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Normalization method for asphalt mixture fatigue equation under different loading frequencies

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Abstract: In order to analyze the effect of different loading frequencies on the fatigue performance for asphalt mixture, the changing law of asphalt mixture strengths with loading speed was revealed by strength tests under different loading speeds. Fatigue equations of asphalt mixtures based on the nominal stress ratio and real stress ratio were established using fatigue tests under different loading frequencies. It was revealed that the strength of the asphalt mixture is affected by the loading speed greatly. It was also discovered that the fatigue equation based on the nominal stress ratio will change with the change of the fatigue loading speed. There is no uniqueness. But the fatigue equation based on the real stress ratio doesn't change with the loading frequency. It has the uniqueness. The results indicate the fatigue equation based on the real stress ratio can realize the normalization of the asphalt mixture fatigue equation under different loading frequencies. It can greatly benefit the analysis of the fatigue characteristics under different vehicle speeds for asphalt pavement.

Key words: road engineering; asphalt pavement; fatigue equation; loading speed; loading frequency; strength; stress ratio

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1 Introduction

Fatigue failure is one of the most common failure modes of asphalt pavement, and the fatigue performance of asphalt mixtures has become an important research issue all over the world [1−2]. Researchers have carried out many in-depth studies and acquired valuable information on the fatigue performance of asphalt mixture, focusing on the stress−strain relationship, damage, and energy dissipation [3−7].

Currently, most of the research considering the effects of vehicle speeds on the fatigue failure characteristics of asphalt pavement adopts fatigue tests under different loading frequencies to simulate the real-world conditions, and different researchers propose different correlations between the loading frequency and vehicle speed [8−9]. Meanwhile, during the structural design of asphalt pavement, most researchers choose the experimental results of material fatigue tests under a fixed loading frequency for computation and analysis. This frequency is usually the one corresponding to the average vehicle speed [8], without further consideration on the experimental results under other loading frequencies. Therefore, the effects of other vehicle speeds on the fatigue failure rate of pavement are not considered, and a certain degree of un-scientificity during the parameter selection procedure of asphalt pavement structure design is introduced artificially.

Asphalt mixture is a typical viscoelastic material [10−12]. Its mechanical properties, such as strength and stiffness, are affected by the temperature and loading speed [13−14]. Its fatigue properties are also affected and different fatigue loading frequencies correspond to different loading speeds [15−17]. According to the literature available, there are few research results that focus on the quantitative evaluation of the effects of vehicle speed on fatigue characteristic of asphalt pavement; while the vehicle speed has great influence on the fatigue failure of pavement. The lower the vehicle

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speed, the greater the fatigue failure effect of the pavement. Conversely, a higher vehicle speed has less effect on the fatigue failure of pavement. However, due to the limitation of pavement grade, design standards, traffic safety, and mechanical properties of vehicles, the vehicle speed cannot be improved without limits. In China, the design speed for expressways and 1st class highways is 60−120 km/h, and for 2nd, 3rd, and 4th class highway is 20−80 km/h, with similar standards overseas. Generally, the speed of vehicles operating on pavement with a variety of grades covers a wide range, and even on pavements with the same grade, the speed of different vehicles varies greatly.

The traditional fatigue equation of asphalt mixture refers to the one under a particular loading frequency. Different loading frequencies correspond to different loading speeds. The fatigue strength is not equal under different loading speeds of asphalt mixture. It causes that the fatigue equations under different loading frequencies are not the same. So, the fatigue loading frequency affects the fatigue equation parameters of asphalt mixture directly.

Fatigue tests under a single frequency are unable to characterize the influence of various vehicle speeds on the fatigue performance of asphalt pavement. So, strength tests at different loading speeds were carried out in this work to reveal the law of the strength of asphalt mixture changing with the loading speed. A conventional S−N fatigue equation and a fatigue equation adopting the speed-related stress ratio are established using fatigue tests under different loading frequencies. The different loading frequencies corresponded to different conventional S−N fatigue curves, and the fatigue curve implementing the speed-related stress ratio under different frequencies is represented as a line in a log−log plot. Therefore, the normalization of asphalt mixture fatigue equation under different loading frequencies is realized, and it provides convenience and theoretical basis to analyze the effects of vehicle speeds.

2 Design of raw materials and mix proportions of asphalt mixture

Previous researches have proved that the SBS modified asphalt mixture has favorable anti-fatigue performance at the temperature ranging from −30 to 20 °C, because the addition of the SBS modifier improves the anti-fatigue performance [18]. In order to study the strength and fatigue performance of asphalt mixture, SBS modified asphalt mixture AC-13C was selected as the research mixture with basalt as the aggregate. The experimental results of raw materials and the designed gradation of mineral aggregate are listed in Tables 1−3.

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

Test item		Test result	Technical requirement
Penetration (25 °C, 100 g, 5 s)/ 0.1mm		55	30−60
Penetration index		0.525 (R^2=0.997)	≥0
Duclity (5 cm/min, 5 °C)/cm		32	≥20
Softening point, $T_{\mathrm{R\&B}}$/°C		78	≥60
Kinematic viscosity (135 °C)/(Pa·s)		2.35	≤3
Flash point/°C		271	≥230
Solubility/%		99.94	≥99
Elastic recovery(25 °C)/%		80	≥75
Dissociation of storage stability, softening point difference after 48 h/°C		1.8	≤2.5
Residuum after TFOT (or RTFOT)	Quality change/%	0.2	≤±1.0
	Residual penetration ratio (25 °C)/%	74	≥65
	Residual ductility (5 °C)/cm	18	≥15

Table 2 Test results of bulk density of aggregate

Grain size/mm	13.2	9.5	4.75	2.36	1.18
Density/(g·cm^{-3})	2.735	2.732	2.731	2.720	2.717
Grain size/mm	0.6	0.3	0.15	0.075	Mineral powder
Density/(g·cm^{-3})	2.720	2.720	2.719	2.720	2.758

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

Sieve size/mm	Passing rate/%		Synthesized gradation/%
	Upper limit	Lower limit	
16	100	100	100
13.2	100	90	95.5
9.5	85	68	74.5
4.75	68	38	48.8
2.36	50	24	34.2
1.18	38	15	23.7
0.6	28	10	15
0.3	20	7	11.1
0.15	15	5	8.8
0.075	8	4	5.9

The mix design of the asphalt mixture was carried out based on the Marshall proportion test method with the optimum asphalt-aggregate ratio determined as 5.25%. The test results of the density and void content under the optimum asphalt-aggregate ratio are listed in Table 4.

Table 4 Results of Marshall test with optimum asphalt-aggregate ratio

Asphalt-aggregate ratio/%	Bulk specific density/(g·cm^{-3})	Air void/%	Void filled with asphalt/%	Void in mineral aggregate/%	Marshall stability/kN	Flow value (0.1 mm)
5.2	2.455	5.2	67.2	16.1	15.7	27.9

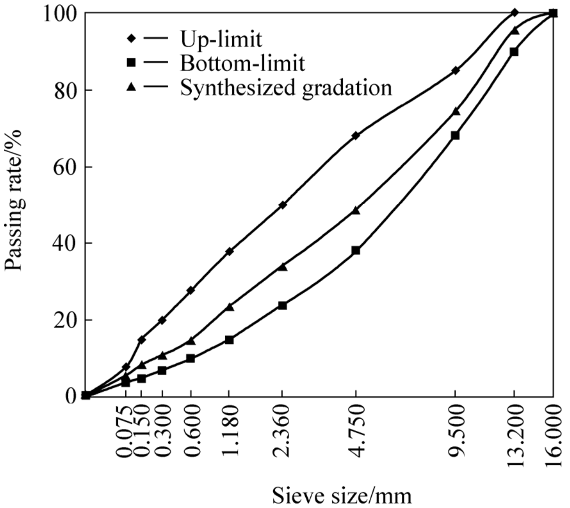

Fig. 1 Aggregate gradation of asphalt mixture

3 Test results and related analyses of asphalt mixture strength at different loading speeds

During the strength test of the asphalt mixture, the direct tensile strength test was adopted as the stress form since it is the simplest. According to the forming method of rutting plates in the Marshall dynamic stability test, the asphalt mixture was first mixed and wheel ground into plate specimens with dimensions of 300 mm×300 mm×50 mm; after they were cooled, they were cut into small beam specimens with dimensions of 25 cm× 5 cm×5 cm.

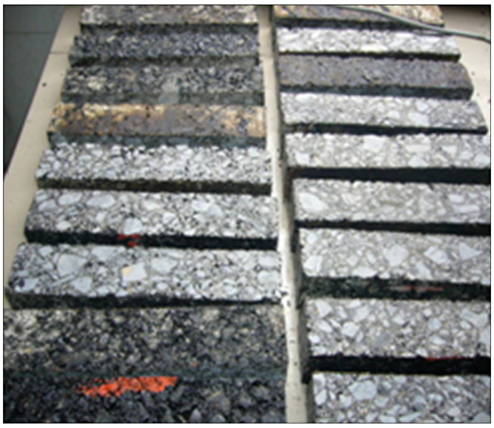

Fig. 2 Small beam specimens of asphalt mixture

The standard direct tensile strength test was carried out first using the MTS-Landmark material test system which was produced in America. The experimental temperature was 15 °C, and the specimens were placed in an environmental chamber for 24 h before the experiment to ensure the temperature homogeneity in the specimens. The loading speed was chosen as 2 mm/min, which is the most commonly used test speed in China.

The direct tensile strength test was repeated 3 times under each condition, and the results are listed in Table 5. The average value, 1 .963 MPa, was selected as the final result of the standard strength test.

Table 5 Test results of standard direct tensile strength

Test number	Tensile strength/MPa	Average/MPa	Standard deviation	Variable coefficient
1	2.101	1.963	0.120	0.061
2	1.894			
3	1.894			

After that, 14 different loading speeds including 0.0037−37 MPa/s were selected for direct tensile strength tests. The test results are listed in Table 6.

Table 6 Test results of direct tensile strength at different loading speeds

Number	Loading speed/ (MPa·s^{-1})	Specimen area/mm^2	Failure load/N	Strength/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

As displayed in Table 6, the strength of the asphalt mixture is obviously affected by the loading speed. Within the loading speed range tested, the maximum value of 5.227 MPa is six times the minimum value of 0.844 MPa. The direct tensile strength value in Table 6 at different loading speeds is plotted in Fig. 3.

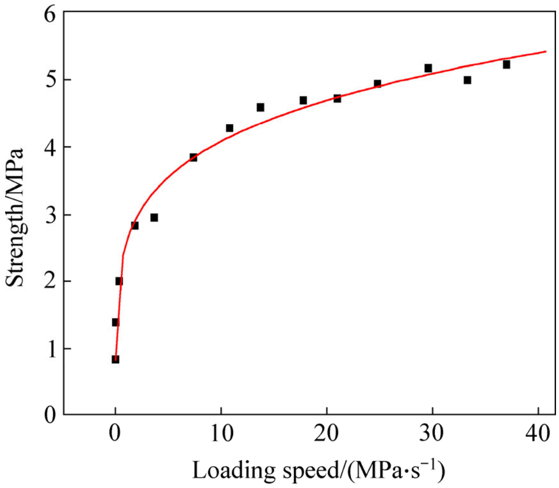

Fig. 3 Direct tensile strength vs loading speed of AC-13C at 15 °C

Using the nonlinear fit between loading speed and direct tensile strength, the regression relationship between them can be obtained by

$$S_\text{v}=2.583v^{0.2}, R^2=0.984 \tag{1}$$

where S_v is the direct tensile strength, v is the loading speed and R is the relation coefficient.

According to the linear fitting result, the loading speed has great influence on the strength of the asphalt mixture and they follow a power function change law. The strength value corresponding to the loading speed in the fatigue test is defined as the fatigue speed related strength.

When conducting fatigue tests of asphalt mixture, the loading frequency of 10 Hz is commonly used [2, 6−7, 9]. Thus, the loading cycle and unloading cycle are 0.1 s in total, among which the loading procedure counts for 0.05 s, half of the total time. In China, the tire ground pressure is set as 0.7 MPa in the asphalt pavement design. Then, for fatigue tests carried out with the stress of 0.7 MPa, the corresponding loading speed is 0.7 MPa/0.05 s=14 MPa/s. Based on Table 6 and Eq. (1), it can be calculated inversely that the loading speed corresponding to the standard strength test result of 1.963 MPa (2 mm/min) is just 0.35 MPa/s. That is to say, the loading speed of 2 mm/min is equivalent to the loading speed of 0.35 MPa/s, which is 14/0.35=40, less than that of 14 MPa/s corresponding to 0.7 MPa. Also, the strength corresponding to the loading speed of 14 MPa/s is calculated as 4.379 MPa, which is 1.970, larger than that of 1.963 MPa. Therefore, it can be proved that using the standard strength test to determine the stress ratio of conventional S−N fatigue equation is erroneous, since it is just a man-made strength ratio that does not consider the effects of loading speeds and lacks actual mechanical significance.

4 Fatigue equation of asphalt mixture under different loading frequencies considering effects of loading speeds

The stress ratio is determined based on the standard strength test results during the establishment of the conventional S−N fatigue equation; while the standard strength test is usually carried out at a fixed loading speed. Since the loading speed in the standard strength test does not correspond to that in the fatigue test procedure, there is no relationship among loading speeds under different loading frequencies. Therefore, this stress is defined as the nominal stress ratio t_nominal, during the determination of which the standard strength test of the asphalt mixture should be carried out first. According to Table 5, the standard strength S_t is 1.963 MPa.

Corresponding to the previous strength tests, the direct tensile fatigue test, which has the simplest stress condition, was also carried out during the fatigue test of the asphalt mixture. The loading control mode is stress control. The fatigue life is the loading times when the specimen was fractured. The test temperature was set as 15 °C, and the specimens were placed in an environmental chamber for 24 h in order to obtain a uniform temperature distribution. The fatigue test was also conducted in the constant temperature environmental cabinet with a temperature of 15 °C. The nominal stress ratio was set as 0.3, 0.4, 0.5, 0.6 and 0.7, and the loading frequency was set as 1, 10, 20 and 50 Hz. The fatigue load was a continuous haversine load with the waveform shown in Fig. 4.

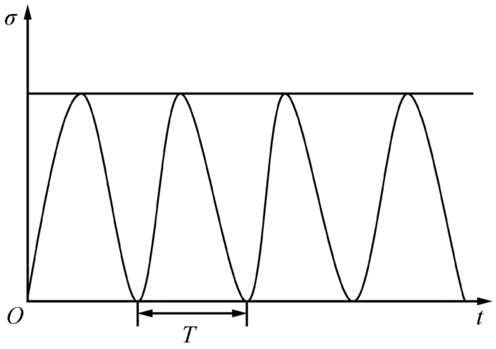

Fig. 4 Waveform of loads applied during fatigue tests

The fatigue loading speed during fatigue tests can be calculated according to the loading frequency f with period of T and stress σ, as shown in Eq. (2).

$$v=\frac{\sigma}{T/2}=2f\sigma \tag{2}$$

Then, based on the correspondence between the strength and loading speed indicated by Eq. (1), the fatigue speed related strength S_vf can be determined.

The real stress ratio t_{real} is defined as the ratio of stress level "σ" to the fatigue speed related strength "S_{vf}" under its corresponding loading speed.

$$t_{\text{real}} = \sigma / S_{\text{vf}} \tag{3}$$

where σ is the stress amplitude applied during fatigue test and its value is the product of the nominal stress ratio and standard strength; S_{vf} is the fatigue speed related strength under the loading speed corresponding to the loading frequency and stress level.

A small beam direct tensile fatigue test was conducted on the previously mentioned AC-13C asphalt mixture using the MTS-Landmark materials test system. The real stress ratio and fatigue life under different loading frequencies and stress levels are summarized in Table 7.

For the vehicles on the actual asphalt road, the loading speed is usually in the range of 4−84 MPa/s. In order to satisfy the research needs, the range of loading speed for fatigue test is slightly wider than the normal one. Based on regression analysis on the fatigue test results in Table 7 using the unified equation form of $N_{\text{f}}=k(1/t)^n$, the fatigue regression curves respectively represented by the nominal stress ratio and real stress ratio under different loading frequencies were obtained as shown in Fig. 5 and Fig. 6.

The regression parameters k, n, k', n' of the fatigue equation are summarized in Table 8.

As shown in Fig. 5, different loading frequencies correspond to different conventional S−N fatigue curves. This is theoretically caused by the fact that during the determination of the stress ratio in the conventional S−N fatigue equation, the strength value obtained using the standard strength test is chosen. This strength value is obtained under a fixed loading speed and has nothing to do with the loading frequency and the stress level. Meanwhile, during the standard strength test, the loading speed is much lower than that in the half circulation of the fatigue test, i.e. the loading procedure which is related to the loading frequency and the stress level. Actually, the true strength during fatigue tests is much greater than the nominal strength obtained via standard strength tests and its fatigue curve does not pass through the strength failure point at which both the stress ratio and fatigue life are 1. If the fatigue equation extends to both ends, a relatively large deviation will be caused and increase with the degree of extension.

According to the fatigue equation shown in Fig. 6,

Table 7 Summary of real stress ratio and fatigue life under different loading frequencies and stress

Loading frequency/Hz	Nominal stress ratio	Stress level/MPa	Loading speed/(MPa·s^{-1})	Fatigue speed related strength/MPa	Real stress ratio	Fatigue life	
						1	2
1	0.4	0.78	1.57	2.814	0.28	1518	1330
	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	30820	35231
	0.4	0.78	15.68	4.471	0.18	22313	18887
	0.5	0.98	19.60	4.676	0.21	7883	5807
	0.6	1.18	23.52	4.850	0.24	3058	3478
	0.7	1.37	27.44	5.003	0.27	1712	1388
20	0.3	0.59	23.52	4.850	0.12	117293	106538
	0.4	0.78	31.36	5.139	0.15	37717	28197
	0.5	0.98	39.20	5.375	0.18	9627	8234
	0.6	1.18	47.04	5.575	0.21	5027	7375
	0.7	1.37	54.88	5.751	0.24	3036	4066
50	0.3	0.59	58.80	5.831	0.10	198472	132897
	0.4	0.78	78.40	6.178	0.13	56327	49754
	0.5	0.98	98.00	6.462	0.15	16231	19430
	0.6	1.18	117.60	6.703	0.18	9863	8853
	0.7	1.37	137.20	6.914	0.20	3763	4084

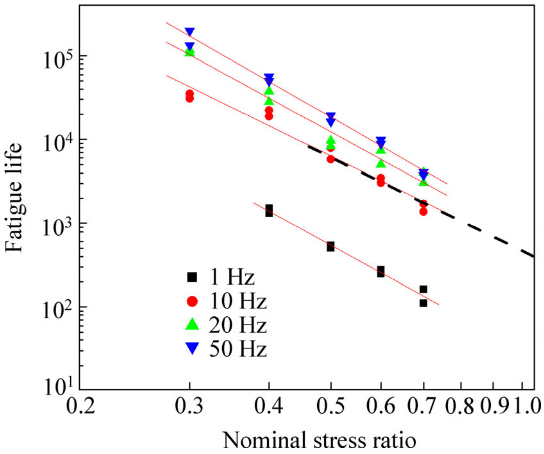

Fig. 5 Fatigue curves based on nominal stress ratio

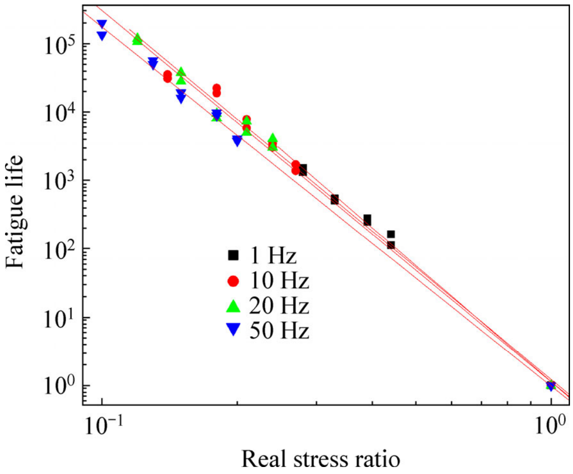

Fig. 6 Fatigue curves based on real stress ratio

Table 8 Fitting results of fatigue equation parameters based on nominal and real stress ratios

Loading frequency/Hz	Nominal stress ratio			True stress ratio		
	k	n	R^2	k'	n'	R^2
1	29.819	4.245	0.998	1.046	5.734	0.999
10	537.03	3.55	0.974	1.192	5.427	0.994
20	620.869	4.305	0.991	1.021	5.514	0.999
50	926.83	4.333	0.999	1.028	5.236	0.999

which is established based on the real stress ratio of the speed related strength, the fatigue curves under various loading frequencies are very close to each other and all of them pass through the strength failure point (1, 1). That is to say, the fatigue equation represents the characteristic of the strength failure of asphalt mixture. It reveals the internal connection between the strength failure and the fatigue failure. Therefore, the fatigue equation represented by the real stress ratio is much more accurate than the one represented by the nominal stress ratio. The test result is able to extend to both ends. What’s more, the expression form of this fatigue equation is simple and clear.

The exponent n' of each fatigue regression equation based on the real stress ratio under different loading frequencies has little variation from each other. Therefore, the fatigue test results under different loading frequencies can be uniformed by taking advantage of the real stress ratio of the loading speed and regressed as a single curve, as shown in Fig. 6.

As it can be observed from Fig. 7 that the fatigue curves based on the real stress ratio under different frequencies can be regressed as a single curve, indicating that the influence of the loading frequency and loading speed on the fatigue performance of asphalt mixture is equivalent and the normalization of the asphalt mixture fatigue equation under different loading frequencies is achieved.

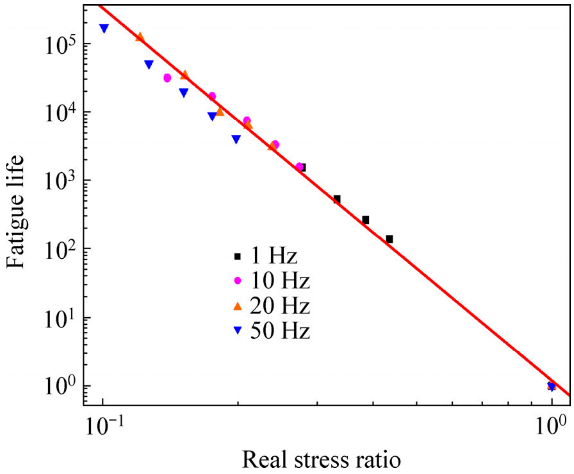

Fig. 7 Normalized fatigue curve based on real stress ratio under different loading frequencies

The unified fatigue equation of asphalt mixture under different frequencies based on the real stress ratio is

$$N_{\mathrm{f}} = \left(\frac{1}{t_{\mathrm{real}}}\right)^{n'} = \left(\frac{S_{\mathrm{vf}}}{\sigma}\right)^{n'} = \left(\frac{S_{\mathrm{vf}}}{\sigma}\right)^{5.426} \qquad (4)$$

5 Conclusions

1) Loading speed has a significant impact on the strength of asphalt mixture.

2) The fatigue equation based on the real stress ratio reveals the internal connection between the strength failure and fatigue failure for asphalt mixture.

3) The fatigue equation represented by the real stress ratio is able to prolong to both ends. But the nominal one cannot be prolonged.

4) The fatigue equation based on the real stress ratio can realize the normalization of the asphalt mixture fatigue equation under different loading frequencies.

5) The fatigue equation based on the real stress ratio

provides an analytical method to evaluate the fatigue failure of asphalt pavement for the different vehicle speeds.

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