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FREQUENCY EFFECT ON THE COMPRESSIVE FATIGUE BEHAVIOUR OF PLAIN AND FIBER-REINFORCED CONCRETES

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ABSTRACT

This paper presents very recent experimental results aimed at disclosing the loading frequency effect on the fatigue behaviour of a plain concrete and two types of fiber-reinforced concretes, using polypropylene and steel fibers. Compressive fatigue tests were conducted on 123 cubic specimens (100 mm in edge length). Four different loading frequencies were set as 4 Hz, 1 Hz, 0.25 Hz and 0.0625 Hz, respectively. The maximum stress applied on the specimen was 85% of the compressive strength and the stress ratio was set constant as 0.3. The results show that the loading frequency effect on the fatigue behaviour of the plain concrete is pronounced. The fatigue life (the number of cycles to failure) at the lower frequencies is less than that at higher frequencies. However, the fibers can improve the fatigue behaviour significantly under low loading frequencies. Such trend can be attributed to the effectiveness of the fibers in bridging the cracks, and thus inhibiting crack extension during the load cycles. The influence of the frequency and the improvement of the fibers can be explained comparing the strain history during the tests.

Key words: Fatigue, Fiber Reinforced Concrete, Loading Frequency, Compression

1 INTRODUCTION

Interests in the fatigue of concrete began more than a hundred years ago with the development of reinforced concrete beams. With the technological development in high-strength concrete (HSC), HSC is very often used in modern complicated structures of considerable height and span. However, HSC is more brittle than conventional concrete, so, an alternative method is performed to introduce more ductility by adding fibers into the concrete matrix, thus, a type of fiber-reinforced concrete (FRC) is made. Nowadays, the fatigue behaviour of FRC is also getting more and more attention.

Since the beginning of fatigue studies on concrete, numerous experiments have been conducted to study the influence of different fatigue parameters [1-19]. These parameters were either set by the fatigue test conditions, such as the minimum stress σ_{min}, the maximum stress σ_{max} and the loading frequency f, or determined by material properties, for example the static material strength σ_c, which can be the compressive strength f_c or the tensile strength f_t, or any other critical stress defined accordingly. Other parameters included the stress ratio R, defined as $\sigma_{min}/\sigma_{max}$, or the stress level S, defined as σ_{max}/σ_c.

Regarding the effect of loading frequency f on the fatigue life (the number of cycles to failure, N) of plain concrete, the first studies [1, 2] show that when f was between 4.5 Hz and 7.5 Hz, the loading frequency had slight effect on the fatigue life N, however, when f was lower than 0.16 Hz, the fatigue life decreased. Some other researches [6, 20] suggested that the loading frequency had minor influence on the fatigue life when the loading frequency was between 1 Hz and 15 Hz, and the maximum stress S_{max} was less than 75% of the compressive strength f_c. After that, it was shown that when S_{max} was greater 75% f_c, the loading frequency influenced N strongly [21].

The classical fatigue equation as shown in equation 1 has been proposed to describe the relation among the maximum stress, compressive strength σ_c, stress ratio R, number of cycles to failure and a material parameter β [7].

$$\frac{S_{max}}{\sigma_c} = 1 - (1 - R)\beta \log N \qquad (1)$$

The same relation was confirmed for fatigue strength of concrete in compression and in tension for splitting tests of cubes [11, 12]. Though the influence of loading frequency (or time) has been observed as early as 1960s [5] and confirmed in 1970s [8, 9, 22], it was not included until Hsu [13] and Furtak [14] updated the equation by considering the loading time and frequency. Zhang *et al*. [16] further improved the equation of Furtak by redefining the stress ratio R when there is stress reversal.

Hsu [13] proposed two models according to the fatigue life, i.e., low-cycle fatigue ($N<10^3$) for structures subjected to earthquake is expressed as equation 2; high-cycle fatigue ($10^3<N<10^7$) for airport pavements, bridges and highways is shown as equation 3, where T is the period of the repeated loads ($T=1/f$):

$$\frac{S_{max}}{\sigma_c} = 1 - 0.0662(1 - 0.556R)\log N - 0.0294 \log T \qquad (2)$$

$$\frac{S_{max}}{\sigma_c} = 1.20 - 0.20R - 0.133(1 - 0.779R)\log N - 0.053(1 - 0.445R)\log T \qquad (3)$$

Another model was developed [14] containing a frequency influence coefficient C_f to consider the effect of the loading frequency as described in equation 4:

$$\frac{S_{max}}{\sigma_c} = CN^{-A}(1 + BR\log N)C_f \qquad (4)$$

where A, B, C, a and b are adjusting parameters and C_f is determined by equation 5:

$$C_f = 1 + a(1 - bR)\log f \qquad (5)$$

An improvement on the previous equation was made [16], including reversal stress besides the loading frequency as expressed in the equation 6:

$$\frac{S_{max}}{\sigma_c} = (ab^{-\log f} + c)[1 - (1 - R')\beta \log N] \qquad (6)$$

Drawing the loading frequency with respect to the number of cycles to failure adopting equations 2 to 6, figure 1 was obtained, setting σ_{max}/σ_c=0.75 and R=0.1.

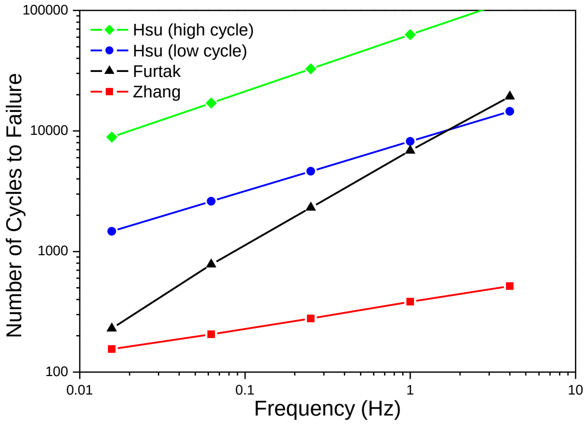


Figure 1: Fatigue life × Frequency by adopting different models.

From figure 1, it is clear that the fatigue life decreases with a decrease in loading frequency. It is worth noting, those equations were obtained based on the plain concrete fatigue tests. With respect to the fatigue behaviour of FRC in compression, the researches are scarce [23-26] and the parameter of loading frequency has not been taken into account.

Thus, in order to evaluate the effect of the loading frequency on the compressive fatigue behaviour of plain concrete and fiber-reinforced concretes, a series of compressive fatigue tests were performed. The results show that the loading frequency effect on the fatigue behaviour of the plain concrete is pronounced. However, for the fiber-reinforced concretes the fatigue life under low loading frequencies gets closer to that under high loading frequencies.

2 MATERIAL CHARACTERIZATION

Three types of concretes were made of the same concrete matrix, using ASTM type I cement 52.5R, sand size no greater than 4 mm, siliceous gravel aggregate of 12 mm maximum size and superplasticizer (Glenium C-355). The mixing proportion by weight were 1 : 0.35 : 1.89 : 2.17 : 0.014 (cement : water : sand : siliceous gravel : plasticizer).

Different type of fiber and the fiber content are as follows:

Concrete 1 (C1): plain concrete without fibers;

Concrete 2 (C2): polypropylene fiber reinforced concrete; corrugated polypropylene fibers, with 40 mm length, rectangular cross section (0.50 × 1.30 mm), aspect ratio 62, fiber volume ratio 0.56%;

Concrete 3 (C3): steel fiber reinforced concrete; hooked end steel fibers with 35 mm in length, diameter 0.55 mm, aspect ratio 64, fiber volume ratio 0.64%.

The tests were divided in twelve series: three types of concrete and four loading frequencies.

For each type of concrete 40 cubic specimens (100 mm in edge length) were made for the fatigue tests and 6 cubes were concreted to measure the quasi-static compressive strength at the stress rate 0.2 MPa/s.

To obtain the standard mechanical properties four cylinders were cast, for each type of concrete. Table 1 presents the quasi-static compressive strength f_c; elastic modulus E; Poisson´s ratio v.

Table 1: Mechanical properties

Concrete	f_c (MPa)	E (GPa)	v
C1	75	34	0.20
C2	86	42	0.22
C3	86	38	0.21

3 FATIGUE TESTS

The fatigue tests were performed by a servo-hydraulic machine. The load control was applied with a sine signal as shown in figure 2.

The maximum stress S_{max} applied on the cubic specimen was 85% of the cubic f_c, the stress ratio R (S_{min}/S_{max}) was 0.3, where S_{min} is the minimum stress, S_m is the mean stress and S_a is the stress amplitude. Four different loading frequencies were adopted, 4 Hz, 1 Hz, 0.25 Hz and 0.0625 Hz, respectively.

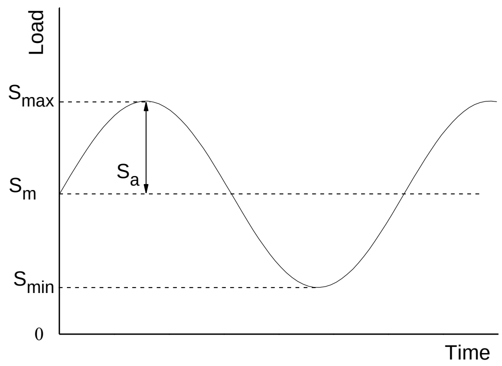


Figure 2: Sine signal used on fatigue tests.

The fatigue tests were realized in two stages. First, steps of 100 kN/min were made until the load reaches the equivalent mean stress S_m. Then the fatigue test starts following the sine signal (figure 2), where the load and displacement where stored for each maximum and minimum every cycle.

The fatigue tests were initiated on plain concrete at 4 Hz, where the concrete were six months old. The cubic static compressive strength was 74 MPa. The remains fatigue tests were performed when the concrete has one year old where the cubic f_c was 79 MPa for the plain concrete (C1) used for the fatigue test at 1 Hz, 0.25 Hz and 0.0625 Hz. For the fiber reinforced concretes the cubic f_c was 74 MPa and 89 MPa for (C2) and (C3), respectively.

3.1 Results and discussion

Thirteen tests were conducted on plain concrete at loading frequency 4 Hz, the rest loading frequencies, 10 tests were performed. The number of cycles to failure N for each tested specimen is presented in table 2.

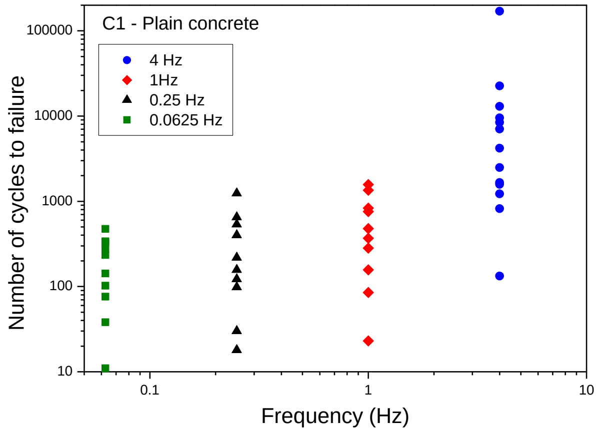
Figure 3 shows the number of cycles to failure *versus* the frequency in log scale for the plain concrete (a), the polypropylene fiber-reinforced concrete (b) and the steel fiber-reinforced concrete (c), respectively.

Table 2: Experimental results on fatigue tests

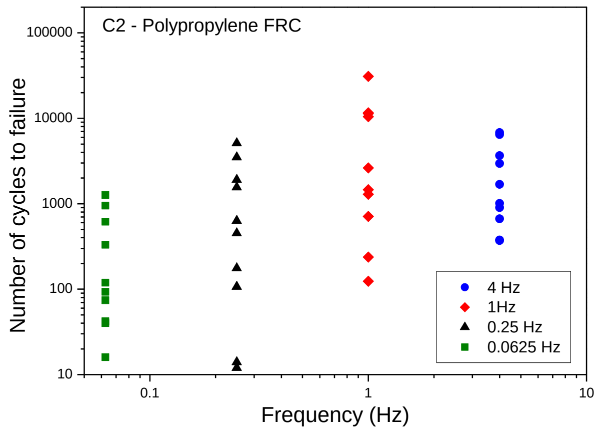
	4 Hz	1 Hz	0.25 Hz	0.0625 Hz
C1	821	23	18	11
	1222	85	30	38
	1578	157	98	76
	1660	282	122	102
	2485	368	157	142
	4192	479	219	234
	7038	759	400	275
	8411	833	535	329
	9521	1351	650	339
	13020*	1571	1242	473
C2	371	124	12	16
	376	237	14	40
	668	710	107	42
	900	1294	176	74
	1685	1457	451	93
	2962	2629	632	119
	3656	10480	1559	331
	6446	11383	1905	617
	6792	11589	3500	949
	6799	31020	5113	1264
C3	849	154	237	221
	1176	412	314	256
	1347	746	716	741
	1398	1344	751	1121
	1673	2077	986	1144
	1751	2365	1014	1246
	2042	3120	1291	1273
	2635	3945	2432	1304
	4070	4082	3659	1875
	5952	7438	5541	2409

*Three results more at 4 Hz for C1: 133, 22570 and 170256 cycles.

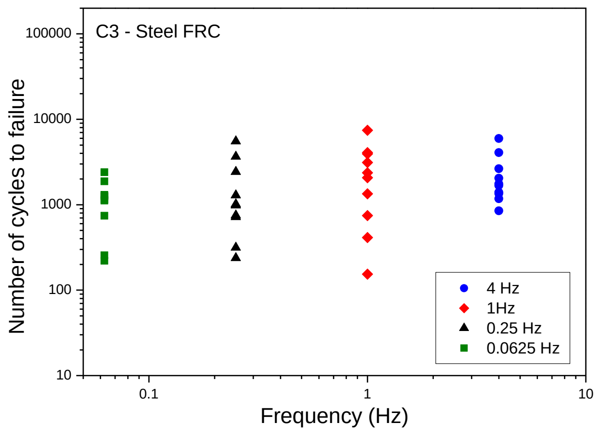
Comparing the results of the plain concrete and that of the fiber-reinforced concretes, it can be seen that the numbers of cycles to failure decreases as the loading frequency decreasing. Furthermore, this decrease is more pronounced for plain concrete.



(a) Plain Concrete



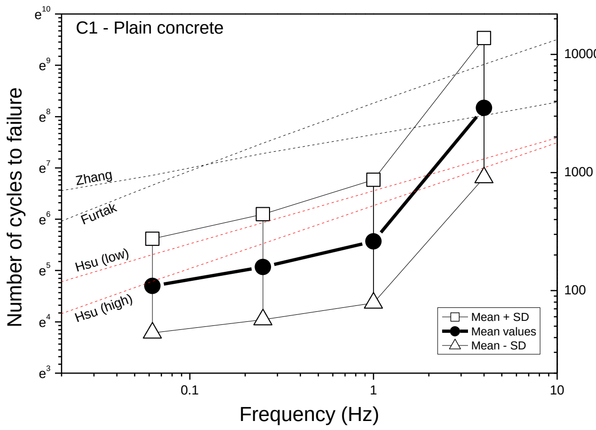
(b) Polypropylene fiber reinforced concrete



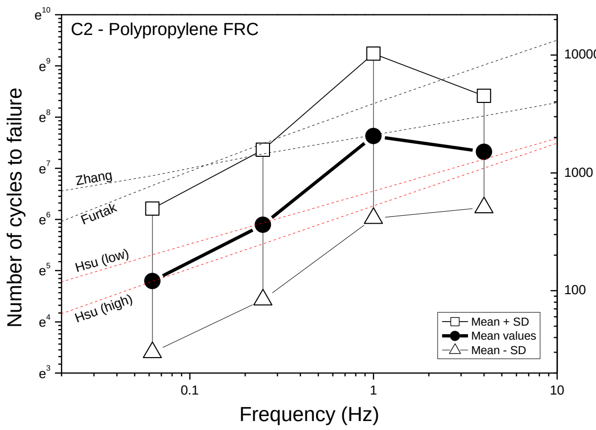
(c) Steel fiber reinforced concrete

Figure 3: Number of cycles versus frequency.

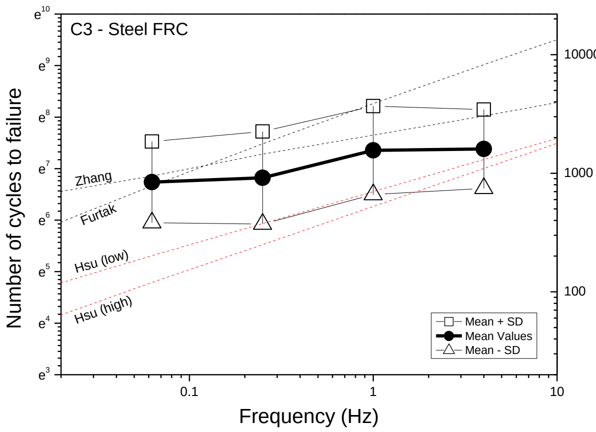
The number of cycles to failure on fatigue tests follows Weibull distribution. So, in figure 4 we present the mean value (solid symbols) and standard deviation (hollow symbols) of the number of cycles for each loading frequency for plain concrete (a), polypropylene FRC (b) and steel FRC. The models proposed by others authors [13, 14, 16], plotted using the same parameters applied on the experimental fatigue tests, are also presented by the dashed lines crossing the graphics.



(a) Plain Concrete



(b) Polypropylene fiber reinforced concrete



(c) Steel fiber reinforced concrete

Figure 4: Number of cycles versus frequency (Mean ± Standard deviation).

The addition of fiber improves the fatigue life for the lower frequencies (0.25 Hz and 0.0625 Hz); nevertheless no significant gain was observed at the higher frequency (4 Hz).

3.2 Strain history

From the maximum displacement in each cycle the secondary strain rate [27] was obtained during the tests. As the tests were conducted in load control, the strain rate is a response from the specimen during the test.

From each fatigue test the cyclic creep curve (time *versus* maximum strain) was obtained as shown in figure 5. In this type of curve three different stages are usually observed: in the first 10 to 15% of the total number of cycles to failure there is a quick increase of deformation; then a linear branch, that represent the major part of the test time, extends until around 85% of the number of cycles, where the slope of this linear branch is the secondary strain rate $\dot{\varepsilon}$; final stage was characterized by a sudden increase in the deformation shortly preceding the complete failure of the specimen.

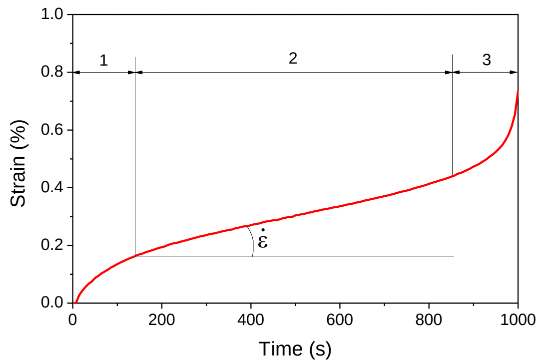


Figure 5: Typical evolution of strain versus time

Figure 6 presents the envelopes of the cyclic creep curves for each series of fatigue tests, i.e., three concrete types divided in four graphics for each loading frequency.

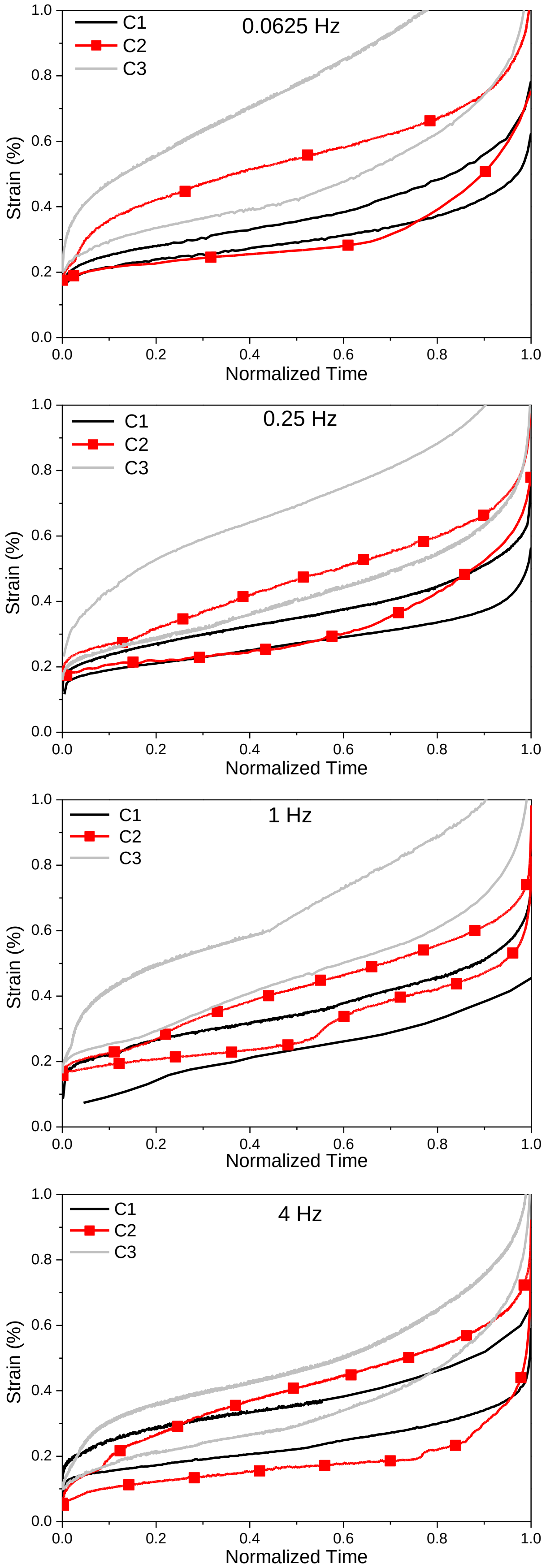


Figure 6: Evolution of strain versus time curves.

For a better comparison the graphics were limited to strain 1%, even that in some cases the final strain top was 1%, and the time was normalized.

Comparing the curves on figure 6 we can observe the differences on the final strain (strain at the rupture, or when the normalized time is equal to unit) and the shape of the curves among the plain concrete C1 and the fiber reinforced concretes C2 and C3.

The evolution of the strain and the final strain were usually smaller for plain concrete, higher for steel FRC and polypropylene FRC. This shows that the addition of the fibers allowed the specimens support higher deformations, and the effectiveness of the steel fibers was better than the polypropylene fibers.

Besides, it can be seen a jump (or a break of tendency) in the central branch of the FRCs. This jump could be understood as the work of the fibers bridging the crack evolution. This break of tendency is more pronounced for the polypropylene FRC.

In these experimental tests, the stress rate was controlled and the strain rate was obtained from the evolution of the deformations.

The stress rate can be calculated according to equation 7 where $\Delta\sigma$ is the stress variation from minimum to maximum:

$$\sigma = 2\Delta\sigma f \qquad (7)$$

The explanation of the bigger fatigue life for the higher frequencies can comes from the stress rate. The tests were set to S_{max} = 85% of the quasi-static compressive strength f_c on cubes. This quasi-static f_c was measured at a stress rate 0.2 MPa/s. For the fatigue test, the imposed stress rate was around 6 MPa/s for 0.0625 Hz; 25 MPa/s for 0.25 Hz; 100 MPa/s for 1 Hz; and 400 MPa/s for 4 Hz. When the concrete is submitted to dynamic conditions, the compressive strength at highest stress rate can reach 15% greater than quasi-static f_c [28, 29].

Assuming that at the higher frequency 4 Hz the tests were performed in a dynamic condition and at the lower frequency 0.0625 Hz the tests could be considered quasi-static, and imagining that the development of crack propagation is different for quasi-static and dynamic conditions, we can understand why the fatigue life *N* is smaller for the lower frequencies.

Figure 7 shows the relation among the fatigue life, the secondary strain rate and loading frequency for the twelve series of tests: three types of concrete and four loading frequencies.

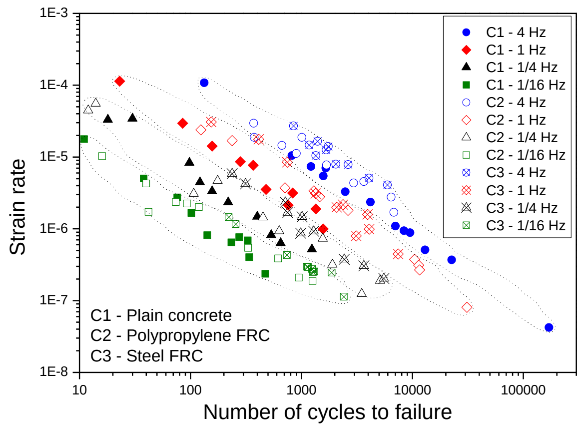


Figure 7: Strain rate × number of cycles.

From figure 7 it is observed that the fatigue life is lower as higher as the strain rate is, no matter which type of concrete or frequency. In the figure, the results are grouped by different loading frequency. Furthermore, the strain rate is greater for the higher frequencies.

4 CONCLUSIONS

In this paper, the loading frequency effect on the fatigue compressive behaviour of a plain concrete and two types of FRCs were investigated.

The results show that the loading frequency effect on the fatigue behaviour of the plain concrete is pronounced. The number of cycles to failure at lowest loading frequency (0.0625 Hz) is at least one order of magnitude lower that at highest loading frequency (4 Hz). However, for polypropylene and steel-fiber reinforced concretes, the numbers of cycles to failure under low loading frequencies get closer to that under high loading frequencies, namely, the same order of magnitude for steel FRC. Such trend can be attributed to the effectiveness of fibers in bridging the cracks, and thus inhibiting crack extension during the load cycles.

Furthermore, the strain history was studied, and it is confirmed that there is a strong relationship between the fatigue life and the secondary strain rate.

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