FLEXURAL FATIGUE OF CONCRETE FOR AIRPORT PAVEMENTS

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Through a series of experiment in laboratory, this paper mainly clarifies the effects of the factors such as maximum stress level, minimum stress level, loading frequency and rest period on the fatigue life of concrete for airport pavement, and analyzes the failure probability due to flexural fatigue under different stress level. As a result, it is found that under high stress level, namely the maximum stress level is equal to or greater than 80%, the minimum stress level has no clear influence on the fatigue life of concrete, but when the maximum stress level is 70% its effect can not be ignored. Accordingly, the flexural fatigue equation of concrete for airport pavement, considering the minimum stress level, is derived.

Key Words: *flexural fatigue equation, concrete, stress level, loading frequency, rest period, airport pavement*

1. BACKGROUND

In the design method for concrete pavement, the flexural fatigue has been one of the important problems. The current design criterion for concrete pavement in airport (1990)[1)] does not fully consider the fatigue of concrete. The current criterion for concrete pavement in road (1984)[2)] takes it into account, but which does not suit well that in airport. In general, the traffic loading in highway is high frequency and light load while in airport it is low frequency and heavy load. Therefore, it is necessary to study the fatigue of concrete for airport pavement in order to prolong its service life.

Since Van Ornum[3)] gave the first fatigue curve of concrete cubes in compression in 1903, many scholars in home and abroad have researched the fatigue property of concrete and obtained many valuable results.

In Japan, the design method for concrete pavement in road, which is the same as PCA method[4)], is based on the research result of Iwama[5)]. However, the composite stress of the warping stress and the traffic load stress is taken into account in this method.

According to the condition of low frequency and heavy load in airport, the purposes of this study are to clarify the effects of main factors on the fatigue life and derive the flexural fatigue equation of concrete for airport pavement, based on a series of experiments in laboratory.

2. LABORATORY EXPERIMENT

(1) Material and mixing

The cement in this experiment is the Portland cement, and the aggregates are crushed stone, natural sand and crushed sand. The maximum size of coarse aggregate in the concrete is 40mm. The mixing proportions of concrete are shown in **Table 1**. The target flexural strength of concrete is 5N/mm^2 after curing 28days. The size of specimens is 15×15×53cm. There are three specimens for flexural strength test, whose mean strength is 4.97N/ mm^2.

(2) Experiment method

Before the fatigue experiments, the specimens

Table 1 Mixing proportion of concrete

Aggregate maximum size(mm)	Slump (cm)	Air content (%)	Water-cement ratio (%)	Sand percentage (%)	Unit weight (kg/m^3)				
					Water	Cement	Fine aggregate	Coarse aggregate	Admixture
40	2.5±1.0	4±1.0	45	36	153	340	663	1187	0.850

Table 2 Experiment conditions and number of specimen

Minimum stress level (%)	0															
Loading frequency (Hz)	10				1				0.1				0.01			
Rest period (s)	0	1	10	100	0	1	10	100	0	1	10	100	0	1	10	100
Maximum stress level (%)	Number of Specimen															
70	5				5				5				5			
80	5				12	12	12		5				5			
90					7	8	7	9								
Minimum stress level (%)	20															
Loading frequency (Hz)	10				1				0.1				0.01			
Rest period (s)	0	1	10	100	0	1	10	100	0	1	10	100	0	1	10	100
Maximum stress level (%)	Number of Specimen															
70					5											
80	5				5				5				5			
90					5											
Minimum stress level (%)	40															
Loading frequency (Hz)	10				1				0.1				0.01			
Rest period (s)	0	1	10	100	0	1	10	100	0	1	10	100	0	1	10	100
Maximum stress level (%)	Number of Specimen															
70					4											
80	5				5				5				5			
90					5											

should be cured for twelve weeks in water bath at 20 C. Because the fatigue test usually consumes longer time, when testing, it is necessary to apply the grease and wrap the vinyl resin thin film around the specimen in order to prevent it from drying.

According to the testing method for the flexural strength of concrete (JIS A 1106), the vertical load is applied at the third-points of a rectangular beam specimen. The stress wave of the fatigue test is a sinusoidal wave. In the light of the testing duration, the maximum number of loading cycle is limited to 100,000 in most cases.

(3) Experiment conditions

Considering the temperature gradient through the concrete slab and the predominant traffic load on the concrete slab in airport pavement, the experiment conditions are determined in **Table 2**. To investigate four main factors described in 3., the specimens are prepared and tested in a lump for each series.

3. EFFECT OF MAIN FACTORS

It should be mentioned that there are some censored data in the experiment. Those data are not simply omitted, but treated with the method derived from Hamada, et al.[6)]

The following four factors are studied here.

(1) Maximum stress level (S_{max})

On this factor, the stress levels, which is defined as the ratio of the loading strength and the specimen flexural strength, are selected as 0 - 70%, 20% - 70%, 40% - 70%; 0 - 80%, 20% - 80%, 40% - 80% and 0 - 90%, 20% - 90%, 40% - 90% (minimum-maximum), while the loading frequency is 1 Hz and the rest period is 0 s. All data are plotted in **Fig.1**. Obviously, an approximate linear relationship is found. Moreover, under the given minimum stress level the fatigue life decreases with an increase of maximum stress level. This phenomenon indicates when the maximum stress level is higher, that is, it is closer to the strength of

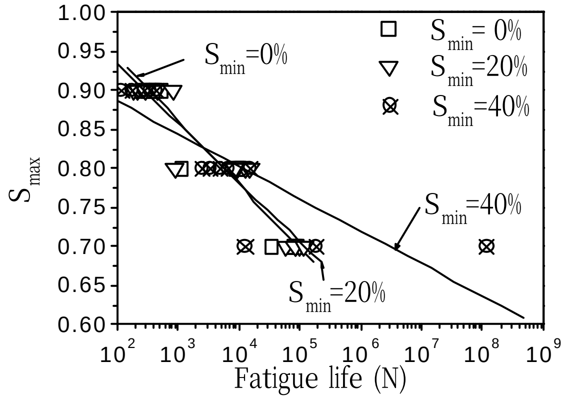

Fig.1 Relationship between S_{max} and fatigue life

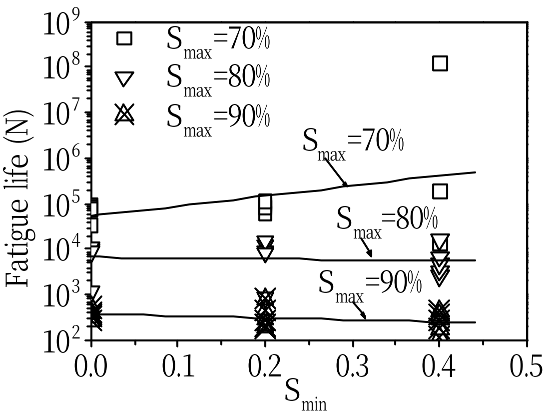

Fig.2 Relationship between S_{min} and fatigue life

concrete, the fatigue life of concrete is shorter.

(2) Minimum stress level (S_{min})

The minimum stress level is set to 0, 20% and 40% in this experiment. **Fig.2** shows its effect on the fatigue life of concrete when the maximum stress level is 70%, 80% and 90%, respectively. The effect can be tested by the statistics. The testing method is: assumed that the means and the variances of two samples are equal. The sample means are tested by t-test while the sample variances are tested by F-test. The process is shown as follow.

When S_{max} is 70%, comparing the two samples (S_{min}=0 and S_{min}=40%) in **Table 3**. Note: There is one censored data, which is labeled by *, when S_{min}=40%.

i) Assumed: The sample means are equal

$$(\bar{X}_1 = \bar{X}_2)$$

Table 3 Two samples of S_{min}=0 and S_{min}=40%

X_1: S_{min}=0		X_2: S_{min}=40%	
N	log N	N	log N
33882	4.530	12771	4.106
91332	4.961	119261387*	8.076
81659	4.912	187289	5.273
88164	4.945		
78410	4.894		
$n_1 = 5$, $\bar{x}_1 = 4.848$		$n_2 = 3$, $\bar{x}_2 = 5.818$	

$$v_1 = \frac{1}{n_1 - 1}\sum_{i=1}^{n_1}\left(x_{1i} - \bar{x}_1\right)^2 = 0.032$$

$$v_2 = \frac{1}{n_2 - 1}\sum_{i=1}^{n_2}\left(x_{2i} - \bar{x}_2\right)^2 = 4.163$$

$$d = |\bar{x}_1 - \bar{x}_2| = 0.970$$

$$t = \frac{d}{\sqrt{\frac{1}{n_1} + \frac{1}{n_2}}\sqrt{\frac{(n_1-1)v_1 + (n_2-1)v_2}{n_1 + n_2 - 2}}} = 1.119$$

When the level of significance (a) is 5%,

$$t_{(n_1+n_2-2,a)} = t_{(6,0.05)} = 1.943$$

$$\therefore \quad t < t_{(6,0.05)}$$

This illustrates that the assumption is true when the level of significance (a) is 5%.

ii) Assumed: The sample variances are equal

$$(\bar{V}_1 = \bar{V}_2)$$

$$F_1 = \frac{v_1}{v_2} = 0.008, \quad f_1 = n_1 - 1 = 4, \quad f_2 = n_2 - 1 = 2$$

$$F_2 = \frac{v_2}{v_1} = 130.09, \quad f_1 = n_2 - 1 = 2, \quad f_2 = n_1 - 1 = 4$$

When the level of significance (a) is 5%,

$$F_{(4,2;0.025)} = 39.2, \quad F_{(2,4;0.025)} = 10.6$$

$$\therefore \quad F_1 < F_{(4,2;0.025)}, \quad F_2 > F_{(2,4;0.025)}$$

This illustrates that the assumption is false when the level of significance (a) is 5%.

In the same manner, it is found that: when S_{max} is 80%, the above assumptions of the two samples (S_{min}=0 and S_{min}=40%) are true when the level of

Table 4 Fatigue life under different loading frequencies

Frequency \ S_{min}		0	20%	40%
10Hz	No.1	62750	78504	42921
	No.2	72537	54322	5158
	No.3	5691	42428	74828
	No.4	22935	12677	5537
	No.5	7817	8792	74629
	Average	34346	39345	40615
1Hz	No.1	10165	12383	2562
	No.2	9583	878	15735
	No.3	1148	9218	3379
	No.4	11256	15375	4933
	No.5	9118	8468	6824
	Average	8254	9264	6687
0.1Hz	No.1	554	546	150
	No.2	756	297	306
	No.3	202	1431	518
	No.4	262	262	725
	No.5	421	421	493
	Average	439	591	438
0.01Hz	No.1	84	95	139
	No.2	141	139	94
	No.3	101	144	36
	No.4	129	27	27
	No.5	97	113	92
	Average	110	104	78

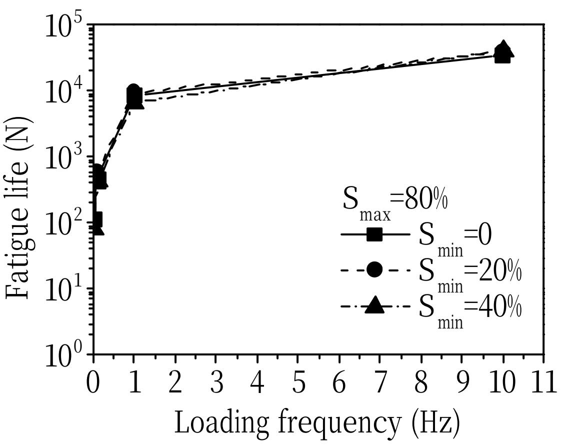

Fig.3 Relationship between loading frequency and fatigue life

significance is 5%; and when S_{max} is 90%, the assumptions of the two samples (S_{min}=0% and S_{min}=40%) are also true when the level of significance is 5%.

On the basis of the above analyses, it is concluded: when the maximum stress level is equal to or greater than 80%, the minimum stress level has no clear influence on the fatigue life of concrete, but when the maximum stress level is 70% its effect can not be ignored. The reason is that 70% of stress

Table 5 Fatigue life under different rest periods

Rest period \ S_{max}		80%	90%
0s	No.1	1069	805
	No.2	9980	700
	No.3	10052	1438
	No.4	2624	797
	No.5	10463	319
	No.6	5103	482
	No.7	25042	1032
	No.8	4505	
	No.9	2532	
	No.10	6031	
	No.11	9720	
	No.12	7036	
	Average	7846	796
1s	No.1	29622	1188
	No.2	10574	639
	No.3	12927	924
	No.4	7120	1084
	No.5	2781	1980
	No.6	1969	525
	No.7	6754	890
	No.8	20969	227
	No.9	10117	
	No.10	19930	
	No.11	8024	
	No.12	21920	
	Average	12726	932
10s	No.1	31366	927
	No.2	1421	144
	No.3	2348	749
	No.4	2178	705
	No.5	30196	1049
	No.6	13837	559
	No.7	28141	339
	No.8	14918	
	No.9	2248	
	No.10	2630	
	No.11	58635	
	No.12	33458	
	Average	18448	639
100s	No.1		255
	No.2		291
	No.3		421
	No.4		486
	No.5		248
	No.6		538
	No.7		150
	No.8		547
	No.9		379
	Average		368

level may be the threshold of the yield stress level.

(3) Loading frequency

Table 4 displays the fatigue life under different loading frequencies at S_{max}=80% and S_{min}=0,

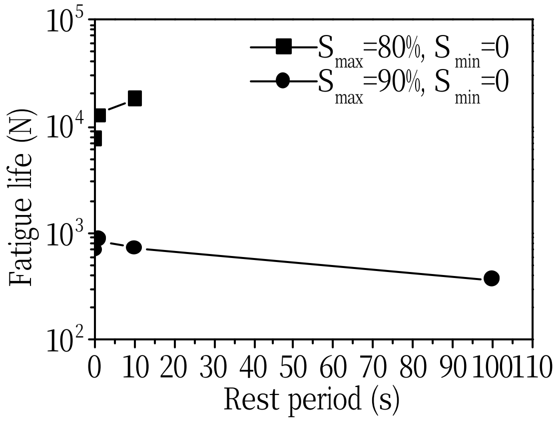

Fig.4 Relationship between rest period and fatigue life

20% and 40%, and the rest period of 0s. Their average fatigue lives are plotted in **Fig.3**. It is obvious that the fatigue life dramatically increases when the loading frequency is less than 1 Hz and the fatigue life at the loading frequency of 10 Hz is a little longer than that at 1 Hz. The finding is consistent with the results from other similar study found in the literature [7].

At this stress level, the higher frequency has not a detrimental effect on the fatigue life of concrete, but the lower frequency has. The reason might be that under lower frequency (here less than 1 Hz) an equivalent dead load, which is similar to the static load and is much larger than the "dynamic" load when the frequency is higher, is applied on the concrete, which forces the concrete to be always in a high stress condition. In airport, the frequency is usually low, so it should be fully taken into account when designing the concrete pavement.

(4) Rest period

Table 5 gives the fatigue life under different rest periods when the maximum stress level is 80% and 90%, respectively, and the minimum stress level is 0. **Fig.4** shows the relationship between rest periods and their average fatigue lives. From the figure, the rest periods have hardly an effect on the fatigue life of concrete when the stress level is 90%, but the fatigue life dramatically increases with the rest period when the stress level is 80%.

This phenomenon can be explained as follows. When the loading stress is sufficiently lower than the yield strength of concrete, the longer rest period can allow redistribution of stress and healing of strain, then the fatigue life of concrete becomes longer [3]. On the contrary, due to the higher stress,

Table 6 Results of fatigue experiment

Minimum stress level	Maximum stress level		
	70%	80%	90%
0	33882 91332 81659 88164 78410	10165 9583 1148 11256 9118	423 264 386 528 329
20%	87691 60349 98732 116428 82672	12383 878 9218 15375 8468	463 185 213 286 813
40%	12771 119261387* 147635804* 187289	2562 15735 3379 4933 6824	116 447 281 178 357

the rest period has no effect on the fatigue life of concrete.

In consideration of the test condition, a flexural fatigue equation of concrete in airport is derived under the condition of loading frequency of 1 Hz and rest period of 0 s. However, the above-mentioned factors must be taken into account when applying the equation to the pavement design.

4. FAILURE PROBABILITY OF FLEXURAL FATIGUE

The fatigue failure probability of material should be considered on researching its fatigue strength. According to the early researches [8), 9), 10), 11)], the relationship between the fatigue life (N) of concrete and the fatigue failure probability (P_f) can be expressed in the logarithmic normal distribution model in terms of simplicity and practicability. Consequently, the fatigue failure probability of concrete flexural fatigue can be decided as follow.

$$P_f = \frac{r}{n+1} \tag{1}$$

where, P_f - fatigue failure probability under given loading cycles,
r - failure number of specimens,
n - total number of specimens under given testing condition.

Table 7 Failure probability of specimens

S_{min}	Order	S_{max} = 70%	P_f	S_{max} = 80%	P_f	S_{max} =90%	P_f
0	1	33882	0.167	1148	0.167	264	0.167
	2	78410	0.333	9118	0.333	329	0.333
	3	81659	0.5	9583	0.5	386	0.5
	4	88164	0.667	10165	0.667	423	0.667
	5	91332	0.833	11256	0.833	528	0.833
20%	1	60349	0.167	878	0.167	185	0.167
	2	82672	0.333	8468	0.333	213	0.333
	3	87691	0.5	9218	0.5	286	0.5
	4	98732	0.667	12383	0.667	463	0.667
	5	116428	0.833	15375	0.833	813	0.833
40%	1	12771	0.167	2562	0.167	116	0.167
	2	187289	0.333	3379	0.333	178	0.333
	3	119261387*		4933	0.5	281	0.5
	4	147635804*		6824	0.667	357	0.667
	5			15735	0.833	447	0.833

* denotes a censored sample.

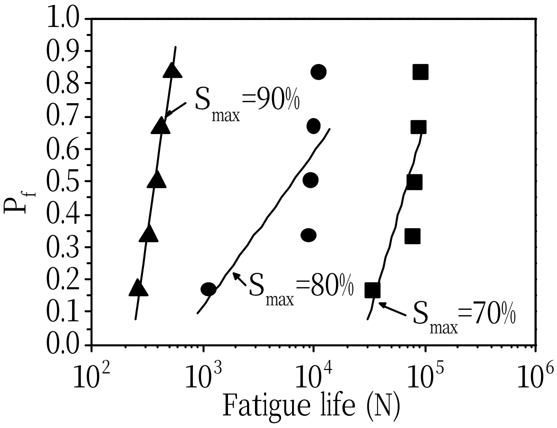

Fig.5 *P-N* diagram (S_{min} =0)

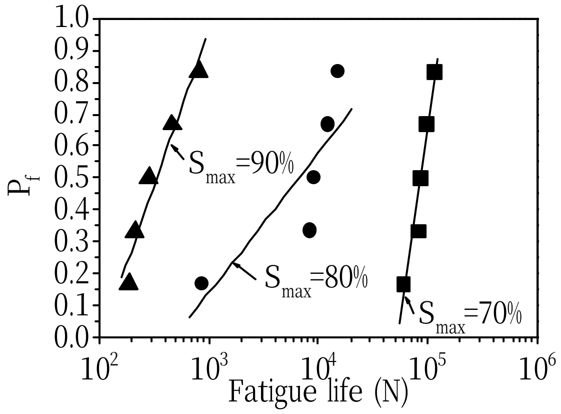

Fig.6 *P-N* diagram (S_{min} =20%)

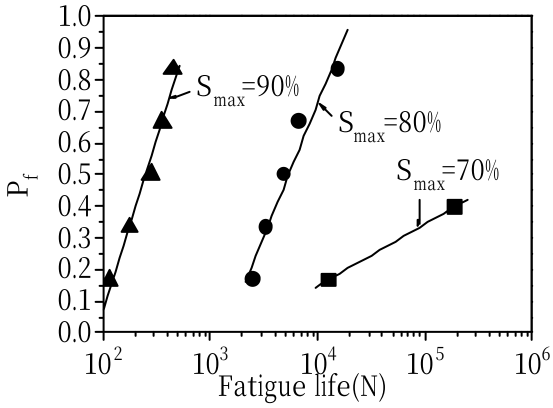

Fig.7 *P-N* diagram (S_{min} =40%)

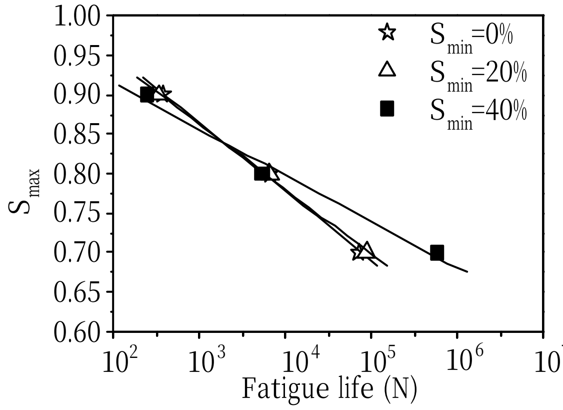

Fig.8 *S-N* diagram under different minimum stress level

Equation (1) is suitable for the normal case, namely, a specimen is failed. When the loading cycles reach limit loading cycles (100,000), but the specimen is not failed, thus this experiment stops. Such data is called as censored data. In this case, the failure probability of concrete flexural fatigue should be decided as follows.

$$P_f = \frac{r}{n+2} \tag{2}$$

Table 6 gives the results of fatigue experiment under 0s of rest period and 1Hz of loading frequency. Note that the data labeled by * are the censored data in the table.

Accordingly, their failure probability (P_f) can be calculated with the equation (1) and (2), and the results are shown in **Table 7**.

Assuming that the failure probability follows the logarithmic normal distribution, the data from **Table 7** are plotted in **Fig.5 - Fig.7**. As the equations can be obtained as to any failure probability, the

Table 8 Analyzed result of data in **Table 6**

$S_r/(100-S_{min})$	Mean fatigue life $(\overline{N})$
0.50	362413
0.63	89174
0.67	6687
0.70	74689
0.75	9264
0.80	8254
0.83	276
0.88	392
0.90	386

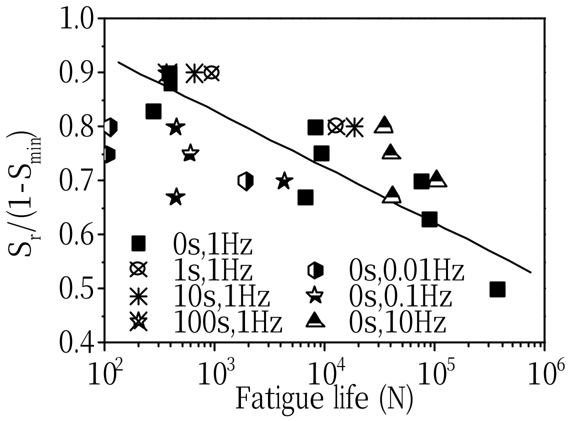

Fig.9 Relationship between stress amplitude and fatigue life

probability should be properly selected from a structural design viewpoint.

Obviously, when the failure probability is the same, the fatigue life of concrete increases with decrease of stress level. Accordingly, the flexural fatigue equation under different minimum stress levels can be obtained with the least squares fit method as follows, when the failure probability is 50%, for instance. These relationships are described in **Fig.8**.

i) for S_{min}=0:

$$S_{max} = 1.129 - 0.088\,log\ N \quad \text{(R=0.999)}$$

ii) for S_{min}=20%:

$$S_{max} = 1.111 - 0.083\,log\ N \quad \text{(R=0.999)}$$

iii) for S_{min}=40%:

$$S_{max} = 1.032 - 0.058\,log\ N \quad \text{(R=0.993)}$$

5. FATIGUE EQUATION CONSIDERING MINIMUM STRESS LEVEL

The relationship between the maximum stress level and the fatigue life is given in S_{max}~N diagram as shown in **Fig.1**, but the authors' results illustrate that the minimum stress level has an influence on the flexural fatigue life of concrete as described above. Therefore, the effect of the minimum stress level must be taken into account for the flexural fatigue equation.

Here, a concept of stress amplitude is introduced, which is the difference between the maximum and minimum stress level, i.e.

$$S_r = S_{max} - S_{min} \tag{3}$$

where, S_r - stress amplitude (%).

On analyzing the results from **Table 6**, it is found that there is a good linear relationship between the mean fatigue life and the stress amplitude at the rest period of 0s and the loading frequency of 1 Hz, as shown in **Table 8**.

The regression equation of the authors' results can be obtained with the least squares fit method as equation (4). Its correlation coefficient is 0.911 and the standard deviation is 0.057.

$$\frac{S_r}{100 - S_{min}} = 1.138 - 0.103\,log\,N \tag{4}$$

Consequently, the equation (4) is regarded as the flexural fatigue equation of concrete in airport.

Additionally, in **Fig.9** the data under other conditions are also plotted. The relationship can not be obtained quantitatively, but it is found that the fatigue life increases with the rest period; and it decreases with the loading frequency. The conclusions are consistent with the previous ones.

6. CONCLUSIONS

The following are the main conclusions of this study.

1) When studying the fatigue of concrete in airport pavement, its features of high stress level in concrete and low frequency loading should be considered.

2) Under the given minimum stress level, the fatigue life decreases with the increase of maximum stress level, which is an approximate linear relationship**.**
3) When the maximum stress level is equal to or greater than 80%, the minimum stress level has no clear influence on the fatigue life of concrete, but when then maximum stress level is 70% its effect cannot be ignored.
4) At $S_{max} = 80\%$, the lower frequency has a detrimental effect on the fatigue life of concrete; but the effect of the higher frequency is not so. The loading frequency of 1 Hz is a threshold value.
5) When the loading stress is lower than the yield strength of concrete, the longer rest period prolongs the fatigue life of concrete. On the contrary, in the higher stress level, the rest period has no effect on the fatigue life of concrete.
6) The fatigue failure probability follows the logarithmic normal distribution model. Moreover, when the failure probability is the same, the lower the stress level, the longer the fatigue life of concrete is. The fatigue equations for different minimum stress levels are obtained when the probability is 50%.
7) Considering the minimum stress level, the flexural fatigue equation of concrete for airport pavements is derived.

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空港舗装用コンクリートの曲げ疲労特性

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本研究では，室内試験により，空港舗装に使用されるコンクリートの曲げ疲労寿命に上限応力，下限応力，載荷速度，休止時間といった要因が及ぼす影響を明らかにし，曲げ疲労による破壊確率について解析した．その結果，上限応力が 80%もしくはそれ以上では下限応力による影響は明らかではないが，上限応力が 70%の場合にはその影響は無視できないことがわかった．そして，この点を考慮に入れた空港舗装用コンクリートの曲げ疲労式を算定した．