B is better than that of group C and D. For group A and group B specimens, the compressive strength and flexural strength are basically the same, and the ultimate strains are similar. But the polyurethane content in group A is very high and the cost is expensive. The mix ratio of group B is more suitable for engineering application. Thermal fatigue properties of polyurethane cement with group B mix ratio will be studied in the following.

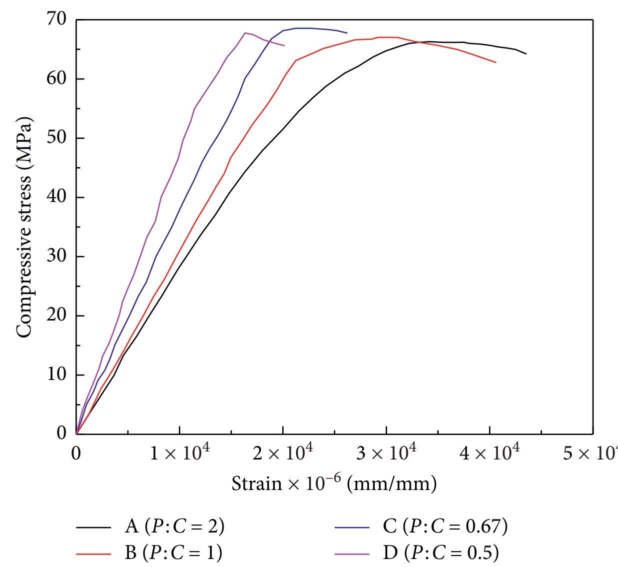


Figure 7: Compressive stress-strain curves of polyurethane cement.

4. Thermal Fatigue Test of PUC

4.1. Specimen Size and Preparation. The four-point bending fatigue test is used as the main test method [24–26], as shown in Figure 9. The specimen size (length × width × height) is 380 mm × 50 mm × 63.50 mm. The specimens of PUC are shown in Figure 10.

4.2. Test Method. The four-point bending fatigue method is adopted in this temperature fatigue test. The loading modes are divided into heating or cooling load by temperature control box and fatigue load by the IPC global UTM-30 test system. The fatigue testing system (UTM-30) can automatically record test data such as load, displacement, and load cycle numbers of specimens.

Firstly, the target temperature of the temperature control box is set to the temperature required for the test. After a period of time, the temperature in the temperature box can reach the set temperature. But at this time, the internal temperature of the specimens in the temperature box cannot necessarily reach the set temperature. After the temperature reaches the set value for 6 hours, the internal and external temperature of the specimens can basically reach the balance. Then, fatigue loading is carried out. In this fatigue test, strain load control mode is adopted, and nonintermittent partial sinusoidal wave is used as the standard loading waveform. The loading frequency is 10 Hz. The strain control levels are 400 $\mu\varepsilon$, 600 $\mu\varepsilon$, 800 $\mu\varepsilon$, 1000 $\mu\varepsilon$, and 1200 $\mu\varepsilon$, respectively. The temperature control levels range from −50°C to 50°C and are divided into 11 grade temperature levels by one level at 10°C.

Normally, if the specimen has not been destroyed when the number of load cycles reaches 2×10^6, the test can be stopped. According to the relevant civil engineering codes, if the specimen is not destroyed after 2×10^6 cycles of cyclic loading, it is considered that the specimen can withstand infinite cycles of loading, that is, it has infinite life.

4.3. Thermal Fatigue Test Results and Analysis. The fatigue life test results of PUC specimens at different temperatures and strain levels are listed in Table 6. When the test temperature is different, the fatigue test results (temperature fatigue test curves) of PUC specimens are shown in Figure 11. Figure 11 shows that there is an approximate linear relationship between temperature fatigue life N (logarithm) and strain level ε of PUC specimens. The least squares method is used for regression analysis of the data at different test temperatures, and the expression of the ε-N curve of PUC specimens is as follows:

$$\varepsilon = \mathrm{A}\lg N + B, \tag{1}$$

where ε is strain level ($\mu\varepsilon$), A and B are regression parameters, which are determined by test conditions, loading mode, and material properties, and N is bending fatigue life.

Based on the fatigue test data in Table 6, the fatigue equations of PUC specimens are obtained by linear fitting, which are listed in Table 7. Fitted fatigue curves are plotted in Figure 11. From the correlation coefficient R in Table 7 and the fitting curves in Figure 11, it can be seen that the fitting fatigue equations of PUC specimens have a good correlation with the fatigue test data.

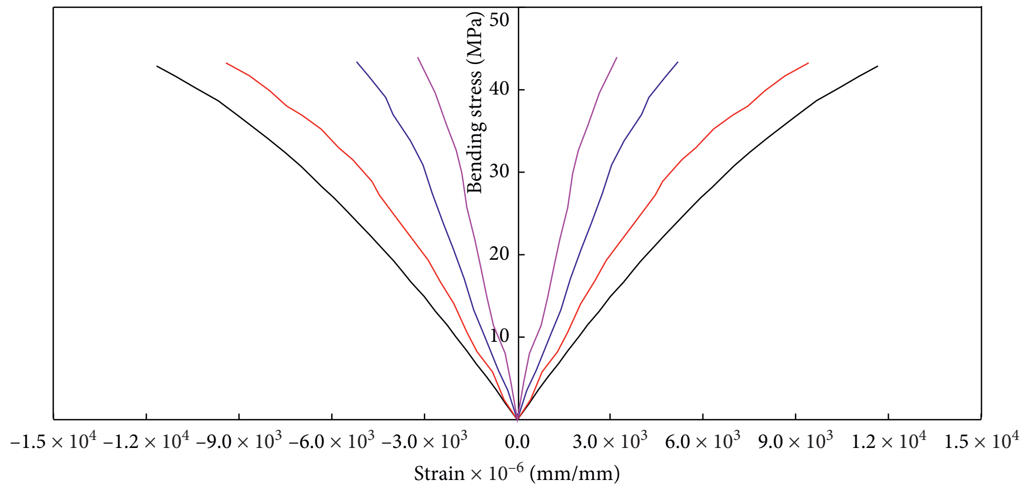


Figure 8: Flexural stress-strain curves of polyurethane cement.

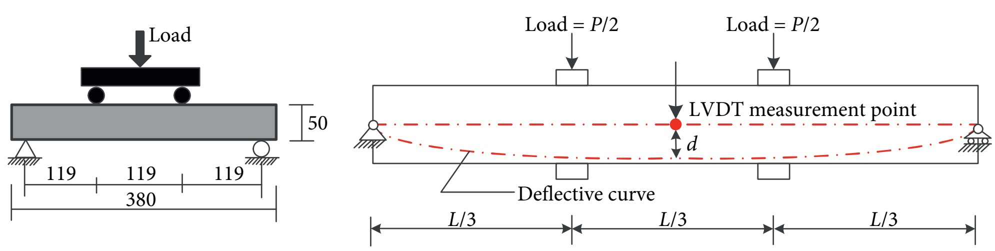
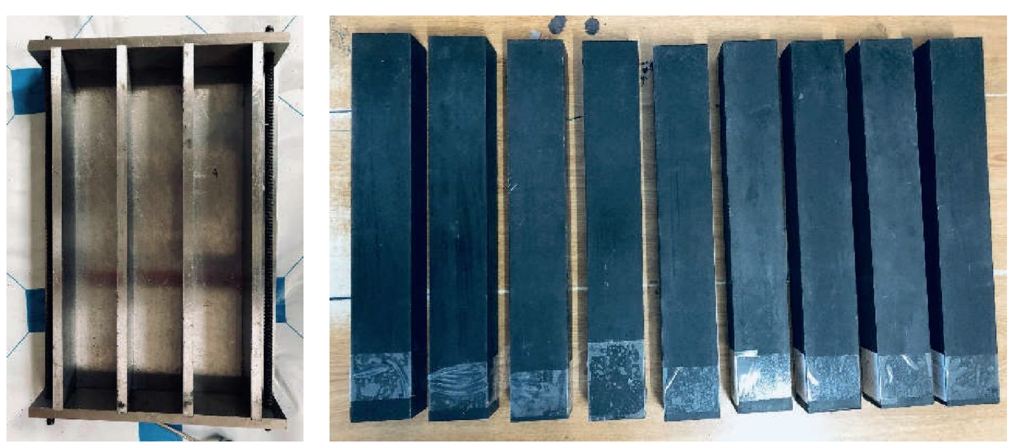


Figure 9: Loading schematic diagram of the four-point bending fatigue test (unit: mm).



(a) (b)

Figure 10: (a) Mould and (b) specimens of polyurethane cement.

Figure 12 shows the fatigue life curves of PUC specimens at different temperature levels. The ambient temperature has a significant effect on the fatigue life of specimens. At the same temperature level, the fatigue life of polyurethane cement specimens decreases with the increase of strain. At the same strain level, the fatigue life of specimens decreases with the decrease of temperature in the range of test temperature. At low strain level, the fatigue life slope of specimens with temperature ranging from 0°C~50°C decreases considerably, while that of specimens with temperature ranging from 10°C~50°C decreases very little, which may be related to the fact that only 2×10^6 times of fatigue tests are carried out. At high strain level, the fatigue life slope of specimens with temperature

Table 6: Fatigue life of polyurethane cement specimens at different temperatures.

No.	Strain level ($\mu\varepsilon$)	−50°C	−40°C	−30°C	−20°C	−10°C	0°C	10°C	20°C	30°C	40°C	50°C
		Fatigue life (number)										
1	400	392631	518763	747390	993724	1498270	>2000000	>2000000	>2000000	>2000000	>2000000	>2000000
2	400	319479	428807	684336	1085284	1665185	>2000000	>2000000	>2000000	>2000000	>2000000	>2000000
3	400	449539	678972	814969	911322	1762258	>2000000	>2000000	>2000000	>2000000	>2000000	>2000000
4	600	192460	365785	383470	632548	1076777	1344321	1734708	>2000000	>2000000	>2000000	>2000000
5	600	244095	290690	442520	695192	1011678	1479783	1854321	>2000000	>2000000	>2000000	>2000000
6	600	156358	255897	490959	589397	1146744	1282322	1777940	>2000000	>2000000	>2000000	>2000000
7	800	84235	163918	246023	398959	656776	890059	1381245	1539169	1745695	>2000000	>2000000
8	800	97053	140931	218287	425446	603375	814969	1459213	1398270	1659952	>2000000	>2000000
9	800	116493	198305	283462	342926	589297	970538	1401234	1678341	1847462	>2000000	>2000000
10	1000	39885	89709	144525	276848	398859	617789	1034321	1232846	1398270	1527104	>2000000
11	1000	50268	107677	126229	244095	354450	695192	1089471	1153423	1286365	1591601	>2000000
12	1000	58929	80858	152710	208220	432195	583844	1115234	1333478	1505625	1458934	>2000000
13	1200	23430	41880	78352	152114	242182	471274	814769	955353	1107718	1204523	1527104
14	1200	20336	57013	73571	123284	262010	422111	759246	897051	1043410	1252403	1453428
15	1200	27467	49874	91132	146818	221750	453059	854321	1068336	1204082	1283428	1603479

ranging from 0°C~50°C decreases considerably, while that of specimens with temperature ranging from 10°C~50°C increases, but the slope is still less than that of specimens with low temperature. The fatigue performance of polyurethane cement is poor at low temperature, which can be improved obviously with the increase of temperature. According to the bending fatigue equation of polyurethane cement listed in Table 7, the fatigue life surface at different temperatures and strain levels can be obtained, as shown in Figure 13.

5. Discussion

5.1. Thermal Fatigue Life Analysis

5.1.1. Expression of Fatigue Life under Temperature Coupling. According to the physical and mechanical properties of polyurethane cement composite, the working environment temperature has an important influence on the fatigue properties. The main components of polyurethane cement are polyurethane and cement. The thermal expansion coefficients of polyurethane and cement are different. Polyurethane cement also generates thermal stress when temperature changes, even without external load. Thermal stress will affect the fatigue properties of polyurethane cement [27].

Temperature has a great influence on the fatigue properties of polyurethane cement. Therefore, the effect of external forces and temperature should be considered in calculating the fatigue life of polyurethane cement specimens. Referring to the power function expression $S^m N = C$ of S~N curve in classical fatigue theory, it is assumed that the expression of temperature fatigue life of polyurethane cement specimens is as follows [28, 29]:

$$S^{m(T)}N = C, \tag{2}$$

where S is stress or strain, $m(T)$ is a function of material performance parameters related to temperature, N is the number of load cycles or fatigue life, and C is a constant.

For formula (2), take logarithms on both sides:

$$m(T)\lg S = \lg C - \lg N. \tag{3}$$

Then,

$$\lg S = \frac{\lg C - \lg N}{m(T)}. \tag{4}$$

Write S in the form of Taylor series:

$$S = \sum_{n=0}^{\infty} \frac{[(A/m(T))(\lg C - gN)]^n}{n!}, \tag{5}$$

where A is a constant. Formula (5) is expanded to preserve the constant term and the linear term:

$$S \approx 1 + \frac{A}{m(T)}(\lg C - gN). \tag{6}$$

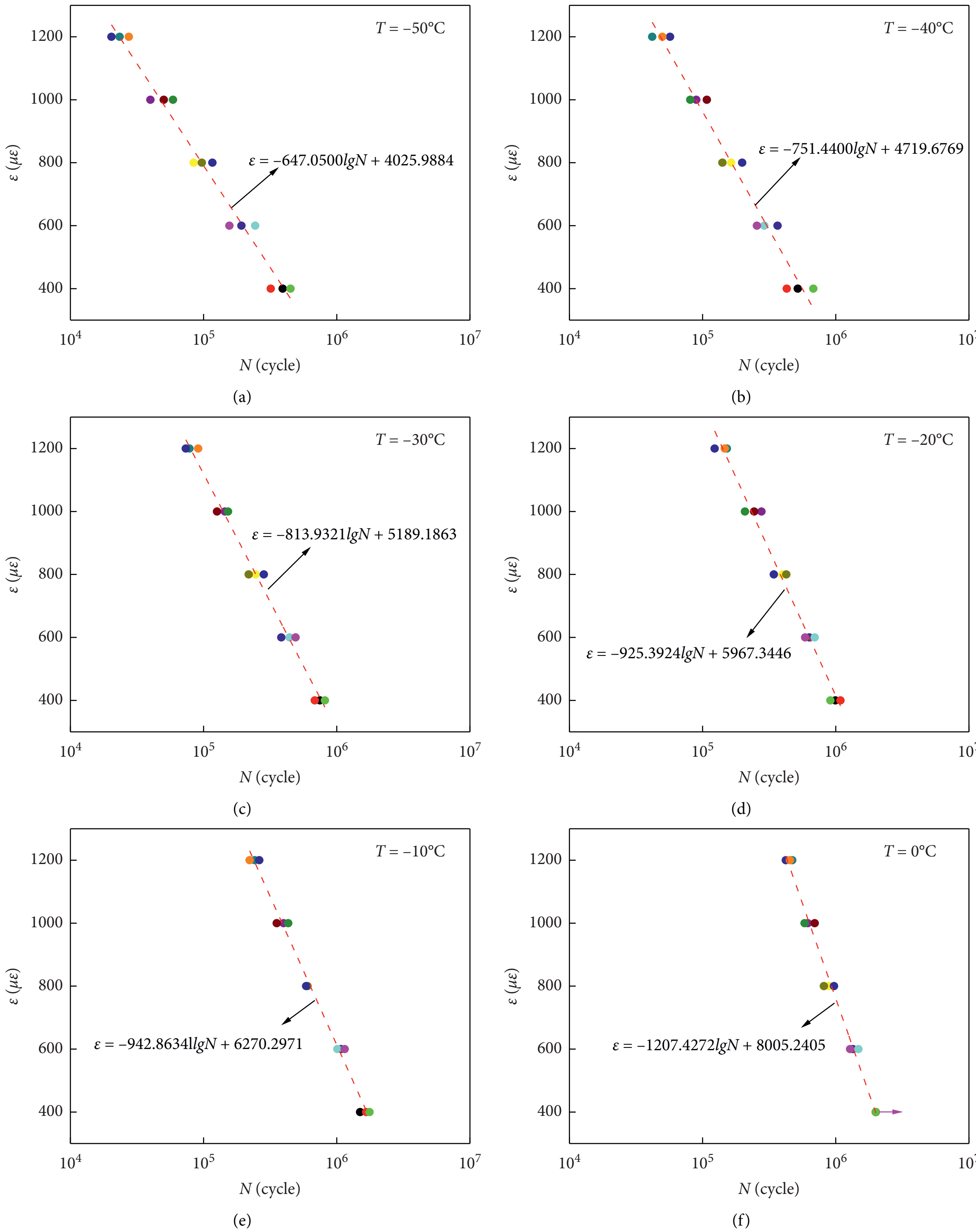


Figure 11: Continued.

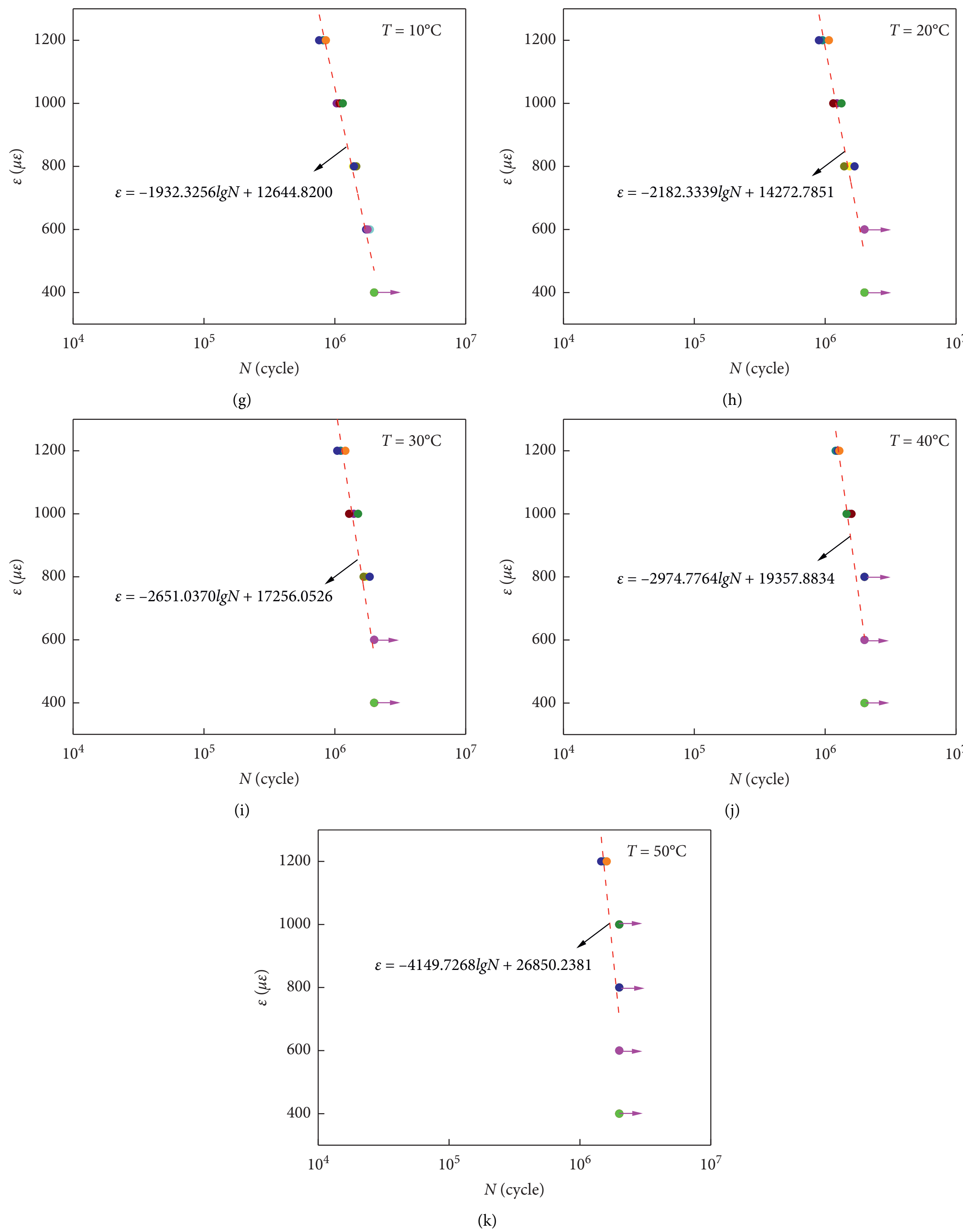


FIGURE 11: Fatigue life results and fitting curves at different temperatures: (a) $T = -50^\circ$C, (b) $T = -40^\circ$C, (c) $T = -30^\circ$C, (d) $T = -20^\circ$C, (e) $T = -10^\circ$C, (f) $T = 0^\circ$C, (g) $T = 10^\circ$C, (h) $T = 20^\circ$C, (i) $T = 30^\circ$C, (j) $T = 40^\circ$C, and (k) $T = 50^\circ$C. Note: the data points with symbol ●→ in the figure indicate that the fatigue life is greater than 2×10^6 times.

Table 7: Bending fatigue equation of polyurethane cement.

No.	Temperature level	Fatigue equation	Correlation coefficient R
1	−50°C	$\varepsilon = -647.0500 lgN + 425.9884$	0.9755
2	−40°C	$\varepsilon = -751.4400 lgN + 4719.6769$	0.9682
3	−30°C	$\varepsilon = -813.9321 lgN + 5189.1863$	0.9857
4	−20°C	$\varepsilon = -925.3924 lgN + 5967.3441$	0.9812
5	−10°C	$\varepsilon = -942.8634 lgN + 6272.2971$	0.9892
6	0°C	$\varepsilon = -1207.4277 lgN + 8005.2405$	0.9858
7	10°C	$\varepsilon = -1932.3256 lgN + 12644.8200$	0.9651
8	20°C	$\varepsilon = -2182.3339 lgN + 14272.7852$	0.9054
9	30°C	$\varepsilon = -2651.0370 lgN + 17256.0256$	0.9697
10	40°C	$\varepsilon = -2974.7764 lgN + 19357.8834$	0.9397
11	50°C	$\varepsilon = -4149.7268 lgN + 26850.2381$	0.9471

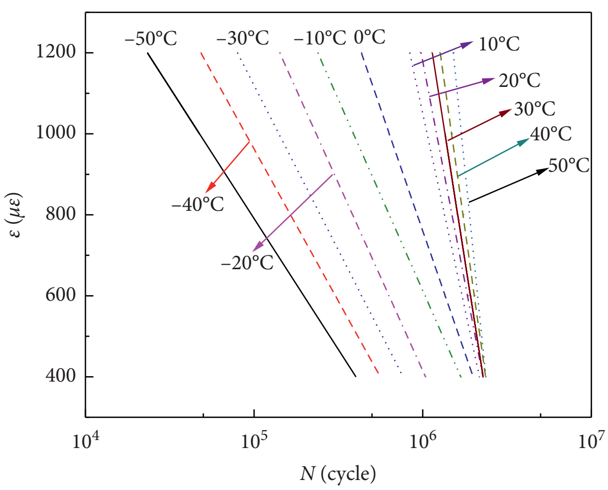


Figure 12: Fatigue life curves at different temperatures.

From Hooke's law expression $S = E\varepsilon$, the maximum tensile strain is calculated as

$$\varepsilon_t = \frac{12\delta h}{3L^2 - 4a^2}, \tag{7}$$

where ε_t is the maximum tensile strain, δ is the maximum strain at the center of the beam, and a is the center distance between adjacent chucks ($L/3$, generally 0.119 m).

Substitute formula (7) into formula (6) to obtain

$$\delta = \frac{3L^2 - 4a^2}{12Eh}\left[1 + \frac{A}{m(T)}(\lg C - \lg N)\right]. \tag{8}$$

Let us assume that the expression of $m(T)$ is

$$m(T) = \frac{A}{A_1 + A_2 e^{A_3 T}}, \tag{9}$$

where $A_1 \sim A_3$ are constants.

Substitute formula (9) into formula (8) and get the following expression after sorting out:

$$\delta = C_1 + C_2 f(T) + [C_3 + C_4 f(T)] f(N). \tag{10}$$

In formula (10), the temperature function is

$$f(T) = e^{C_5 T}, \tag{11}$$

$$f(N) = \lg N. \tag{12}$$

$C_1 \sim C_5$ in formula (10) and (11) are the coefficients to be constant, which are determined by the experimental data. The maximum strain level δ in fatigue test is taken as load, and the unit of temperature T is °C. The fatigue life and fatigue limit of polyurethane cement specimens can be easily estimated by formulas (10)–(12) considering the influence of working environment temperature.

5.1.2. Empirical Formula for Thermal Fatigue Life. According to the fatigue test data of 11 test temperatures listed in Table 6, multivariate nonlinear fitting is carried out to fit the fatigue test data by using formulas (10)–(12). The formula for calculating the fatigue life of polyurethane cement specimens under the coupling action of external force and temperature can be obtained by determining the coefficient $C_1 \sim C_5$.

$$\delta = 2452 + 6135 e^{0.02834t} - \left(410 + 897.7 e^{0.02834t}\right) f(N). \tag{13}$$

The complex correlation coefficient of formula (13) is $r = 0.9215$. Figure 14 shows scatter plots of fatigue life and a fitted fatigue life surface at different temperatures and strain levels. The fatigue life and fatigue limit of polyurethane cement specimens can be easily estimated by formula (13) considering the working environment. The fatigue limit of polyurethane cement specimens can be obtained by substituting $N = 2 \times 10^6$ into formula (13). The fatigue limit corresponding to different temperatures is drawn in Figure 15. It can be seen from Figure 15 that the relative strain fatigue limit of polyurethane cement specimens increases with the increase of temperature in the working environment temperature range of this study. The fatigue limit of polyurethane cement is very small when the temperature is below −30°C, which indicates that the fatigue life of polyurethane cement is very difficult to reach 2×10^6 times at low temperature (below −30°C).

5.2. Comparison of Fatigue Performance between PUC and Asphalt Concrete. The fatigue problem of steel box girder bridge deck pavement has always been a hot issue and an

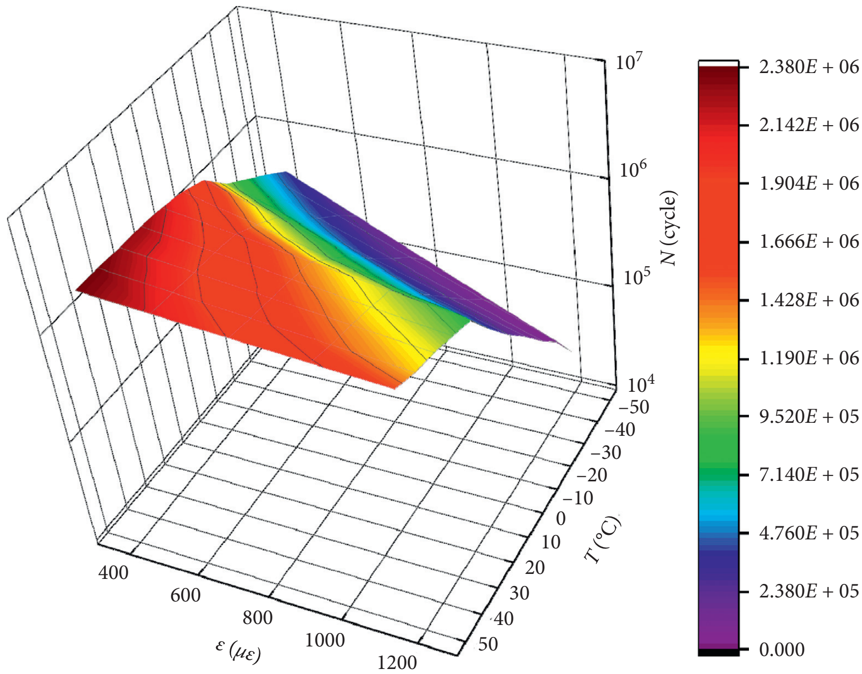


Figure 13: Fatigue life surface.

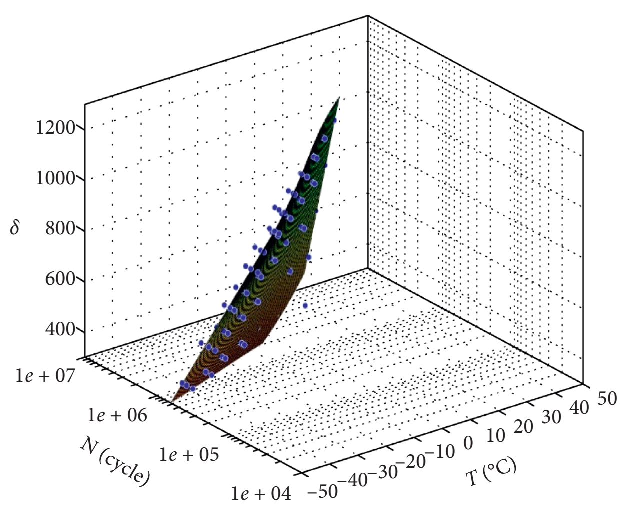


Figure 14: Temperature fatigue life surface and scattering points.

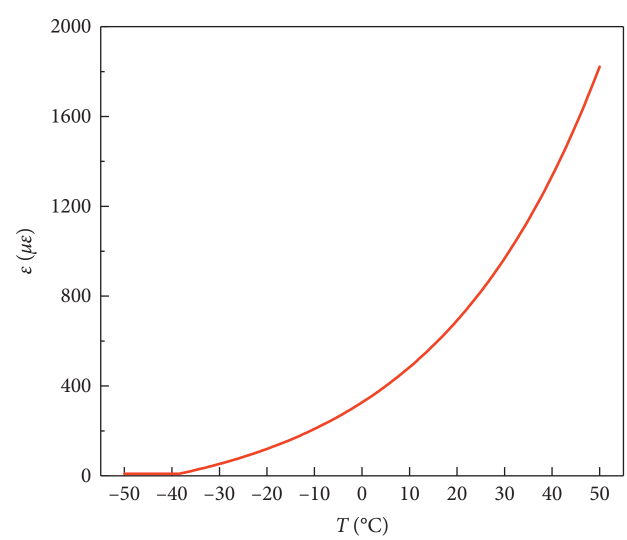


Figure 15: Effect of temperature on strain fatigue limit of polyurethane cement.

urgent engineering problem in the field of steel bridge deck pavement [30, 31]. At present, steel bridge deck pavement mainly uses three kinds of materials: gussasphalt concrete, Stone matrix asphalt (SMA) mixture, and epoxy asphalt concrete. Polyurethane cement composite is also suitable for steel bridge deck pavement because of its high toughness.

Wang et al. [32] analyzed the fatigue properties of three different steel deck pavement materials by the four-point bending fatigue test under strain control mode. The fatigue life results of polyurethane cement and Wang et al.'s three asphalt concretes are listed in Table 8. They are compared in Figure 16.

At different strain levels, polyurethane cement has the largest fatigue life and $N_{PUC} > N_{SMA} > N_{GA} > N_{EA}$. However, the fatigue life of the four materials is similar at the strain level of 600 $\mu\varepsilon$. With the increase of strain level, the fatigue life slope of polyurethane cement decreases slightly and that of modified asphalt SMA10 decreases moderately. However, the fatigue life slopes of gussasphalt concrete GA10 and epoxy asphalt concrete EA10 decrease greatly.

Table 8: Fatigue life comparison between polyurethane cement and asphalt concrete (10^4).

No.	Strain level ($\mu\varepsilon$)	N_{GA}	N_{SMA}	N_{EA}	N_{PUC}
1	600	166	172	159	178.9
2	800	104	124	87	141.4
3	1000	9.3	75	8.1	108.0

Note. N_{GA} represents fatigue life of gussasphalt concrete GA10; N_{SMA} represents fatigue life of modified asphalt concrete SMA10; N_{EA} represents fatigue life of epoxy asphalt concrete EA10; N_{PUC} represents fatigue life of polyurethane cement.

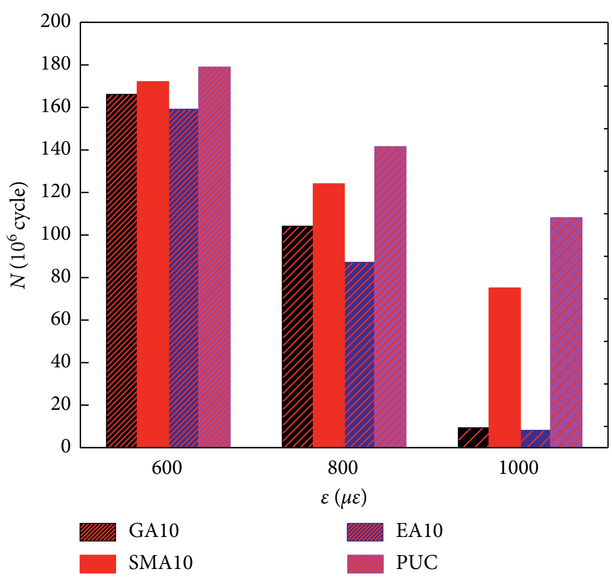


Figure 16: Fatigue life comparison of polyurethane cement and asphalt concrete.

6. Conclusions

In this paper, the composition and preparation process of polyurethane cement composite are introduced firstly. Then, the mix proportion of polyurethane cement is selected through the compression and bending test. Finally, the four-point bending fatigue test is carried out under different temperatures and strain levels. The fatigue life prediction model is proposed. The conclusions are as follows:

(1) The mixing ratio of polyurethane cement has little influence on compressive strength and flexural strength, but it has a great influence on compressive and flexural modulus of elasticity. Polyurethane cement with mixing ratio of 1 has the best performance.

(2) Temperature and strain have a great influence on the fatigue life of polyurethane cement. The fatigue life increases with the increase of temperature, but it decreases with the increase of strain.

(3) According to the classical fatigue equation and the influence factors of temperature, a fatigue life prediction model of polyurethane cement is proposed, which can evaluate the fatigue life and limit under the joint action of temperature and strain.

(4) The fatigue life of polyurethane cement is longer than that of asphalt concrete (gussasphalt concrete, polymer modified asphalt concrete, and epoxy asphalt concrete). Polyurethane cement can be used as a good material for steel bridge deck pavement.

Data Availability

The data used to support the findings of the study are included within the article and supplementary information file.

Conflicts of Interest

The authors declare no conflicts of interest.

Acknowledgments

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Supplementary Materials

This section contains Matlab code. Figure 8: compressive stress-strain curves of polyurethane cement. Figure 9: flexural stress-strain curves of polyurethane cement. Figure 15: fatigue life curves at different temperatures. Figure 16: fatigue life surface. Figure 18: effect of temperature on strain fatigue limit of polyurethane cement. (*Supplementary Materials*)

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