Green Buildings and Materials
Volume 2, Issue 1, No. 2
Received 9 February 2024; Accepted 15 March 2024
Published online 1 April 2024

Preliminary study on the fatigue performance of fiber reinforced geopolymer composites

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Abstract. Geopolymer concrete (GC) is a kind of green material due to its low CO_2 emission in the manufacturing process without cement. To explore more engineering properties for its future application in the projects, the fatigue performances need to be revealed. Past research has indicated that the use of fibers in geopolymer concrete can increase the fatigue properties by counteracting the brittle nature of the material. In this study, we aimed to investigate the flexural strength and fatigue life of the GC with basalt fiber (BF) and polypropylene fiber (PF) by testing 60 specimens under four-point flexural fatigue. The results indicated that the flexural strength and flexural fatigue life of the GC with fibers were improved significantly compared to those without fiber. It was further found that the flexural strength and flexural fatigue life can be increased by up to 20% and 136.12% respectively. The statistical distribution of the fatigue life was identified to follow the two-parameter Weibull distribution. Furthermore, the coefficients of the fatigue equation were obtained corresponding to different failure probabilities and can be used to predict the flexural fatigue strength for the desired level of failure probability. Overall, this study revealed the fatigue behavior of GC with fibers and the results derived can provide further guidance on the fatigue life of fiber reinforced geopolymer composites.

Keywords. Geopolymer, basalt fiber, polypropylene fiber, flexural strength, fatigue behavior.

1. Introduction

Geopolymer concrete (GC) is an environmentally friendly substitute for ordinary Portland cement concrete (OPC), which presents several advantages in terms of low carbon emissions [1-2] and superior chemical resistance and better mechanical properties [3-8]. Most concrete structures are typically exposed to millions of cycles of repetitive fatigue loads during their service life. Under fatigue loads, the fracture strength of concrete structures is always below its maximum strength. Fatigue behavior is closely related to the development of concrete cracks. Similar to ordinary Poland cement concrete, geopolymer concrete is a brittle material by nature and thereby faces the same fatigue problem. Considering previous research showed that prior to the fracture of concrete, adding fibers, the concrete enabled control of cracking through fiber bridging, allowing the material to withstand plastic deformation. Therefore, the addition of fibers to develop fiber reinforced geopolymer composites (FRGC) in order to improve the fatigue properties of geopolymer concrete can be considered to be a potential method to counteract the brittle nature of the material.

Previous research on basalt fiber (BF) and polypropylene fiber (PF) reinforced geopolymers showed improvement in fracture toughness of the concrete. It was found that the presence of PF in the concrete matrix greatly increased its fracture behavior and ductility [9].The immediate failure of the specimens within the crack region is prevented due to the bridging effect of the fibers that results in a transfer of stress to other regions of the specimen. The polypropylene fibers display a high tensile strength that has the ability to increases the energy absorption characteristics of the composites [10].

When the geopolymer subjected to internal and external forces, the PF deforms in an elastic manner rather than any deformation of harmful pores which results in a enhancement of strength and roughness [11].

Moreover, it was found that for the pure concrete, a rapid deduction in the load was identified when there was an increase in specimen deflection after peak load.

In the case of hybrid fiber-reinforced concrete, the addition of PF was noted to influence the toughness of the material as the decrease trends were flatter compared to pure concrete [12]. Same as for BF, 0.5% vol. fraction reinforcement significantly enhanced the strength and toughness of the concrete [13]. However, the fatigue performance of fiber-reinforced geopolymer concrete is barely reported. Therefore, two types of PF and one type of BF reinforced geopolymer concrete were tested in this study and the influence on fatigue life was analyzed. At the same time, the fatigue properties of cement concrete and plain geopolymer concrete were also tested and compared. The results can provide reliable references for future design and application in the geopolymer concrete field.

2. Materials and methods

2.1. Materials

Crushed stone with a maximum nominal particle size of 22 mm was used as coarse aggregate in the concrete. The fine aggregate used consisted of natural sand with particle size of smaller than 4 mm. The chemical composition of Class F fly ash is provided in Table 1. The median particle size of the fly ash was 13.504 µm. The alkali activator for the concrete consisted of Sodium Silicate (SS) solution and Sodium Hydroxide (SH), and was prepared by dissolved sodium hydroxide particles with purity of 98% pellets in distilled water (The molarity of the SH solution is 11.4mol/L.). The silica modulus (Ms) of SS solution was 3.23 (Ms= SiO2/Na2O, Na2O= 8.83%, SiO2 = 27.64% by mass). The alkaline activator was prepared 24 h prior to mixing of the concrete to achieve ionization equilibrium. Two different types of nonmetallic fiber were used, namely PF and BF, whose properties are listed in Table 2.

Table 1. The chemical composition of fly ash

Compounds	SiO_2	Al_2O_3	CaO	Fe_2O_3	MgO	K_2O	SO_3	TiO_2	Na_2O
(%)	50.76	27.32	5.4	4.64	3.72	4.85	2.0	1.16	0.8

Table 2. Physical and mechanical properties of fibers

Type of fiber	Density (kg/m³)	Diameter (mm）	Length (mm)	Compressive strength（MPa)	Elasticity modulus（GPa)	Elongation at break（%）
PF	920	11	9	560-650	3.5-8	15
BF	2650	7-15	9	4150-4800	100-110	3.3

2.2. Mix proportions

A total of five concrete mixes (designated as OPC, GC, PF10, PF15 and BF15) were prepared in the present study, including one OPC mix and four geopolymer concrete mixes with different fiber dosages and types. PF10 and PF15 were fly ash-based geopolymer composites with PP fiber content of 1.0 kg/m³ and 1.5 kg/m³, respectively. BF15 was a fly ash-based geopolymer concrete containing basalt fiber of 1.5 kg/m³. Both OPC and four GPC mixes were designed to achieve the C50 strength grade. Table 3 shows the detailed mix proportions of all the five concrete types.

Table 3. Concrete mix design（kg/m³)

Mix proportion	OPC	GC	PF10	PF15	BF15
Coarse aggregate	1008	1201	1201	1201	1201
Fine aggregate	700	539	539	539	539
Cement	552	0	0	0	0
H_2O	171	0	0	0	0
Superplasticizer	1.656	0	0	0	0
Fly ash	0	460	460	460	460
Sodium silicate solution	0	133.4	133.4	133.4	133.4
NaOH	0	20.9	20.9	20.9	20.9
H_2O	0	45.8	45.8	45.8	45.8
PF	0	0	1	1.5	0
BF	0	0	0	0	1.5

2.3. Mixing procedure and preparations of specimens

To prevent the agglomeration of fibers, the fly ash and all the aggregates were firstly dry mixed in a pan mixer for 1–2 mins prior to adding the fibers. After adding the fibers, pre-mixed alkali solutions were gradually poured into the mixer for a further 2–3 mins until a uniform mixture was attained.

The geopolymer concrete was covered with plastic sheet to prevent moisture loss, and cured at 80℃ in an oven for 24 h. The OPCs were cured at ambient temperature for 24 h after the casting. The specimens were then demolded and cured under a standard fog room condition for 3 months to ensure the GC was sufficiently cured.

The compressive strength was tested according to GB/T 50081-2002 using 150 mm×150 mm ×150 mm cubic specimens, and the static flexure strength was tested with 100 mm×100 mm×400 mm prismatic specimens. The number of specimens is shown in Table 4.

Table 4. Stress levels and number of specimens

Samples	The number of specimens for flexural tests	The number of specimens for fatigue tests			
		S=0.70	S=0.75	S=0.80	S=0.90
OPC	3	3	0	3	3
GC	3	3	0	3	3
PF10	3	3	3	3	0
PF15	3	3	3	3	0
BF15	3	3	3	3	0

2.4. Methods

The flexural strength of prismatic specimens (100 mm×100 mm×400 mm) adopted the four-point method with 0.2 kN/s acceleration speed, and the compressive strength of the cubic specimens (150 mm×150 mm ×150 mm) adopted a loading speed of 10 kN/s.

The fatigue tests for concrete specimens were conducted by testing prism specimens with a dimension of 100 mm×100 mm×400 mm using EHF-UM servo-hydraulic machine with 5t capacity. In applying the fatigue load, a constant amplitude cyclic loading was adopted under load control. The loading regime can be characterized by a sinusoidal waveform, as shown in Figure 1. In order to avoid the void phenomenon by zero drift in long-time testing, the characteristic value of cyclic load R was set to 0.1.

The frequency is commonly within the range of 3-10Hz [14-20], and 5Hz was adopted as the variable frequency to simulate the worst-case scenario. Before commencing each fatigue test, static preloading of 1kN was applied on the specimens to ensure the proper initial load setting. The maximum number of cycles was set to 2 million. Note that some tests were stopped without reaching the maximum number of fatigue cycles due to failure of the specimens that occurred earlier.

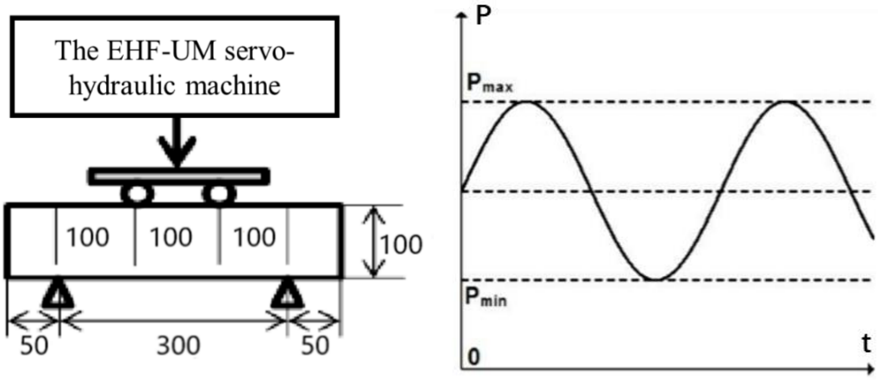


Figure 1. Loading method

3. Results and discussion

3.1. Flexure strength and compressive strength of concrete under static load

Table 5. Strengths of the concrete samples

Type of concrete	Flexural strength /MPa	Compressive strength /MPa	The ratio of flexural to compressive strength
OPC	5.2	58.2	0.089
GC	5.9	55.9	0.106
PF10	6.4	58.0	0.110
PF15	6.7	58.3	0.115
BF15	6.9	59.7	0.116

The flexure strength and compressive strength are shown in Table 5. The results indicate that the flexural strength of GC increases by 14.18% while the compressive strength decreases by 3.93% compared to that of OPC. At the same time, GC also exhibited an improved toughness of concrete and also an improved the ratio of flexural to compressive strength by 19.10%. For a given type of fiber, strength increases with an increase in fiber content. The flexural strengths and compressive strength of PF10 and PF15 were 6.98% and 13.16%, 3.8% and 4.3% higher than that of GC, respectively. For the specimens containing the same content of basalt and PF, the improvement in the flexural strength was almost the same. The flexural strength of BF15 increased by 30.34% over that of OPC.

Compared with OPC, GC can greatly improve the toughness of concrete in advance of the same strength. The addition of PF and BF in plain geopolymer concrete can further improve the strength of GC along with the toughness of the concrete. This is in agreement with the results from Sukontasukkul [21] and LI Weimin [13]. BF can be identified to be effective in improving the toughness of the plain geopolymer concrete than PF at the same dosage.

3.2. Flexural fatigue tests

3.2.1. Fatigue life

The fatigue life of different types of concrete under various stress levels are shown in Table 6. The fatigue life of GC is lower than that of OPC with an identical compressive strength grade. It was because that the tested samples were at the age of 3 months. Geopolymer concrete has higher strength at an early age, its later strength development is not as fast as cement concrete, so the later fatigue life of geopolymer concrete is lower. At the same time, we can also observe that the fatigue life of geopolymer concrete with the same compressive strength grade is less discrete.

As shown in Table 6 and Figure 2, when the stress level is 0.7, the fatigue lives of PF10， PF15 and BF15 are 46590， 55600 and 67051 cycles, respectively, which is 64.07%, 95.8% and 136.12% higher than that of the GC. When the stress level is 0.8, the fatigue lives of PF10, PF15 and BF15 are 52.01%, 93.79% and 105.38% higher than that of GC, respectively. It reveals that PF and BF can significantly improve the fatigue life of geopolymer concrete. This is because that the strength and the deformability of concrete is greatly improved. At the same time, it shows that the enhancement of fatigue life is more obvious under low stress levels.

Within a certain range, the higher the content of PF, the better fatigue behavior of the geopolymer concrete has. With the same fiber content, the fatigue behavior of GC with BF was better than that using PF. Compared with PF15, the fatigue lives of BF15 increase by 20.6%, 67.49% and 5.97% at stress levels of 0.7, 0.75 and 0.8, respectively. This may be due to the elastic modulus of BF being 20-30 times higher than that of PF. In addition, because of the lower density of polypropylene, PF tend to gather in the middle and upper parts of the specimens during the geopolymer concrete mixing process, so the number of fibers in the tensile zone of the specimens is fewer [22]. Therefore, the effect of polypropylene fibers on crack inhibition is inferior to that of BF under fatigue loading.

Table 6. Laboratory fatigue-life data

Samples	OPC		GC			PF10		
	0.7	0.8	0.7	0.8	0.9	0.7	0.75	0.8
1	91946	10099	11005	2371	178	21579	46658	6087
2	92003	10178	13435	12003	222	77533	8424	16873
3	2000000*	1620511*	60751	6432	438	40658	22469	8667
Average	91975	10139	28397	6935	279	46590	25850	10542

Samples	PF15			BF15		
	0.7	0.75	0.8	0.7	0.75	0.8
1	35392	6618	11568	20584	3842	10321
2	478422*	39226	5322	453010*	34343	30847
3	75808	21866	23429	113518	75223	1562
Average	55600	22570	13440	67051	37803	14243

Note： The band * indicates that the fatigue life is quite scattered, so it is not considered in fatigue life statistics.

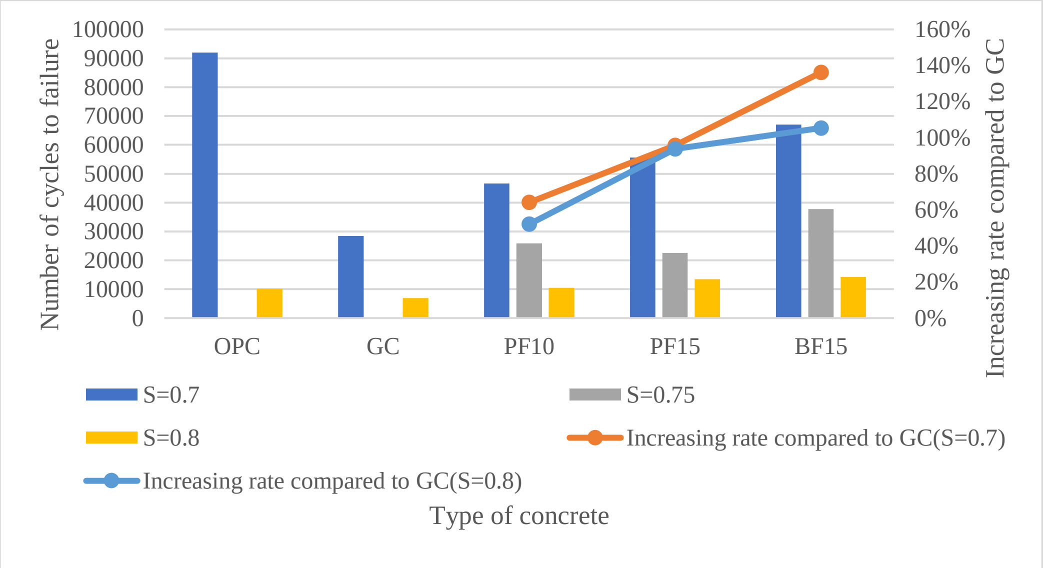
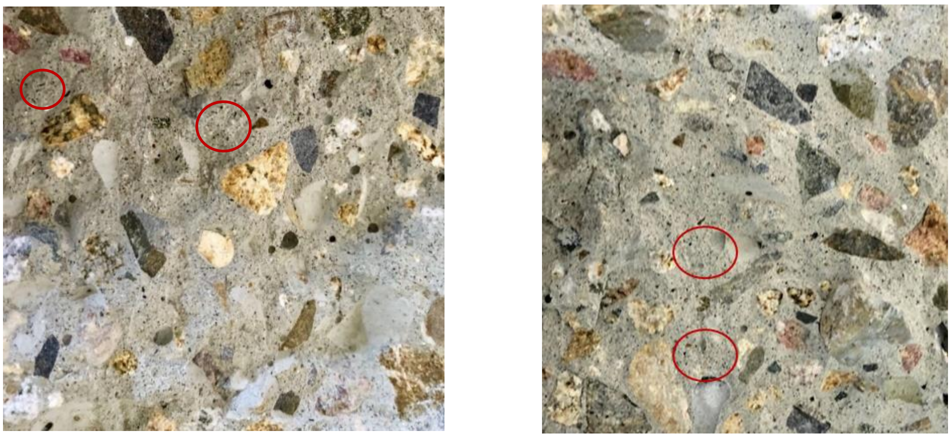


Figure 2. The fatigue-life of concrete and the increasing ratio compared with GC at different stress levels



(a) PF15 (b) BF15

Figure 3. Fracture surfaces of geopolymer concretes with fibers

3.2.2. Fracture surface of the fatigue test specimens

The fracture surfaces of FRGC are shown in Fig.3(a) and (b). The small particle size points in the figures were the fiber fractures. It could be seen that fatigue fracture surfaces of different fiber geopolymer concrete with the same content were very similar. And the fibers were distributed evenly in the matrix without any agglomeration occurring, indicating a proper mixing of the concrete. It could observe from the fracture surfaces that, at the failure, the fiber rupture occurred instead of being pulled out from the matrix. The bond between the aggregates and mortar was good. The fracture surfaces were in good agreement with the fatigue results of geopolymer concrete which were less discrete.

4. Fatigue equation at different failure probabilities

4.1. Statistical analysis method of fatigue life

Many past studies regarding the fatigue behavior of concrete have reported results that indicated that a large variability is usually seen in the fatigue life data of concrete [22-28], where this variability is affected by many factors, including material heterogeneity, specimen size, quality error, maintenance conditions, and load error [29]. Therefore, it is important to select a feasible method to process the fatigue test data.

At present, the normal distribution function and Weibull distribution statistical models are usually used for analyzing the probabilistic distribution of fatigue results. The advantage of the Weibull probability density function is that it has the minimum safe life, it can describe fatigue life when the initial strength does not follow a normal distribution and it incorporates a large number of distributions including normal distributions. The safe life or minimum safe life corresponding to the extremely high reliability range (99.99%-100%) is in accord with the real situation. Therefore, Weibull theory is often used to analyze the fatigue life of concrete in engineering [30,31]. In this study, the two parameter Weibull distribution is adopted.

Weibull probability density function：

$$\mathrm{f(N)} = \frac{b}{N_a-N_0}\left(\frac{N-N_0}{N_a-N_0}\right)^{b-1}\exp\left[-\left(\frac{N-N_0}{N_a-N_0}\right)^{b}\right], (N \geq N_0) \tag{1}$$

where N_0 is the minimum life parameter, N_a is the scale parameter, and b is the shape parameter. When b = 1, the Weibull density function is an exponential distribution; when b = 2, it is Reyleigh distribution; when b = 3.5-4, it is approximately a normal distribution.

The Weibull distribution function can be derived from the density function given in equation (1):

$$\mathrm{F(N)} = 1 - \exp\left[-\left(\frac{N-N_0}{N_a-N_0}\right)^{b}\right] \tag{2}$$

Because the equation contains three parameters N_0, N_a and b, the distribution function is called a three parameter Weibull distribution function. The minimum life of concrete specimens is $N_0 \geq 0$, and for the sake of simplicity, we take N_0=0, then formula (2) can be rewritten as follows.

$$\mathrm{F(N)} = 1 - \exp\left[-\left(\frac{N}{N_a}\right)^{b}\right] \tag{3}$$

The failure probability

$$\mathrm{P'} = \mathrm{P}\left(\mathrm{N} \leq N_p\right) = \mathrm{F}\left(N_p\right) = 1 - \exp\left[-\left(\frac{N}{N_a}\right)^{b}\right] \tag{4}$$

Taking logarithms twice on both sides of Eq. (4):

$$\mathrm{Y = bX\text{-}a} \tag{5}$$

Where $\mathrm{Y} = \mathrm{In}\left(\mathrm{In}\frac{1}{1-\mathrm{F(N)}}\right), X = \mathrm{InN}, \mathrm{a} = \mathrm{bIn}N_a$.

Eq. (5) shows that the relationship between $\mathrm{InIn}\frac{1}{1-\mathrm{F(N)}}$ and InN is linear, which can be used to verify whether the fatigue-life data follows the two-parameter Weibull distribution or not. If this relationship approximately follows a linear trend (or correlation coefficient r is high), it indicates that the data follows the two-parameter Weibull distribution.

The X value in Eq. (5) can be directly obtained from the test data, and the Y value can be obtained by the following steps.

The failure probability can be obtained by arranging the test data in the order from small to large and using empirical formulas.

$$\mathrm{P'} = \mathrm{F(N)} = \frac{j}{1+k} \tag{6}$$

F (N) is obtained from Eq. (6), and Y can be obtained by substituting F (N) into the definition of Y.

From the graph of $\mathrm{InIn}\frac{1}{p}$ along the InN continuum, points with big dispersion can be eliminated in the process of data fitting. The analysis of fatigue life data from Table 5 at all stress levels is shown in Figure 4.

In Figure 4, the Weibull distribution test results of BF15, PF10 and PF15 show a good linear trend. Thus, the fatigue life of FRGC follows the two parameter Weibull distribution. The correlation coefficient is close to 1.

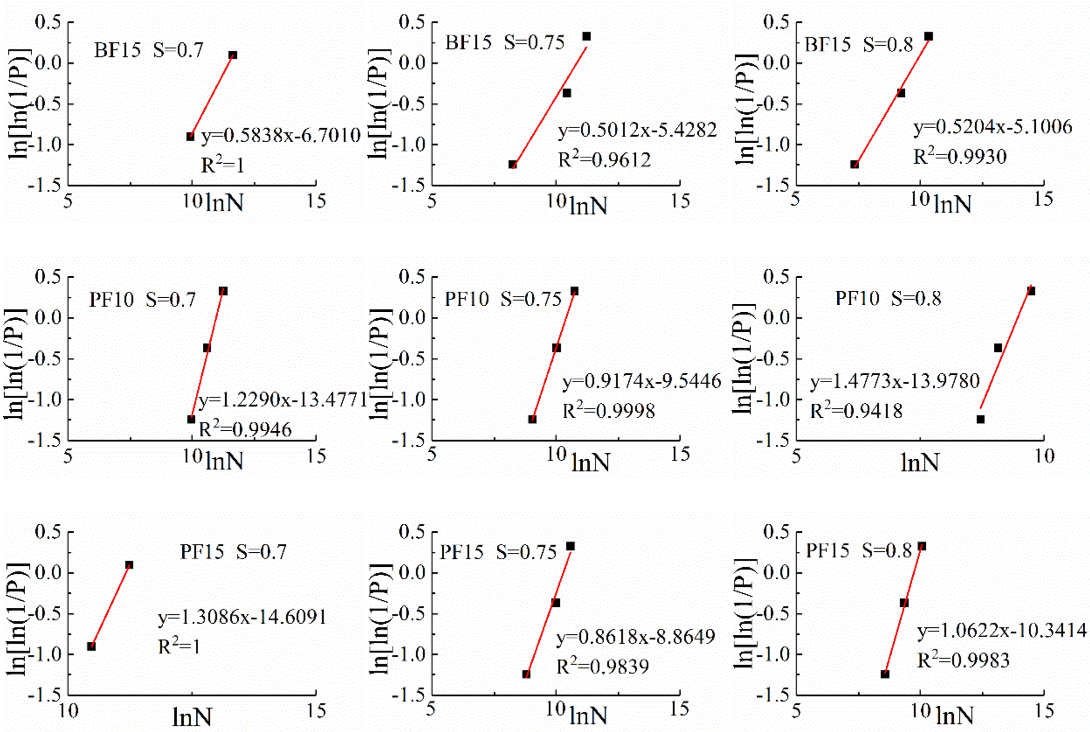


Figure 4. $\text{InIn}\frac{1}{p}$ - lnN curves of BF15, PF10 and PF15

4.2. Fatigue equations corresponding to different failure probabilities

It is necessary to establish the $P'{-}S\ {-}N$ curve and fatigue equation corresponding to different failure probabilities, based on reliability requirements. $P'{-}S\ {-}N$ curve is used to classify the fatigue life of the same type of concrete at different stress levels according to the failure probability P'. Then considering the fatigue life at different stress levels with the same failure probability P' as a whole, and draw a diagram with stress level and fatigue life based on it can be drawn. Thus, a series of curves are obtained, which are the $P'{-}S\ {-}N$ curves.

4.2.1. Fatigue life at different failure probabilities

The equation for calculating fatigue life can be derived from Eq. (3).

$$\mathrm{N} = N_a[-\mathrm{In}(1-P')]^{\frac{1}{b}} \tag{7}$$

The fatigue life corresponding to different expected failure probabilities can be calculated using Eq. (7), where the failure probabilities assumed within the range between 5% to 50%. The calculated results are shown in Table 7.

Table 7. Calculated fatigue-lives corresponding to different failure probabilities

Type of concrete	S	P'					
		0.05	0.1	0.2	0.3	0.4	0.5
BF15	0.7	596	2045	7397	16518	30560	51548
	0.75	134	564	2531	6468	13271	24441
	0.8	60	239	1011	2491	4967	8929
PF10	0.7	5162	9272	17075	25009	33499	42942
	0.75	1295	2838	6432	10724	15863	22125
	0.8	1722	2803	4659	6400	8161	10034
PF15	0.7	7289	12634	22418	32081	42215	53304
	0.75	934	2154	5146	8868	13454	19172
	0.8	1032	2032	3437	6405	8983	11973

Table 7. shows for the higher failure probability, the corresponding fatigue life will be longer. At the same time, the impact of PF on geopolymer concrete is better than that of the BF when the failure probability is low. However, with an increase of failure probability, the fatigue life of geopolymer concrete increased with the addition of BF obviously. For example, when the failure probability is 0.5, the fatigue life of BF15 exceeds that of PF10, and is close to PF15. It illustrates that for geopolymer concrete, the effect of BF is better than that of PF at a high failure probability, while the effect of PF is better than that of BF at a low failure probability.

4.2.2. Double logarithm fatigue equation at different failure probabilities

The double logarithmic fatigue equation can satisfy the boundary conditions of the fatigue model shown as Eq. (8), so it is often used to analyze the fatigue life of concrete in practice. In order to establish the double logarithmic fatigue equation, it is assumed that the fatigue life of the concrete satisfies the following relationship with the corresponding stress level at a certain failure probability.

Without considering the durability limit of concrete, the boundary conditions of fatigue equation can be expressed as follows:

$$\begin{cases} \text{when } N = 1, \ S = 1 \\ \text{when } N \to \infty, \ S \to 0 \end{cases} \tag{8}$$

$$LgS = \lg a + b \lg N \tag{9}$$

The fatigue life of BF15, PF10 and PF15 in Table 6 are analyzed by linear regression Eq. (9), thus the corresponding double logarithmic fatigue equation at different failure probabilities can be obtained. The double logarithmic fatigue equations of BF15, PF10 and PF15 (P′-lgS-lgN curve) are illustrated in Figure 5, and the correlation coefficients are shown in Table 8. The curve slope and intercept of BF15 are bigger than that of PF15, which suggests that the equivalent fatigue life of BF15 is better compared to polypropylene fiber geopolymer concrete under a two-parameter Weibull distribution.

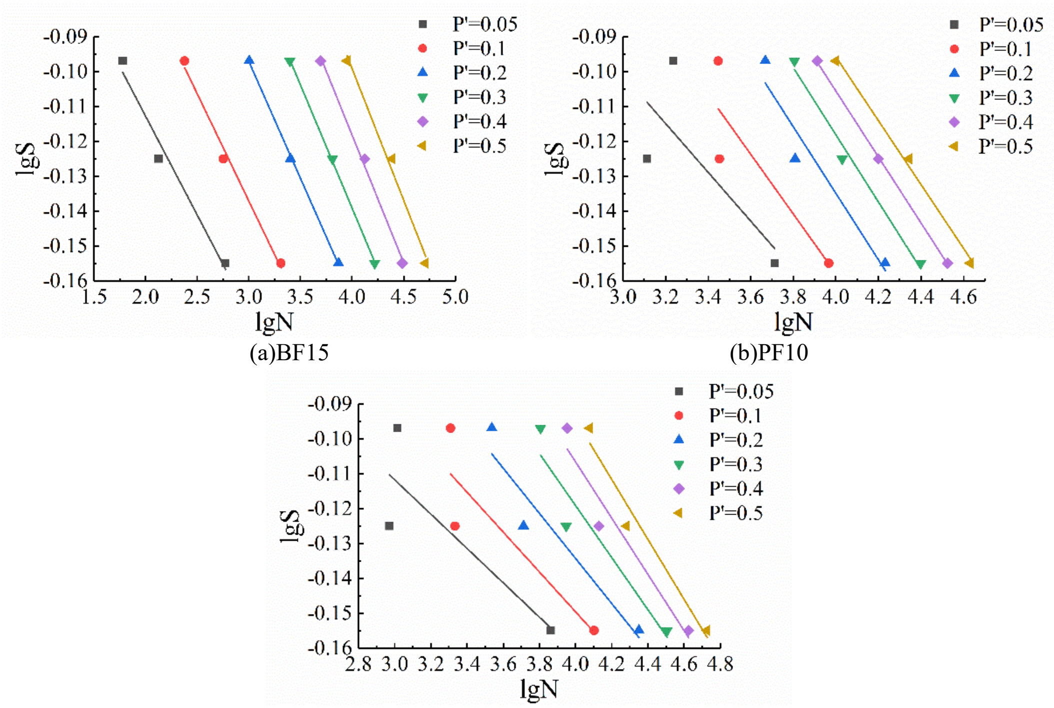


Figure 5. lgS - lnN curves of BF15, PF10 and PF15 at different failure probabilities

Table 8. Recursive coefficients

Type of concrete	P′	b	lga	R	R²
BF15	0.05	-0.0566	0.0004	0.9882	0.9766
	0.1	-0.0615	0.0475	0.9954	0.9908
	0.2	-0.0670	0.1040	0.9965	0.993
	0.3	-0.0706	0.1432	0.9997	0.9994
	0.4	-0.0733	0.1749	0.9978	0.9956
	0.5	-0.0755	0.2028	0.9945	0.989
PF10	0.05	-0.0699	0.1089	0.7643	0.5842
	0.1	-0.0855	0.1842	0.8798	0.7741
	0.2	-0.0953	0.2465	0.9655	0.9321
	0.3	-0.0963	0.2673	0.9928	0.9857
	0.4	-0.0945	0.2726	0.9999	0.9998
	0.5	-0.0915	0.2704	0.9975	0.9951
PF15	0.05	-0.0492	0.0360	0.8540	0.7293

	0.1	-0.0571	0.0790	0.8887	0.7898
	0.2	-0.0647	0.1244	0.9558	0.9136
	0.3	-0.0746	0.1793	0.9516	0.9056
	0.4	-0.0806	0.2159	0.9689	0.9388
	0.5	-0.0859	0.2491	0.9818	0.964

It can be seen from Table 8 that lgS and lgN maintain a strong linear relationship. At all stress levels, the correlation coefficients R corresponding to failure probabilities are all above 0.90 except for the failure probability P' of PF with 0.05 and 0.1. This reveals that the equivalent fatigue life of three kinds of fiber-reinforced geopolymer concrete follows the two-parameter Weibull distribution under different variable frequencies.

5. Conclusions

The fatigue performances of ordinary Portland cement concrete, geopolymer concrete and fiber-reinforced geopolymer composites were studied and compared by flexural fatigue experiments. Based on the study the following conclusions can be drawn:

(1) Compared with OPC, the ratio of flexural strength to compressive strength of GC was higher and the discreteness of fatigue life of GC was lower under the same strength condition. It provided a theoretical basis for using geopolymer concrete instead of cement concrete in construction.

(2) The flexural strength and fatigue life of geopolymer concrete can be significantly increased by adding fibers. With the same fiber content, the fatigue characteristics of BF reinforced geopolymer concrete was better than PF reinforced geopolymer concrete, and the fatigue life can be increased by up to 67.5%. Besides, the effect of fibers on improving the fatigue performances of geopolymer concrete was more significant at lower stress levels.

(3) The fatigue life of PP and BF reinforced geopolymer concrete follow a two parameter Weibull distribution, and the linear correlation coefficient was higher than 0.9.

(4) According to the fatigue test results, the double logarithmic fatigue equations of the PP and BF reinforced geopolymer concrete, considering failure probability were obtained, and the ultimate fatigue strength can be further deduced, which can guide further study on the fatigue life of fiber reinforced geopolymer composites.

Acknowledgements

We would like to thank the financial support from Sichuan Province Key Research and Development Project(24QYCX0386), the Open Fund of Sichuan Provincial Engineering Research Center of City Solid Waste Energy and Building Materials Conversion and Utilization Technology （No. GF2022ZD003).

Nomenclature

Symbols	Definitions
b	The shape parameter
BF	Basalt fiber
BF15	Fly ash-based geopolymer concrete with basalt fiber of 1.5 kg/m^3
FRGC	Fiber reinforced geopolymer composites
f(N)	The Weibull probability density function
F(N)	The Weibull distribution function
GC	Geopolymer concrete
Ms	The silica modulus of Sodium Silicate solution
N	The fatigue life
N_0	The minimum life parameter
N_a	The scale parameter
OPC	Ordinary Portland cement concrete
P'	The failure probability
PF	Polypropylene fiber
PF10	Fly ash-based geopolymer concrete with polypropylene fiber content of 1.0 kg/m^3
PF15	Fly ash-based geopolymer concrete with polypropylene fiber content of 1.5 kg/m^3
R	The characteristic value of cyclic load
SH	Sodium Hydroxide
SS	Sodium Silicate

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