Fatigue performance of aging asphalt mixtures*)

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Abstract: Fatigue and aging inevitably exist in asphalt pavement. To reveal fatigue characteristics, strength tests were carried out under different loading rates (v). The rules of dynamic loading strength (S_{dz}) and v were acquired and the real stress ratios corresponding to the fatigue test loading rates were obtained. Fatigue equations describing fatigue life (N_f) as a function of the nominal (t_m) and real (t_s) stress ratios were also acquired. It was discovered that the equations could be extended to the strength failure point ($t_s = 1$, $N_f = 1$) based on the real stress ratio, but not the nominal stress ratio. The equation provided the theoretical method to design a method to assess aging of asphalt pavement.

Keywords: road engineering, asphalt pavement, fatigue, aging, stress ratio.

Odporność zmęczeniowa starzonych mieszanek asfaltowych

Streszczenie: Przeprowadzono testy nawierzchni asfaltowych stosując różne szybkości obciążania (v). Określono zależności matematyczne między wytrzymałością na obciążenia dynamiczne (S_{dz}) i v oraz równania opisujące trwałość zmęczeniową (N_f) w funkcji rzeczywistego współczynnika asymetrii cyklu (t_s) i nominalnego współczynnika asymetrii cyklu (t_m). Stwierdzono, że tylko równanie uwzględniające współczynnik t_s może być stosowane do ekstrapolacji do punktu wytrzymałości na uszkodzenie ($t_s = 1$, $N_f = 1$). Równanie to pozwala na zaprojektowanie teoretycznej metody oceny starzenia się nawierzchni asfaltowej.

Słowa kluczowe: inżynieria drogowa, nawierzchnia asfaltowa, zmiany zmęczeniowe, starzenie, współczynnik asymetrii.

The asphalt pavement has already experienced short-term and long-term aging when the fatigue failure takes place, and the fatigue performance is reflected by the degree of aging in the asphalt mixture. Asphalt pavement should be evaluated under different degrees of aging, but few studies have given sufficient account of the differences in aging degrees, instead using the original asphalt mixture to conduct fatigue tests. This results in large differences from the actual fatigue properties of the pavement. To reduce the differences and reflect the real fatigue performance of the pavement, it's necessary to explore the aging effect on fatigue performance of asphalt mixtures.

According to the methods of asphalt aging tests introduced by Strategic Highway Research Program (SHRP), a loose mixture is heated for four hours at 135 °C with forced ventilation in an oven, which is called short-term oven aging (STOA), and then the formed specimen is heated for five days at 85 °C in the delay oven with forced ventilation, which is called long-term oven aging (LTOA). This is an effective way to simulate the aging that occurs during construction and is used in a laboratory setting [1—4]. Due to the enormous amount of time and the expense of age and fatigue testing on asphalt mixtures, aging factors have not been considered in the majority of research concerning asphalt fatigue properties.

To date, the problems of aging asphalt have not been comprehensively considered when pavement is designed in all parts of the world, so the effects of aging on the life of asphalt pavement have not been studied accurately. The study of fatigue performance in different degrees of aging plays a significant role in improving design parameters and asphalt mixtures, and preventing early damage, as well as improving road performance and extending the life of asphalt pavement.

A major deficiency of the existing design specifications of asphalt pavement in China using the S-N fatigue equation is that the specifications drop the fatigue equation to the value of fatigue life $N_f = 1$, which is the ultimate tensile strength calculated from the fatigue equation when the asphalt mixture is damaged under a single loading. Due to this imprecision, the method to calculate the tensile strength coefficient lacks experimental verifica-

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tion based on the artificial ultimate tensile strength. The fatigue equation is derived from the regression analysis, taking into account certain test conditions and scopes of application. For example, the scope of the double logarithmic linear relationship is $N_f = 10^4—10^8$ in Pell's research, and this relationship does not exist beyond the scope. There is necessary to perform experimental verification whether the relationship can be extended [5, 6]. Generally speaking, the relationship curve inside or outside of the scope appears as the curved line. In the case of low cycle fatigue, the fatigue curve does not show any clear linear relationship, but an upward convex and curve downward. The ultimate tensile strength values obtained by dropping the fatigue equation to $N_f = 1$ is inaccurate [7].

The traditional stress ratio in the fatigue test is determined by the standard strength value. But the standard strength is tested under the conditions of a fixed loading rate. Asphalt mixtures are a typical viscous-elastic material, whose stiffness and strength indicators are affected significantly by loading rates and temperatures [8—11]. Different loading rates will lead to different strengths. So the inconsistencies in strength are the main reason for the problems of inaccurate calculation. As the loading rate of a standard strength test is much smaller than that of a fatigue test in 1/2 cycle (related to the stress level and loading frequency), there is a greater difference from the strength value corresponding to the fatigue loading rate. The stress ratio (σ/s) based on standard strength is defined as the nominal stress ratio, and the stress ratio determined by the strength value corresponding to the fatigue loading rate is defined as the real stress ratio. That is to say, the stress ratio used in traditional fatigue test analyses is the nominal stress rather than the real stress ratio. Therefore, the strength values derived from the fatigue equation established under the basis of normal stress ratios by using $N_f = 1$ is not the ultimate tensile strength, and it is not accurate for calculating the structure coefficient in tensile strength.

Studies on the fatigue properties of asphalt rarely consider the effects of the loading rate on strength, which is the basis for determining the fatigue stress ratio, and the erroneous results would lead to a distortion of the fatigue equation and does not reflect the strength characteristics of $N_f = 1$ when the stress ratio $\sigma/s = 1$. This is because the loading rate is slow during the standard strength test, but faster during the fatigue test, so the real strength is much higher than the nominal strength obtained by standard strength tests [12—18].

Therefore, the change law in strength with the loading rate is revealed by analyzing the loading rate of the asphalt mixture impact strength, and the fatigue equation of aging asphalt is established based on the real stress ratio, which has important theoretical significance and engineering application value in improving asphalt pavement design.

EXPERIMENTAL PART

Materials

The AC-13C fine-grade asphalt mixture was chosen to the study. Styrene-butadiene-styrene (SBS) modified asphalt (I-D) was used as a binder and the basalt as an aggregate. Both were produced in Nanjing (Jiangsu province, China). The optimum asphalt-aggregate ratio was 5.3 wt % as determined by the method of Marshall proportions for the asphalt mixture.

The characteristics of raw materials (asphalt binder, aggregate, mineral powders) and the mixture for AC-13C asphalt mixture are shown in Tables 1—4.

Table 1. Test results of SBS modified asphalt (I-D)

Property		Test result	Technical requirements (Chinese Standard)
Penetration number (25 °C, 100 g, 5 s), 0.1 mm		56	30 to 60
Penetration index PI		0.533	≥0
Ductility (5 cm/min, 5 °C), cm		34	≥20
Softening temperature (TR&B), °C		79	≥60
Kinematic viscosity (135 °C), Pa · s		2.31	≤3
Flashing temperature, °C		267	≥230
Solubility, %		99.92	≥99
Elastic recovery (25 °C), %		77	≥75
Storage stability segregation — 48 h softening temperature difference, °C		1.5	≤2.5
After STOA residue	Quality change, %	0.1	≤±1.0
	Residue penetration ratio (25 °C), %	73	≥65
	Residue ductility (5 °C), cm	16	≥15

Table 2. Density of mineral (basalt) aggregate

Sieve size, mm	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075	Mineral powders
Density, g/cm^3	2.731	2.730	2.729	2.715	2.716	2.717	2.717	2.718	2.719	2.753

Table 3. Mineral aggregate gradation of AC-13C fine-grade asphalt mixture

Mesh size, mm	16	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
Passing rate, %	100	95	74	48.5	34	23.5	15	11	8.5	6

Table 4. Marshall test results for asphalt mixture at the optimum asphalt aggregate ratio

Asphalt-aggregate ratio, wt %	Bulk specific gravity of asphalt mixture, g/cm^3	Void volume, %	Void filled with asphalt, %	Void in mineral aggregate, %	Marshall stability, kN	Marshall flow value, 0.1 mm
5.3	2.455	5.2	67.2	16.1	15.7	27.9

Methods of testing

Using the SHRP method, delayed oven heating was used in the long-term oven aging (LTOA) test, and the test conditions were fixed at the temperature of 85 °C. The aging time was five days. This method simulates the aging degree of the actual pavement for six to nine years. This is not accurate to test the fatigue because the failure does not necessarily occur in 6—9 years of traffic use, and could happen in an earlier or later stage. Therefore, five different aging levels (0, 1, 3, 5, and 7 days) were chosen to simulate the actual aging degrees of the road surface when the fatigue damage happens.

The strength and fatigue tests of asphalt mixtures were performed on the material test system equipment (MTS Landmark®, USA). First, the asphalt mixture was compacted and shaped into a plate specimen measuring 30 × 30 × 5 cm, and then cut into a beam shape that was 25 × 5 × 5 cm. The force and displacement of each stress cycle were captured automatically by the data acquisition system. The corresponding stress and strain values were obtained by calculation, and the time intervals of the data acquisition system were set depending on the experimental conditions. The loading methods in strength and fatigue tests were used with direct tensile tests at the temperature of 15 °C, and the test specimens were stored in an environmental chamber for 24 h beforehand to ensure a consistent temperature inside and outside the specimen.

RESULTS AND DISCUSSION

Speed characteristics of asphalt mixture strength

The results of strength and fatigue test of the original asphalt mixture were taken as examples and the results of the different degrees of aging were analyzed in the same way.

First, the standard direct tensile strength (S_t) test was performed three times in parallel with the loading rate of 5 mm/min, and the mean value obtained was 1.963 MPa. The results are shown in Table 5.

Table 5. Standard direct tensile strength (S_t) test results

Test number	S_t, MPa	Average value, MPa	Standard deviation	Variation coefficient
1	2.101	1.963	0.120	0.061
2	1.894			
3	1.894			

The tensile strength under different v is defined as the dynamic load strength (S_{dz}). The S_{dz} were determined for various loading rates (v) in the range of 0.0037—37 MPa/s, and the results are shown in Table 6. It can be easily seen that v affected S_{dz} of the asphalt mixture significantly, and the maximal S_{dz} is more than six times higher than the minimal in the loading scope.

Table 6. Direct tensile strength (S_{dz}) test results under different loading rates (v)

Test number	v, MPa/s	Sample area, mm^2	Destroy load, N	S_{dz}, MPa
1	0.0037	2695.7	2276	0.844
2	0.037	2688.2	3749	1.395
3	0.37	2727.2	5453	2.000
4	1.85	2662.8	7548	2.835
5	3.70	2676.6	7910	2.955
6	7.40	2799.6	10757	3.842
7	10.80	2778.3	11892	4.280
8	13.72	2915.4	13888	4.589
9	17.77	2813.1	13027	4.695
10	21.00	2869.8	13550	4.722
11	24.80	2818.7	13927	4.941
12	29.60	2703.0	13969	5.168
13	33.30	2625.1	13119	4.998
14	37.00	2703.1	14129	5.227

The effect of v on S_{dz} at 15 °C for AC-13C is shown in Fig. 1.

The regression equation between S_{dz} and v has the form:

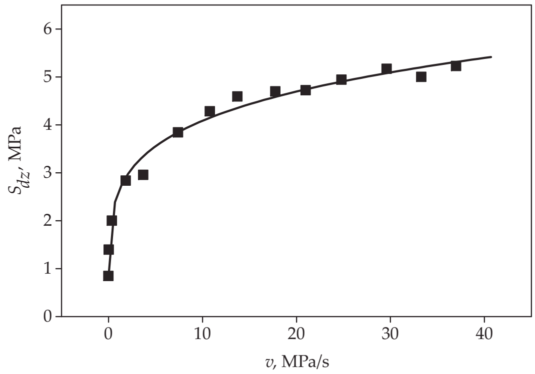

Fig. 1. Direct tensile strength (S_{dz}) versus loading rate v at 15 °C for AC-13C

$$S_{dz} = 2.583v^{0.2} \quad (1)$$
$$R^2 = 0.984$$

According to the fitting results v has significant influence on S_{dz} of asphalt mixtures, and the relationship between them is the power function. The strength corresponding to the loading rate in fatigue tests is defined as fatigue dynamic load strength.

A loading frequency of 10 Hz is typically used in fatigue tests of asphalt mixtures. If the fatigue test is carried out under the stress level of 1 MPa, v value is 20 MPa/s in the process. According to eq. (1), v was approx. 0.25 MPa/s, corresponding to S_t of 1.963 MPa. Value 20 MPa/s was roughly 80 times higher than 0.25 MPa/s. Whereas S_{dz} corresponding to v of 20 MPa/s was 4.703 MPa [from eq. (1)], and was 2.396 times higher than 1.963 MPa. Therefore, the traditional stress ratio used in fatigue tests is not correct, and is just a nominal stress ratio.

Fatigue properties of aging asphalt mixture characterized by real stress ratio

The defined nominal stress ratio is denoted by t_m, and the real stress ratio is denoted by t_s.

The standard static load strength test of asphalt mixtures should be taken first into account for determining t_m. The quasi-static load strength was S_t = 1.963 MPa (in Table 5).

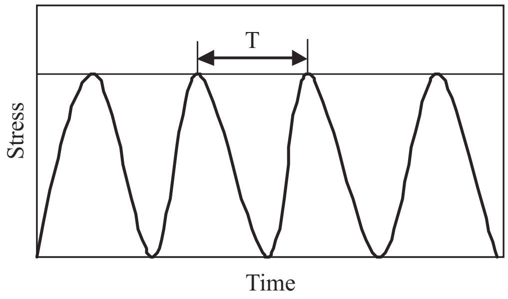

Fig. 2. Loading wave of fatigue test process

In fatigue tests t_m was 0.3, 0.4, 0.5, 0.6 and 0.7, and the loading frequency was 1, 10, 20, and 50 Hz. A continuous haversine loading curve describing the dependence between stress level (σ), applied in the fatigue test, and time (t), shown in Fig. 2, illustrates the fatigue loading process.

The v value can be calculated from the loading frequency (f) or cycle (T) and σ in fatigue tests according to equation:

$$v = \frac{\sigma}{T/2} = 2f\sigma \quad (2)$$

The S_{dz} value is then calculated from eq. (1), and t_s can be expressed as:

$$t_s = \sigma / S_{dz} \quad (3)$$

The direct tension fatigue tests of the AC-13C were carried out at 15 °C for the beam specimens of the asphalt mixture. Results of the tests are summarized in Table 7.

Table 7. Results of the direct tension fatigue tests for AC-13C carried out at 15 °C

f, Hz	t_m	σ MPa	v MPa/s	S_{dz} MPa	t_s	N_f, cycles	
						Sample 1	Sample 2
1	0.4	0.78	1.57	2.814	0.28	1 518	1 330
	0.5	0.98	1.96	2.943	0.33	510	541
	0.6	1.18	2.35	3.053	0.39	250	280
	0.7	1.37	2.74	3.149	0.44	163	112
10	0.3	0.59	11.76	4.219	0.14	30 820	35 231
	0.4	0.78	15.68	4.471	0.18	22 313	18 887
	0.5	0.98	19.60	4.676	0.21	7 883	5 807
	0.6	1.18	23.52	4.850	0.24	3 058	3 478
	0.7	1.37	27.44	5.003	0.27	1 712	1 388
20	0.3	0.59	23.52	4.850	0.12	117 293	106 538
	0.4	0.78	31.36	5.139	0.15	37 717	28 197
	0.5	0.98	39.20	5.375	0.18	9 627	8 234
	0.6	1.18	47.04	5.575	0.21	5 027	7 375
	0.7	1.37	54.88	5.751	0.24	3 036	4 066
50	0.3	0.59	58.80	5.831	0.10	198 472	132 897
	0.4	0.78	78.40	6.178	0.13	56 327	49 754
	0.5	0.98	98.00	6.462	0.15	16 231	19 430
	0.6	1.18	117.60	6.703	0.18	9 863	8 853
	0.7	1.37	137.20	6.914	0.20	3 763	4 084

The fatigue regression curves describing dependence of N_f on t_m and t_s (for various f value), shown in Figs. 3 and 4, were generated through the regression analysis according to equation:

$$N_f = k(1/t)^n \quad (4)$$

where: t — t_m or t_s.

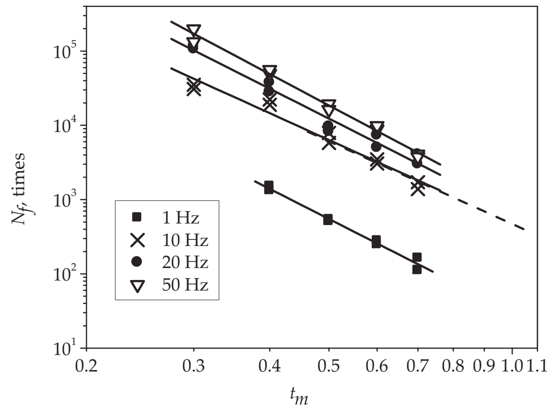

Fig. 3. Fatigue curves based on nominal stress ratio (t_m) under various loading frequencies (f)

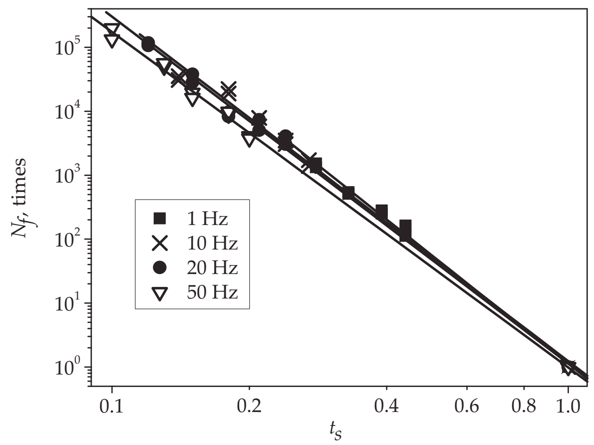

Fig. 4. Fatigue curves based on real stress ratio (t_s) under various loading frequencies (f)

The regression parameters based on t_m and t_s of fatigue equations are summarized in Table 8.

T a b l e 8. Fitting results of fatigue equation parameters based on nominal (t_m) and real (t_s) stress ratios

		f, Hz			
		1	10	20	50
t_m	k	29.819	537.03	620.869	926.83
	n	4.245	3.55	4.305	4.333
	R^2	0.998	0.974	0.991	0.999
t_s	k	1.046	1.192	1.021	1.028
	n	5.734	5.427	5.514	5.236
	R^2	0.999	0.994	0.999	0.999

According to Fig. 4 and Table 8, the fatigue curve based on t_s crossed the strength failure point ($t_s = 1$, $N_f = 1$), and the parameters k in fatigue equation should be „1". Among the regression results excluding 10 Hz, the parameters k in every fatigue equation were all close to "1". Parameters k corresponding to 10 Hz were too large, which may have been caused by the results error related to $t_s = 0.14$. The fatigue equation based on t_s can be extended to $N_f = 1$. Therefore, the fatigue equation based on t_s revealed the internal relation between strength failure and fatigue failure.

In double logarithmic coordinates, the fatigue curves are straight lines for t_s and t_m (Figs. 3 and 4). However, the slope of true stress ratio is larger, and the intersection of the horizontal axis is close to one, which means that the fatigue equation also reflects the strength of asphalt mixture failure characteristics. The intersection of the horizontal axis for t_m is larger than one, which is clearly not in accordance with the actual case. Therefore, the fatigue equation represented by t_s is much more accurate than that represented by t_m. And moreover, the test results can be lengthened to both ends of the extension until they cross the axis.

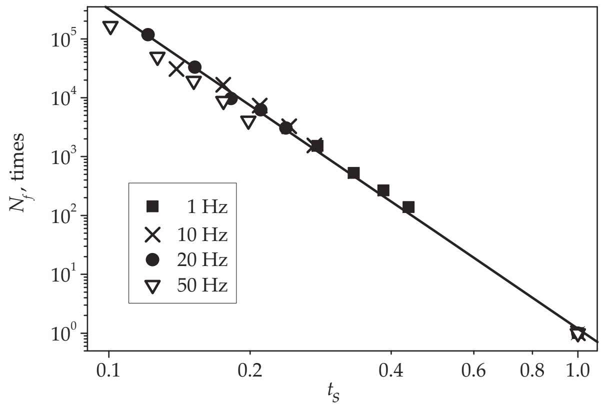

Fig. 5. Unified fatigue curves based on real stress ratio (t_s) under various loading frequencies (f)

At the same time, the difference of n among fatigue equations based on t_s in various f is slight, so fatigue test results under various f can be uniform to a curve with t_s, as shown in Fig. 5.

The fatigue curves based on t_s for various f can be uniform to a straight line (Fig. 5), which indicates that the effects of different loading frequencies and loading rates on the fatigue characteristics are equivalent.

The normalized fatigue equation based on t_s for various f of the asphalt mixture is:

$$N_f = \left(\frac{1}{t_s}\right)^n = \left(\frac{S_{dz}}{\sigma}\right)^n = \left(\frac{S_{dz}}{\sigma}\right)^{5.426} \qquad (5)$$

$$R^2 = 0.993$$

Asphalt fatigue curve based on the real stress ratio for various degrees of aging

The asphalt mixture fatigue test results of the other aging degrees (1, 3, 5, and 7 days) were analyzed with the same method as above (see Fig. 6).

According to Fig. 6, when N_f for various degrees of aging is fitted with t_s, the fatigue curve shows a good linear relationship in double logarithmic coordinates, and

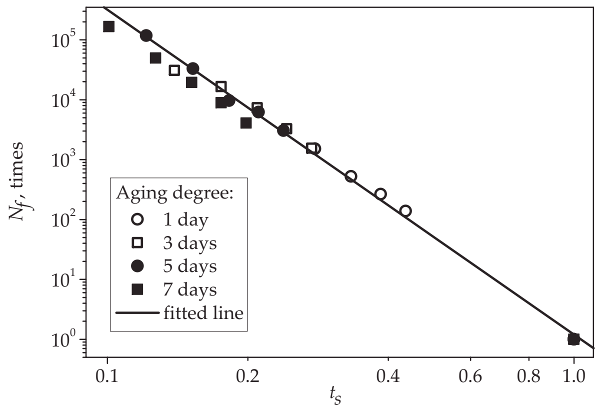

Fig. 6. Summary fatigue curves of asphalt mixture at different degree of aging

it can be extended to the point ($t_s = 1$, $N_f = 1$), without any change in the linear relationship.

The results show that all the aging asphalt mixture fatigue equations can be extended to the same point — the strength failure point — (1, 1) based on t_s. The tensile strength structure coefficient calculation is in line with its definition using t_s. This research, to some extent, makes up for the deficiencies in current asphalt pavement design specifications in China.

CONCLUSIONS

— The loading rate has a significant effect on the strength of an asphalt mixture, and in a certain range of loading rates, the strength increases with the loading rate and changes according to power function.

— According to the change rule between strength and loading rates, this paper proposes the concept and determining method for the real stress ratio, which is the basis of the approach to build the new, more accurate fatigue equation.

— In double logarithmic coordinates, the fatigue life versus the real stress ratio or nominal stress ratio gave straight lines. The fatigue equation curve can be extended to the strength failure points when the fatigue life is one represented by the real stress ratio. It also reveals the mutual relationship of fatigue failure and strength failure.

— The fatigue curves based on real stress ratios for various frequencies can be uniform to a straight line, which indicates that the effects of different loading frequencies and loading rates on the fatigue characteristics are equivalent.

— When the fatigue lives of different degrees of aging asphalt mixtures were fitted with the real stress ratios, the fatigue curves showed a good linear relationship in double logarithmic coordinates, and the fatigue curves can be extended to the condition of $t_s = 1$, $N_f = 1$, without any change in the linear relationship.

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