Study on Expected Fatigue Loading Cycles for Accelerated Loading Test of Asphalt Pavement Structure

Shujuan Wang[1,a], Zhiguo Chen[1,b], Weijun Qin[1,c], Ziqi An[2*], Ruoting Shen[1,d]

[1]Jilin Provincial Transport Scientific Research Institute, Jilin, China
[2]School of Transportation and Geomatics Engineering, Shenyang Jianzhu University, Shenyang, China

[a]289619065@qq.com; [b]1367087060@qq.com; [c]65311621@qq.com; [*]744577382@qq.com; [d]530293811@qq.com

Abstract. Accelerated loading test is a common method to study the performance of asphalt pavement, in the process of previous research, there is no conclusion yet on the design of the loading times plan before the test is carried out. For this study proposes a method for determining the expected number of loading cycles in the preliminary stage of accelerated loading tests, aiming to provide references for the rational formulation of accelerated loading test schemes. Considering accelerated loading tests as a special service condition for typical pavement structures, the differences between loading conditions and general actual service conditions are taken into account. Based on the current design specifications for asphalt pavement structures in China, considering differences in axle load, loading rate, lateral distribution of wheel tracks, temperature, reliability, and other states, the correspondence between loading states and actual service states is achieved. On this basis, a method for determining the expected fatigue loading cycles is provided. Results: The expected loading cycles are calculated for outdoor and indoor loading conditions based on measured traffic parameters or structural design life. Under conditions of a loading rate of 8 km/h and a half-axle load of 80 kN, the calculated results are as follows: for outdoor loading, the expected loading cycles are approximately 198,000 based on measured parameters and approximately 10.74 million based on structural design life; for indoor loading, the expected loading cycles are approximately 192,000 based on measured parameters and approximately 10.40 million based on structural design life. The expected loading cycles are of great significance for designing accelerated loading tests and improving test results. On the one hand, they are closely related to the duration and cost of the tests; on the other hand, the difference between expected and actual loading cycles provides the basis for further refining the data of the pavement performance degradation model. This provides a reference for the design of accelerated loading tests for asphalt pavements.

Keywords: ARA, Accelerated Loading, Expected Loading Cycles

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1 Introduction

Accelerated loading tests refer to applying repeated loading by prototype wheels on specially constructed test tracks or existing pavements in a 1:1 scale under controlled conditions and within a short period, aiming to study the degradation law of pavement performance and pavement structure behavior. Accelerated loading tests have evolved from test tracks to test loops to the current movable accelerated loading equipment, and have become relatively mature[1].

A large number of accelerated loading tests have been conducted domestically and internationally. However, as far as the loading times of the test program is concerned, there is no fixed calculation method, and it is usually considered that loading to a fixed rutting depth or loading to the cracks of the carriageway until cracks appear in some areas[2]-[3], or the expected number of times of loading is determined by simple axle loading conversion[1]. There are certain deficiencies in the design of such a loading times plan. There is no relatively accurate expected loading times and a lack of expectations for the test cycle, which will result in a waste or lack of investment in time, money and labor costs, and affect the overall progress of the project. Therefore, it is particularly important to develop a reasonable and convenient method for calculating expected loading cycles.

Expected loading cycles are based on the consideration of differences between loading states and actual service states of pavement structures, combined with the current asphalt pavement design specifications and equipment characteristics in China, and considering the correspondence between different parameters. This paper proposes a method for determining loading cycles, which can effectively complement the deficiencies in the design of loading schemes.

2 Study on State

The state correspondence proposed in this paper is based on the consideration of structural design parameters and equipment characteristics. For fatigue expected loading, the states mainly include: environmental state, reliability state, axle load, and lateral distribution of wheel tracks, as shown in Figure 1. Accelerated Loading Tests.

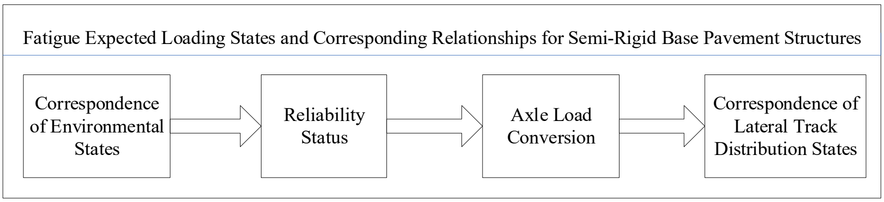

Fig. 1. Flowchart of State Correspondence for Expected Fatigue Loading Cycles

2.1 State Correspondence for Fatigue Loading

2.1.1 Correspondence under Different Environmental Conditions

Asphalt mixtures are temperature-sensitive materials, and their mechanical properties vary with temperature changes[5]. Fatigue cracking, as a temperature-sensitive phenomenon, is closely related to environmental changes. Environmental factors in road engineering generally refer to temperature and humidity, both of which have a significant impact on pavement performance and fatigue cracking life. In actual road conditions, the temperature and humidity of pavement structures vary with the changing seasons, exhibiting randomness. Additionally, in colder regions, freeze-thaw cycles occur. Full-scale accelerated loading tests can be conducted outdoors according to project requirements or indoors on test tracks. In indoor accelerated loading tests, the pavement structure temperature is mainly controlled at room temperature. Unlike actual roads, indoor test conditions are controllable, and there are no freeze-thaw cycles within the pavement structure. The main differences in environmental parameters lie in the adjustment coefficients ka for seasonal frozen soil regions and the temperature adjustment coefficients k_{t2}. There are various methods to determine these parameters. In this study, considering that outdoor tests should be completed within a few months, the average monthly temperature is treated as the annual average temperature. A relationship model between the annual average temperature and temperature adjustment coefficients is established, as shown in Figure 2, to facilitate the conversion of environmental states.

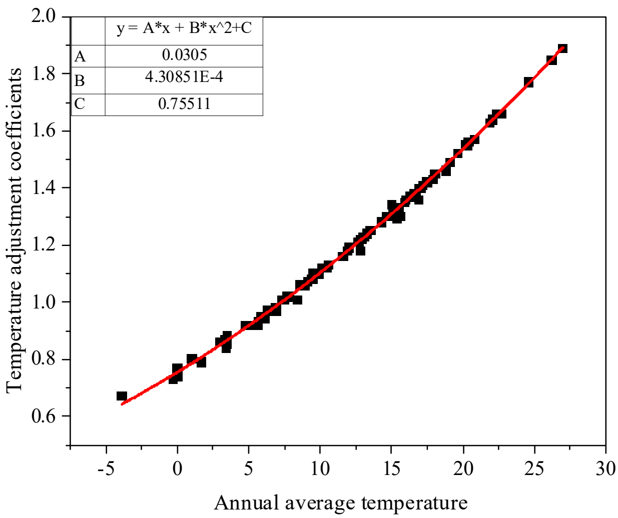

Fig. 2. Correction of Temperature Adjustment Coefficients

The approach for establishing the correspondence between the state of stabilizing materials inorganic binders and the environmental state of asphalt mixture layers is similar. After establishing the correspondence between environmental states, the calculation of fatigue cracking cycles for the inorganic binder layer can be conducted as shown in Equation 1.

$$N'_{f2} = N_{f2} \times \frac{k_{T2}}{k_a} \times \left(\frac{k_a'}{k_{T2}'} \right) \tag{1}$$

In the equation: N'_{f2}—The expected number of load cycles after corresponding to the environmental state (standard axle load, measured traffic parameters, or structural design life);

N_{f2}—The expected number of load cycles (standard axle load, measured traffic parameters, or structural design life);

k_{T2}—Temperature adjustment coefficient;

k_a'—Adjustment coefficient for seasonal frozen soil regions during accelerated loading tests;

k_{T2}'—Temperature adjustment coefficient under accelerated loading conditions.

2.1.2 Corresponding to Different Reliability States

Pavement performance exhibits significant variability, influenced by various objective factors including inherent differences in material properties, uncertainties in design parameters, and model errors resulting from design analysis models. In the "Highway Asphalt Pavement Design Code" (JTG D50-2017)[4], the target reliability for highways is set at 95%, corresponding to a target reliability index β=1.65. A 95% reliability implies that at the end of the design life, the majority of pavement structures remain intact, with fatigue being a rare occurrence. Therefore, on average, most pavement structures should remain undamaged, indicating that the average lifespan of pavement structures far exceeds the design life. Determining the actual reliability of accelerated loading test sections is currently challenging and involves numerous theoretical and practical issues. In the absence of knowledge about the actual reliability, setting the target reliability to 50% and the failure probability to 50% is relatively reasonable. In this case, the target reliability index for the structure is β_0=0. The calculation of the expected number of load cycles after corresponding to the reliability state is expressed in Equation 2.

$$N'_{\beta 2} = 10^{0.57(\beta-\beta_0)} \times N'_{f2} \tag{2}$$

In the equation: $N'_{\beta 2}$—The target number of load cycles after corresponding to the environmental state and the reliability state is;

N'_{f2}—The expected number of load cycles after corresponding to the environmental state (standard axle load, measured traffic parameters, or structural design life);

β—According to the "Highway Asphalt Pavement Design Code" (JTG D50-2017), the reliability index specified for highway design;

β_0—The reliability index for accelerated loading test sections.

2.1.3 Axle Load Conversion

The axle load conversion formula specified in the "Highway Asphalt Pavement Design Code" (JTG D50-2017)[4] directly utilizes the theory of layered elastic systems for calculation. Asphalt mixtures are viscoelastic materials, which can lead to unequal ratios of actual mechanical responses under different loadings compared to the load ratio.

$$EALF_{mij} = c_1 c_2 \left(\frac{P_{\mathrm{mij}}}{P_{\mathrm{s}}} \right)^{\mathrm{b}} \tag{3}$$

In the equation: P_s—Design axle load (kN);

P_{mij}—For the i-th axle type in the j-th axle load interval of M-class vehicles, the single-axle load (kN) is specified. For tandem and tridem axles, the axle load is evenly distributed among each individual axle;

b—The conversion factor for analyzing fatigue in the stabilized inorganic binder layer, b=13.

When conducting axle load conversion for the stabilized inorganic binder layer, the study utilizes the bottom tensile stress of the stabilized inorganic binder layer as the criterion for verification. Therefore, the load ratio part in Equation 3 can be converted to Equation 4, where the conversion exponent b adopts the recommended value specified in the code.

$$\left(\frac{P_{mij}}{P_{\mathrm{s}}} \right)^{\mathrm{b}} \cong \left(\frac{\sigma_{\mathrm{i}}}{\sigma_t} \right)^{\mathrm{b}} \tag{4}$$

In the equation: σ_i—The bottom tensile strain of the asphalt mixture layer under accelerated loading conditions (1Hz, 160kN);

σ_t—The bottom tensile strain of the asphalt mixture layer under design conditions (10Hz, 100kN)

b—When analyzing fatigue in stabilized inorganic binder layers, conversion exponents need to be considered. b=13.

2.1.4 Corresponding States of Lateral Distribution Coefficient for Wheel Tracks

For accelerated loading tests, if the lateral distribution function of the wheel tracks is not activated, the wheels will repeatedly move back and forth on fixed tracks for a long time, leading to significant lateral distribution differences compared to the actual vehicle's effect on the pavement. Therefore, considering the lateral distribution coefficient is necessary to establish the expected number of load cycles[6]. The following Fig. 3 shows a typical lateral distribution frequency curve. In this study, we selected 30% as the correction coefficient for the number of load cycles considering the lateral distribution, compared to the fixed position loading. This means that loading once at a fixed position is equivalent to loading 1/0.3=3.33 times when considering the lateral distribution.

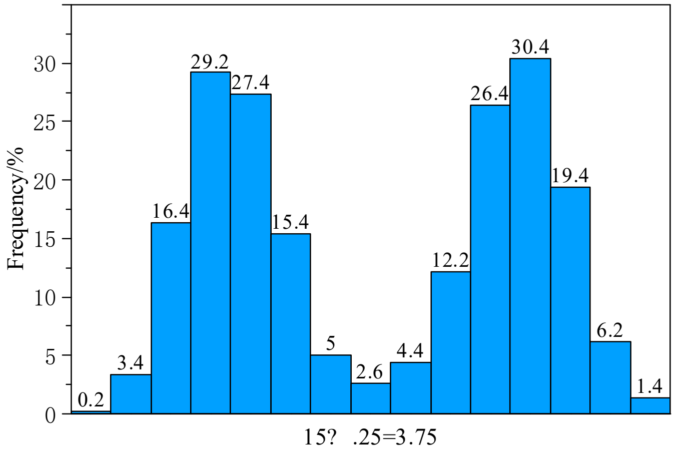

Fig. 3. Lateral Distribution Frequency Curve of Wheel Tracks (Single Lane Unidirectional Travel)

2.2 The Formula for Calculating the Expected Number of Load Cycles Under Fatigue Loading

By integrating the above corresponding relationships, the calculation of the expected number of load cycles for the stabilized inorganic binder layer can be obtained as Equation 5.

$$N_{f2}(Accelerated\ loading) = N_{f2} \cdot \frac{k_{T2}}{k_a} \cdot \frac{k_a{}'}{k_{T2}{}'} \cdot 10^{0.57(\beta-\beta_0)} \cdot \left(\frac{\sigma_t}{\sigma_i}\right)^{13} \cdot \eta \tag{5}$$

In the equation: $N_{f2}(Accelerated\ loading)$—The expected number of load cycles for fatigue under specified axle load in the semi-rigid base layer;

N_{f2}—Expected number of load cycles (standard axle load, measured traffic parameters, or structural design life);

k_{T2}—Temperature adjustment coefficient;

$k_a{}'$—Adjustment coefficient for seasonal frozen soil regions during accelerated loading *tests*;

$k_{T2}{}'$—Temperature adjustment coefficient under accelerated loading conditions;

β—According to the "Highway Asphalt Pavement Design Code" (JTG D50-2017), the specified reliability for highway design;

β_0—Reliability *index* for the accelerated loading test section;

σ_i—Bottom tensile strain of the asphalt mixture layer under accelerated loading conditions (1Hz, 160kN);

σ_t—Bottom tensile strain of the asphalt mixture layer under design conditions (10Hz, 100kN);

η—Lateral distribution coefficient.

3 Design of Preloading Cycle Scheme

The accelerated loading test (see Fig. 4) for this study utilizes the first domestically developed ARA (Accelerated Loading Assembly) full environmental loading equipment, which can perform both field and indoor loading. The dimensions of the equipment are 16.2m×2.6m×4.1m. The wheel load can be adjusted between 20kN and 100kN for semi-axle double-wheel loading. The maximum speed can reach 10 km/h, and the fastest round trip speed can reach 750 cycles per hour. Additionally, the equipment can heat the pavement and simulate rain by spraying water.

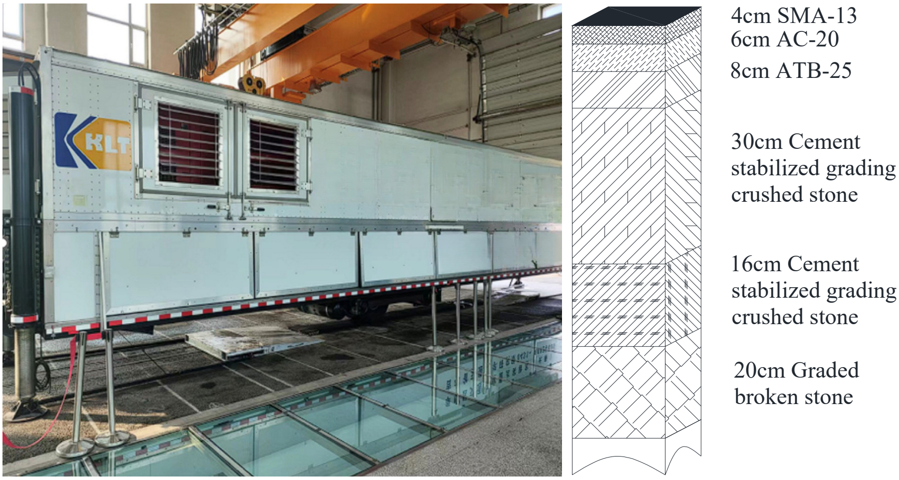

Fig. 4. ARA Full Environmental Accelerated Loading Equipment

Outdoor loading will be conducted at monitoring section K619+000 of the Heilongjiang-Dalian Expressway in Jilin. Simultaneously, to achieve the desired goals more quickly, an indoor loading test pit has been constructed. The pavement structure consists of a semi-rigid base asphalt pavement (4cm SMA-13+6cm AC-20+8cm ATB-25+30cm Cement stabilized grading crushed stone+16cm Cement stabilized grading crushed stone+20cm Graded broken stone). Loading on the pavement follows the principle of "simulating similar axle loads and similar loading environments".

3.1 Established Loading Objectives

For established loading objectives regarding semi-rigid base asphalt pavement structures, it is typically loading based on equivalent axle passes under measured traffic parameters or the fatigue cracking life calculated according to the Chinese standard "Highway Asphalt Pavement Design Code" (JTG D50-2017).

1. Based on measured traffic parameters

The study conducted statistical analysis on the traffic volume in Jilin Province from 2017 to 2022 and calculated the cumulative equivalent design axle load passes for the semi-rigid base according to the specifications. The calculation results are shown in Table 1.

Table 1. Cumulative Equivalent Axle Passes (Measured Load per Single Axle)

Structural layer	2017	2018	2019	2020	2021	5-year Summary
Stabilized layer	1205082	3009854	716487	4163422	2422855	11517700

After conversion, the cumulative equivalent axle passes for the 15 years is 34,553,100. In this study, the calculation of the expected number of load cycles based on measured traffic parameters will be conducted according to this value.

2. Based on the structural design life

If the structure is to be loaded to the upper limit of the structural design life, the calculation of fatigue cracking life should be carried out in accordance with the current specification, and the median value of materials recommended by the specification has certain universality, and without the need to do complex indoor experiments, which can save time and cost, and can be used for the calculation of the expected number of times of the loading action, so that the material parameters in the process of calculations are all in accordance with the specification requirements to take the median value, shown in Table 2.

Table 2. Material Parameters for Structural Calculations

	Material	Thickness /cm	Modulus /MPa	Poisson ratio
Surface layer	SMA-13	4	9750	0.25
Intermediate layer	AC-20	6	10750	0.25
Lower layer	ATB-25	8	9000	0.25
Upper base	Cement stabilized grading crushed stone	30	11000	0.25
Lower base	Cement stabilized grading crushed stone	16	11000	0.25
Function layer	Graded broken stone	20	300	0.35
Subgrade	Clay soil	-	60	0.4

According to the current specifications, the fatigue cracking life is calculated using material parameters taken as the median values as required by the specifications. Utilizing pavement structure design software, the fatigue cracking life of the stabilized layer in the semi-rigid base pavement structure is calculated to be 1,871,007,150. The calculation of the expected number of load cycles based on the structural design life will be conducted according to this value.

3.2 Determining the Expected Number of Load Cycles for Fatigue Loading in the Fieldy

The dynamic strain response of asphalt layer has obvious temperature and load dependence, and presented different characteristics with changes of temperature and load[7]. Based on temperature data investigation, as shown in Fig. 5, it is found that the temperature at a depth of 20mm below the surface of the target loading section reaches up to 53°C at its peak, and the temperature at a depth of 20mm below the surface remains above 40°C during the hottest three months. Therefore, it is not advisable to conduct fatigue loading during these three hottest months (considering studying pavement high-temperature performance from June to August), and fatigue loading will be conducted during the remaining months. Additionally, through the analysis of traffic volume and load characteristics, it is observed that there is overloading phenomenon, with axle loads of heavy vehicles reaching around 150kN. Therefore, for accelerated loading tests, the test axle load is selected as 80kN per half axle (equivalent to 160kN per single axle). Xia et al. conducted a fatigue test of crumb rubber modified asphalt mixture and analyzed the experimental results, concluding that there is an inseparable relationship between loading rate and fatigue life [8]. Regarding speed simulation, lower speeds result in lower dynamic modulus of asphalt mixtures, exacerbating damage. Therefore, the speed is chosen as 8km/h (equivalent to a loading frequency of approximately 1Hz).

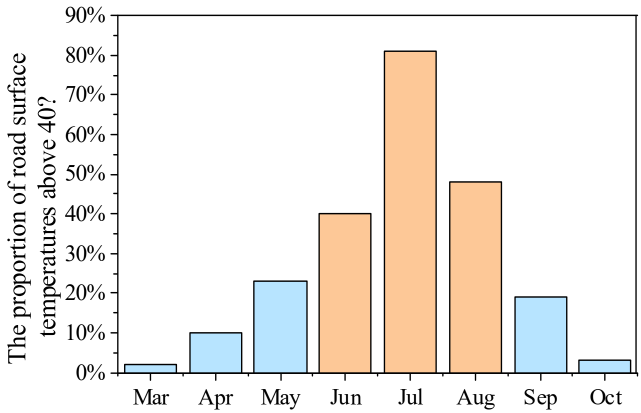

Fig. 5. Monthly Percentage of Dates with Road Surface Temperature Above 40°C

As an example, the calculation process for the expected number of load cycles based on measured traffic parameters is as follows:

1. Corresponding environmental conditions

In this accelerated loading test, fatigue loading is scheduled to be conducted in May, September, and October. The average temperature during these three months is 18.65°C, resulting in $k_{T2}{}'$ 1.472. According to the specifications, the temperature adjustment coefficients for the location of the loading are k_{T2}=0.95, k_a=0.72, $k_a{}'$=1. Substituting these design parameters into Equation 1, the fatigue cracking life after environmental state transformation is calculated as N_{f2}'=30821365, Therefore, the conversion coefficient for the environmental state is calculated as 0.896.

2. Corresponding reliability states

During the process of reliability state correspondence, the structural reliability at the time of design is 95%, while the reliability under accelerated loading conditions is 50%. Corresponding reliability indices are $\beta = 1.65$ and $\beta_0 = 0$. Substituting these parameters into Equation 2, the fatigue cracking life after reliability state correspondence is calculated as $N_{\beta 2}'$=268762305, Therefore, the conversion coefficient for the reliability state is calculated as 8.72.

3. Axle load conversion

Axle load conversion is conducted according to current specifications. In this case, for the stabilized inorganic binder layer under accelerated loading conditions, the bottom tensile stress σ_i is 0.292MPa, and under design conditions,σ_t is 0.183MPa, Substituting these values into Equation 3, the fatigue cracking life after axle load conversion is calculated as 661,155. Therefore, the conversion coefficient for axle load conversion is calculated as $2.46*10^{-3}$。

4. Lateral distribution of wheel tracks

In the calculation process of the expected number of load cycles, if the lateral distribution of wheel tracks is not considered, the lateral distribution coefficient is set to 0.3. If the lateral distribution of wheel tracks is considered, the coefficient is set to 1. In this calculation process of the expected number of load cycles, the lateral distribution of wheel tracks is not considered (coefficient set to 0.3). The calculated fatigue crack count after considering the lateral distribution of wheel tracks is 198,347. After organizing the calculation parameters mentioned above, the relevant calculation parameters for the expected number of load cycles are shown in Table 3. The calculated fatigue loading axle passes (160kN) under different states of field structural design life are shown in Table 4, obtained using Equation 5.

Table 3. Calculation Parameters for Expected Number of Load Cycles in the Field Fatigue Loading

Parameters	K_a	K_a'	K_{T2}	K_{T2}'	β	β_0	$\sigma_{i(160)} MPa$	$\sigma_{t(100)} MPa$	η
Values	0.72	1	1.472	0.95	1.65	0	0.292	0.183	0.3

Table 4. Expected Load Cycle Counts for Field Fatigue Loading (160kN)

Corresponding state relationships	Load cycles		Conversion coefficient
	Measured traffic parameters	Structural design life	
Environment	30821365	1668938378	0.896
Reliability	268762305	14553142654	8.72

Axle load conversion	661155	35800731	$2.46*10^{-3}$
Lateral distribution of wheel tracks	198347	10740219	0.3

3.3 Indoor Expected Load Cycle Calculation

In indoor testing, temperature control can be achieved based on the ARA accelerated loading equipment's capability to simulate full environmental conditions. Therefore, the control temperature for ambient loading is set to 20°C, with an axle load of 160kN and a loading speed of 8km/h. The Table 5, Table 6 and Table 7 show the calculation parameters and results.

Table 5. Calculation Parameters for Expected Number of Load Cycles in Indoor Fatigue Loading

Parameters	K_a	K_a'	K_{T2}	K_{T2}'	β	β_0	$\sigma_{i(160)}MPa$	$\sigma_{t(100)}MPa$	η
Values	0.72	1	1.526	0.95	1.65	0	0.292	0.183	0.3

Table 6. Expected Load Cycle Counts for Indoor Fatigue Loading (20°C, 160kN)

Corresponding state relationships	Load cycles		Conversion coefficient
	Measured traffic parameters	Structural design life	
Environment	29853878	1616550178	0.864
Reliability	260325820	14096317549	8.72
Axle load conversion	640402	34676941	$2.46*10^{-3}$
Lateral track distribution	192120	10403082	0.3

Based on the calculated expected fatigue loading cycles in indoor and outdoor conditions, the recommended acceleration loading scheme is as follows:

Table 7. Accelerated Loading Test Plan

Project	Outdoor Loading		Indoor Loading	
	Based on the measured traffic load parameters	Based on the structural design life	Based on measured traffic load parameters	Based on measured traffic load parameters
Loading Month/Months	5、9、10		At any time	
Simulated Axle Load/kN	160			
Simulated Speed/km/h	8			

Temperature/°C	18.65		20	
Simulated Wheel Track Distribution	N/A			
Preloaded Axle Count/Times	198347	10740219	192120	10403082

4 Conclusion

(1) This paper analyzes the differences between the pavement under accelerated loading conditions and the pavement in actual service conditions. Using the current Chinese asphalt pavement design specifications as a reference, it achieves the conversion between loading conditions and actual service conditions. A method for calculating the expected loading times of fatigue is proposed. This method makes up for the lack of consideration of the expected loading times before the test is carried out. It can help researchers to formulate more effective and accurate loading times plans before the test is carried out. It is of great significance for the design of accelerated loading test scheme.

(2) Using ARA accelerated loading equipment to load semi-rigid pavement structures, outdoor loading plans for HeDa Expressway and indoor loading plans for test tanks were designed. The design of the plans is based on the actual project conditions and divided into outdoor and indoor loading. It is recommended to conduct outdoor fatigue loading in May, September, and October, with an expected number of loading cycles of approximately 198,000 based on measured parameters, and approximately 10.74 million based on structural design life calculations. For indoor loading, since the ARA accelerated loading equipment can control the temperature, loading can be carried out throughout the year. The controlled temperature for fatigue loading is 20°C, with an expected number of loading cycles of approximately 192,000 based on measured parameters, and approximately 10.4 million based on structural design life calculations.

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