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ORIGINAL RESEARCH ARTICLE

Fatigue failure criteria of asphalt mixture under moisture influence and cyclic loading

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Abstract: The fatigue characteristics of asphalt mixtures in terms of permanent deformation were investigated using a triaxial repeated creep test and a small accelerated loading test. The results indicate that when the specimens in the small accelerated loading tests reach fatigue failure, the variation trend of the vertical residual resilient modulus under different test conditions is consistent with that of the residual resilient modulus at the end of the triaxial repeated creep tests. In addition, the vertical strain, displacement, and laminar base strain in the small accelerated loading test exhibit three stages, which are similar to the three stages observed in the triaxial repeated creep tests. Based on a phenomenological method, the test results of the triaxial repeated creep tests and the small accelerated loading tests can be correlated—under the same test conditions, there is a linear relationship between the fatigue lives obtained from the two types of tests. Furthermore, a temperature-equivalent curve for the fatigue life of the triaxial repeated creep tests influenced by temperature is established, thereby defining the failure criteria for the small accelerated loading test. These findings provide a scientific basis for determining the fatigue failure criteria of small accelerated loading tests and offer a new approach to studying the fatigue failure behavior of asphalt mixtures.

Keywords: Asphalt mixture; Triaxial repeated creep test; Modulus of resilience; Fatigue resistance; Environmental durability

1. Introduction

Under the combined effects of loading and environmental factors, the performance of asphalt mixtures gradually degrades until failure, which represents a typical fatigue damage phenomenon.[1,2] Currently, both domestically and internationally, traditional fatigue tests used to evaluate the fatigue performance of asphalt mixtures mainly include four methods: the bending fatigue test, the tension–compression fatigue test, the indirect tensile test, and the accelerated loading test. The small accelerated loading test is a scaled-down, laboratory-simulated accelerated loading fatigue test developed on the basis of full-scale loading tests. Its load reproduction accuracy is nearly 100%; however, due to the complexity of boundary and loading conditions, a unified method for determining its fatigue failure has not yet been established. Therefore, correlating it with traditional fatigue tests is considered a feasible research approach.[3,4]

In terms of selecting indoor small-scale test methods, the commonly used methods often vary among different countries and regions. At times, the analytical results obtained from different test parameters may differ or even conflict. For instance, Shafabakhsh *et al*. evaluated the effect of titanium dioxide on the fatigue performance of an asphalt mixture and demonstrated that variations in test temperatures led to varying contributions of titanium dioxide to fatigue performance.[5,6] In addition, Mannan *et al*.[7] and Pasetto *et al*.[8] employed the four-point bending fatigue test to examine the influence of reclaimed asphalt pavement incorporation on hot-mix asphalt mixtures. Due to the different controlled strain levels adopted in their tests, the former reported that a 20% reclaimed asphalt pavement content enhanced the fatigue performance of the mixture by more than two-fold, whereas the latter observed an increase in fatigue life, but to a lesser extent.[7-9]

Several studies have investigated the fatigue performance of rock asphalt-modified asphalt mixtures using the four-point bending fatigue test, the direct tensile fatigue test, and the splitting fatigue test, respectively. The results showed that the optimal incorporation levels of rock asphalt obtained by the three methods differed, and the improvement effects on the fatigue performance of modified asphalt mixtures under these optimal incorporation levels also varied.[10-13] In addition, other researchers conducted four-point bending fatigue tests, semi-circular bending fatigue tests, and splitting fatigue tests on different types of asphalt mixtures. The findings revealed differences among the test outcomes—notably, the fatigue failure process observed in the semi-circular bending fatigue test was shorter and more sensitive to stress.[14-16] In China, after years of research on the fatigue performance of asphalt and asphalt mixtures, combined with a literature review, the research team led by Songtao *et al*. has defined the applicable scope of typical laboratory fatigue tests.[17-19]

The existing parameters for analyzing fatigue life include the fatigue factor, the 50% stiffness modulus (D_{50}), the damage–load cycle product (S×N), the energy ratio, and the dissipation energy change rate. A review of the literature indicates that the stiffness modulus remains the most commonly used parameter for fatigue life analysis due to its computational accuracy and reliability.[20,21] Therefore, this study establishes a correlation between traditional fatigue tests and the small accelerated loading test through modulus analysis. To ensure that the results of the small accelerated loading test correspond to those of traditional fatigue tests, this study measured the bottom tensile strain and vertical compressive strain of specimens obtained from the small accelerated loading test, calculated the change in resilient modulus, and defined the failure criterion of the small accelerated loading test based on the analysis of residual resilient modulus values.

In addition, previous studies have shown that the fatigue performance of asphalt mixtures varies significantly under different water environments.[22,23] Therefore, to ensure the validity of the correlation between the experimental results of different tests, the testing process should maintain consistent air humidity and specimen moisture content.

2. Raw materials and test design

2.1. Asphalt

The asphalt used in this study was 90# petroleum asphalt (PG 64–28; Inner Mongolia Transportation Group, China), and its main technical indicators are presented in Table 1. The test results comply with the relevant technical requirements specified in the *Technical Specification for Highway Asphalt Pavement Construction* (JTG F40-2004).

2.2. Mineral material

The mineral materials used in this study included mineral powder and aggregates. The coarse aggregates were hard, wear-resistant, non-weathered, and free from impurities, and were sourced from limestone. The fine aggregates (machine-made sand) were produced from limestone parent rock, while the mineral powder consisted of limestone mineral powder. The technical indicators of all mineral materials comply with the requirements specified in the *Technical Specifications for Construction of Highway Asphalt Pavement* (JTG F40-2004).

2.3. Composition of asphalt mixture

According to the theory of integrated design of materials and structures, fatigue failure in the asphalt surface

Table 1. Technical index of the 90# matrix asphalt

Index	Technical requirement	Test result	Standard
Penetration (25°C, 5 s, 100 g, 0.1 mm)	80–100	82.6	T0604-2011
Softening point (°C)	≥of	52.5	T0606-2011
Kinematic viscosity (60100Pa·s)	≥a·s	157	T0625-2011
Ductility (10°C, cm)	≥uc	34.0	T0605-2011

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layer often occurs within the middle and lower layers. Therefore, two types of asphalt mixtures, AC-16 and AC-20, were selected for this study. The gradation curves of the asphalt mixture are shown in Figure 1. Based on the mixture design, the optimum asphalt contents for the AC-16 and AC-20 matrix asphalt mixtures were determined to be 5.0% and 4.7%, respectively.

2.4. Triaxial repetitive creep test design

The triaxial repetitive creep test was conducted using a UTM-100 universal testing machine (manufacturer, country) for asphalt mixtures. The confining pressure was set at 138 kPa, and the test temperatures were 40was conducted using a UTM-100 univedeviatoric stress was maintained at 0.7 MPa. Before testing, the specimens were preloaded with 5% axial stress for 90 s. The loading waveform adopted was the Haversine waveform, which best represents the typical stress state within the pavement structure. This waveform is a semi-sine wave with a loading duration of 0.1 s and an unloading duration of 0.9 s. During testing, the relative humidity was maintained below 30%, and the moisture content of the specimen remained below 5%.

2.5. Small accelerated loading test design

The fatigue performance of the two asphalt mixtures at 25℃ was evaluated using a Model Mobile Load Simulator 3 (manufacturer, country). For the purpose of testing, the multiple thin asphalt surface and base layers were simplified into a single-layer structure. During the tests, the relative humidity was maintained below 30%, and the specimen moisture content remained below 5%, with humidity controlled using industrial air conditioning.

The specific parameters of the test are listed in Table 2. The deformation of the specimens was recorded after every 30,000 loading cycles, and measurements were taken at positions 1.5 cm, 4.5 cm, 7.5 cm, 10.5 cm, and 13.5 cm from the specimen boundary, respectively.

3. Results and discussion

3.1. Analysis of triaxial repeated creep test results

Based on the triaxial repeated creep test, the calculated results correspond to the elastic modulus of the asphalt mixtures (Figures 2 and 3). When the test environment and loading conditions are consistent, the number of load cycles endured by asphalt mixtures of the same gradation is significantly influenced by temperature. However, under the defined termination conditions, the elastic modulus remains largely unaffected by temperature variation. For the AC-20 mixture, the test reached termination when the rebound modulus decreased to 703–706 MPa, whereas for the AC-16 mixture, termination occurred when the rebound modulus decreased to 695–704 MPa.

Although the triaxial repeated creep test does not explicitly employ rebound modulus as a termination criterion, the attenuation pattern of the rebound modulus exhibits a distinct three-stage development. In the first stage, the rebound modulus decreases rapidly; in the second stage, it gradually stabilizes; and in the third stage, it declines rapidly once again, reaching the termination condition. This three-stage pattern is comparable to the reference indicators used

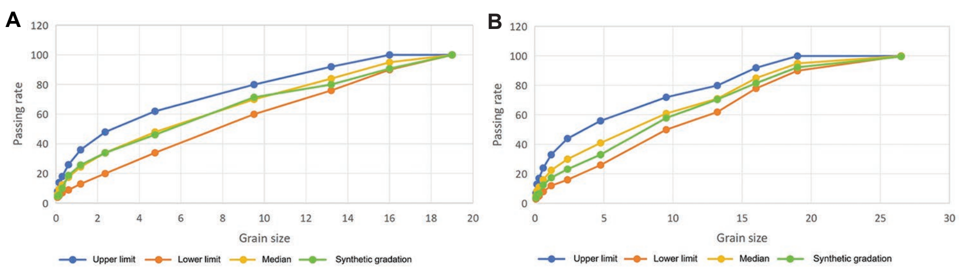

Figure 1. Gradation curves of mineral mixtures for (A) AC-16 and (B) AC-20

Table 2. Setting parameters of the small accelerated loading test instrument

Parameter	Index	Parameter	Index
Loading length of the vehicle	90 cm	Rate of loading	48 times/min
Tire loading width	8 cm	Tire pressure	0.6–0.8 MPa
Pavement plane size	10×90 cm	Temperature	25m
Roller structure	Elastic levitation	Number of data acquisition intervals	30,000 cycles

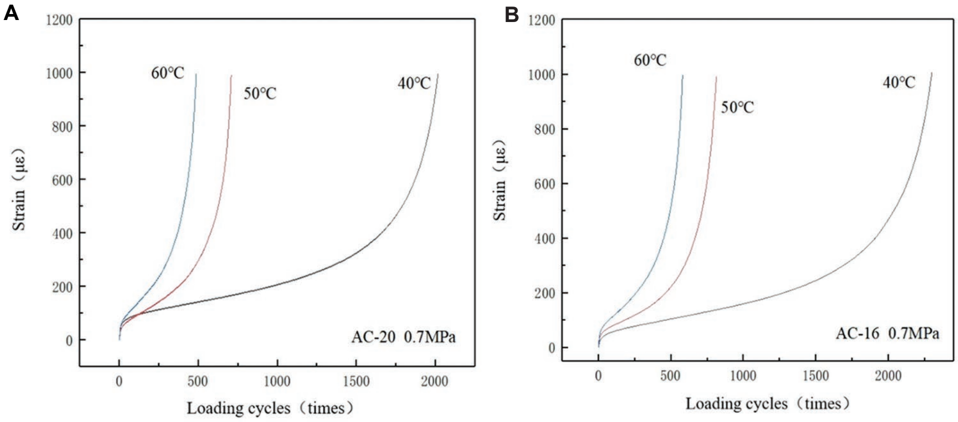

Figure 2. Relationship between permanent strain and the number of load cycles in the triaxial repeated creep test for (A) AC-20 and (B) AC-16

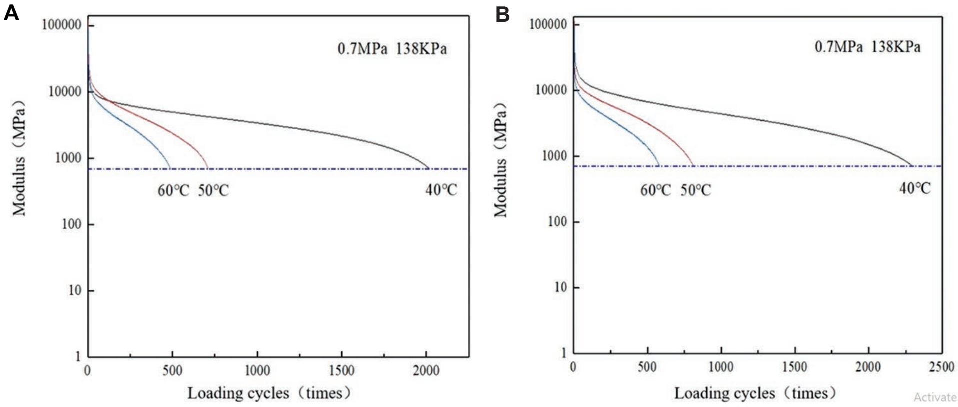

Figure 3. Relationship between modulus of resilience and the number of load cycles in the triaxial repeated creep test for (A) AC-20 and (B) AC-16

in the termination criteria for the four-point bending fatigue test of asphalt mixtures, thereby supporting the evaluation of the fatigue performance of the specimens.

3.2. Analysis of small accelerated loading test results

3.2.1. Microstrain analysis of vertical strain gauge

In this study, the cumulative vertical strain of the AC-20 asphalt mixture, which more readily reached the failure condition, was selected for analysis. As shown in Figure 4, the relationship between the number of load applications in the small accelerated loading test, cumulative vertical strain, and acceleration mainly reflects the self-compaction and pavement settlement of the asphalt mixture during the initial 0–20,000 loading cycles. The cumulative vertical strain began to exhibit significant changes after 20,000–30,000 cycles. During the no-load periods, no vertical displacement of the asphalt mixture was recorded.

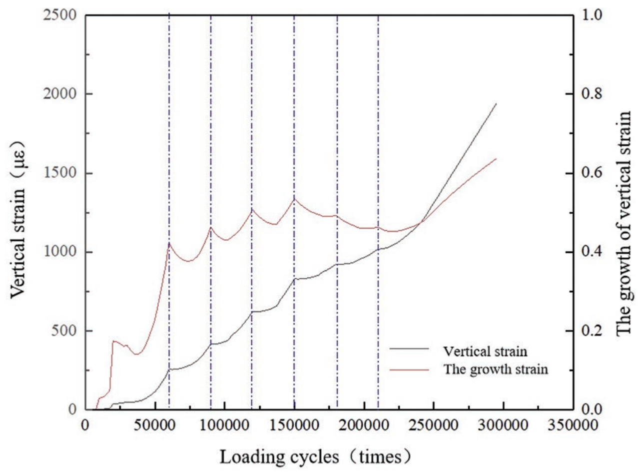

Figure 4. Relationship between the loading cycles and vertical strain in the accelerated loading test

Before 210,000 loading cycles, a distinct change was observed in the vertical strain at the beginning of each loading phase. This is primarily because the rutting depth of the asphalt pavement was measured after every 30,000 loading cycles, allowing the mixture to recover partially during the measurement and rest intervals. This process resulted in a sudden change in the vertical strain and its growth rate after every 30,000 cycles, forming a repetitive pattern before fatigue occurred.

The loading intervals were 30,000–60,000, 60,000–90,000, 90,000–120,000, 120,000–150,000, 150,000–180,000, and 180,000–210,000 cycles, during which the cumulative vertical strain exhibited a significant regular pattern. After 210,000 loading cycles, this regularity became less evident, and after 240,000 cycles, the deformation rate accelerated significantly. These findings indicate that macroscopic cracks had formed by this stage (Figure 5). Therefore, it can be determined that the specimen experienced fatigue failure after approximately 240,000 loading cycles.

Figure 4 illustrates that the vertical strain of the asphalt mixture under accelerated loading can be broadly divided into three distinct stages. The first stage, corresponding to 10,000–20,000 cycles, represents the compaction and settlement phase of the asphalt pavement. During this period, the vertical strain of the asphalt mixture remains minimal and primarily results from load transfer to the underlying layers.

The second stage—the steady growth phase—corresponds to 20,000–240,000 cycles, during which the asphalt pavement exhibits a regular vertical strain curve. In this stage, the asphalt mixture fully demonstrates its viscoelastic–plastic characteristics. Within the loading cycle, it initially exhibits viscoelastic properties before gradually transitioning to viscoplastic behavior under sustained loading. Following loading cessation, a recovery phenomenon of the compressive rebound modulus occurs.

The third stage—the damage growth phase—corresponds to 240,000 to 300,000 cycles and represents the fatigue limit state. At this stage, the asphalt mixture shows signs of structural damage, loses its viscoelastic–plastic material properties, and the vertical strain increases rapidly.

The correlation between the triaxial repeated creep test and the small accelerated loading test was established by calculating and analyzing the variation pattern of the time-dependent rebound modulus obtained from the small accelerated loading test. Figure 6 depicts the relationship between rebound modulus and loading cycles in the small accelerated loading test.

As shon in Figure 6, the modulus curve shows a pronounced decrease at 240,000–250,000 cycles, indicating that the specimen experiences structural instability and failure. This point can be defined as the dividing line between the second and third stages of modulus change, which aligns with the results of the strain analysis (Figure 3). It can be deduced that, although the termination conditions of the triaxial repeated creep test and the small accelerated loading test for the same gradation of asphalt mixture differ, the triaxial repeated creep test adopted in this study maintains a constant eccentric stress amplitude, consistent with the mold settings in the small accelerated loading test.

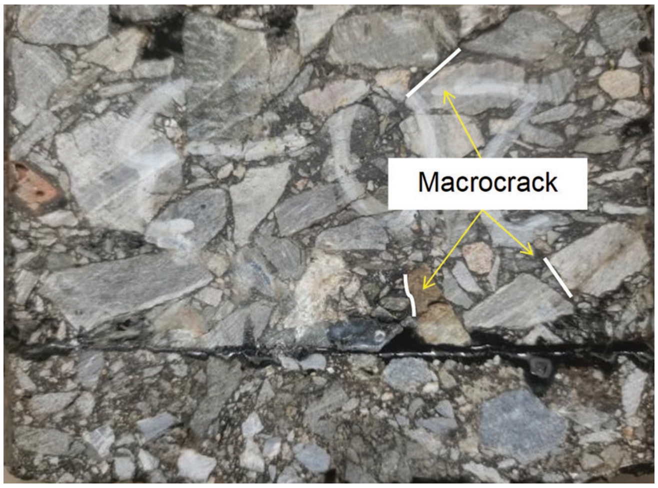

Figure 5. Cross-sectional view of the test specimen

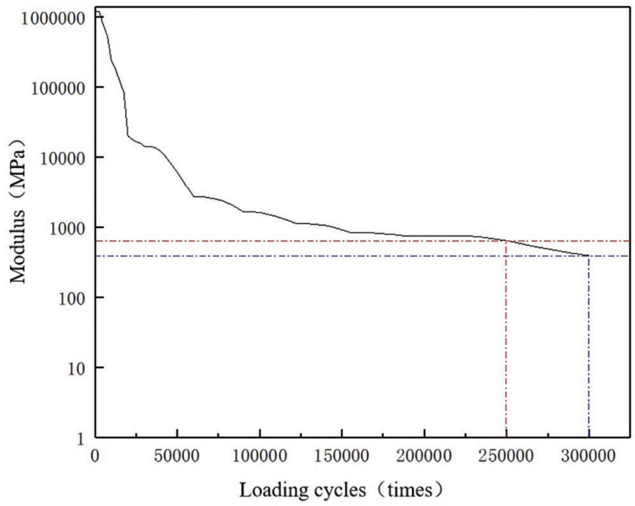

Figure 6. Relationship between rebound modulus and number of loading cycles in the small accelerated loading test. The blue line represents a vertical rebound modulus of approximately 379 MPa after 300,000 cycles, whereas the red line corresponds to a vertical rebound modulus of approximately 644 MPa after 250,000 cycles, closely corresponding to the results of the triaxial repeated creep test.

The loading mode was a semi-sine wave, which is essentially identical to the load type in the small accelerated loading test. In other words, the loading modes and boundary conditions of the two tests are fundamentally similar, and both include loading intervals. In addition, the residual elastic modulus of the same asphalt mixture under the two tests is comparable, reflecting a strong correlation between the fatigue resistance of the asphalt mixture and the rebound modulus. These findings indicate that the rebound modulus of the asphalt mixture measured by the triaxial repeated creep test can be used as a criterion for determining fatigue failure in the small accelerated loading test.

3.2.2 Microstrain analysis of horizontal strain gauge

When the small accelerated loading test specimens are subjected to loading, stress is transmitted downward, generating horizontal tensile strain at the bottom of the specimens. In this study, the bottom-layer strain of the small accelerated loading test specimens was collected and analyzed, and both the cumulative and incremental bottom-layer strains were calculated (Figure 7).

As shown in Figure 7, the bottom-layer strain increments of asphalt mixtures with different gradations exhibit clear regularity, and each loading cycle can be roughly divided into three stages.

In the first stage, the bottom-layer strain increment is initially high but gradually decreases; in the second stage, it continues to decline; and the third stage represents the recovery phase of the bottom-layer strain. However, no abrupt change was observed, indicating that macroscopic cracks caused by horizontal strain have not yet formed. These findings suggest that vertical cracking occurs earlier than transverse cracking at the bottom of the specimen.

3.3. Fatigue equation of the small accelerated loading test

From a phenomenological perspective, the small accelerated loading test and the triaxial repeated creep test of asphalt mixtures exhibit a high degree of consistency in many aspects, including load magnitude, load direction, specimen type, and test conditions. Moreover, their failure modes and termination criteria are essentially identical. From the perspective of the triaxial repeated creep test, the fatigue life obtained from the small accelerated loading test under a simulated real-road loading environment can be used to predict the fatigue life of asphalt movement under actual service conditions.[24,25]

Considering that the temperatures of the triaxial repeated creep test were set at 40°C, 50°C, and 60°C, respectively, and the temperature of small accelerated loading test was 25°C, the ExpDec1 model[26] incorporating temperature parameters was used to establish the fatigue life–temperature equivalence curve of the triaxial repeated creep test under temperature influence (Equation [1]). The specific components and parameters used in the model are presented in Table 3. It should be noted that, due to the difficulty and long period of the accelerated loading test, only one loading temperature was examined in this study.

$$y = y_0 + A_1 \times e^{\left(-\frac{x}{t_1}\right)} \quad (1)$$

where:

(i) y is the number of load cycles at specimen failure.

(ii) x is the temperature of the test.

(iii) A_1 and t_1 are the correlation coefficients for the fatigue life–temperature equivalence relationship in the triaxial repeated creep test, respectively.

Figure 8 shows the fatigue life of the triaxial repeated creep test influenced by temperature and the

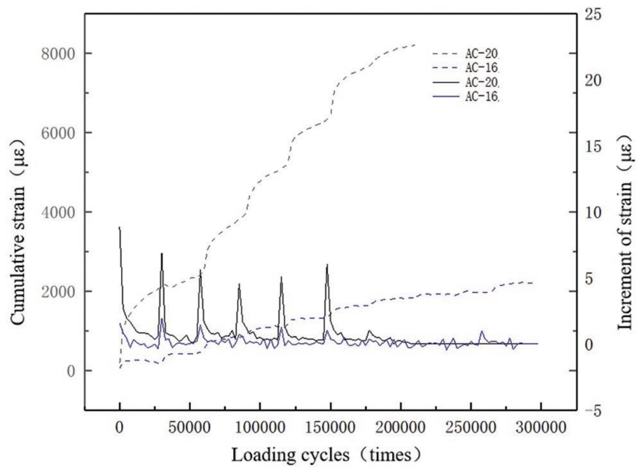

Figure 7. Relationship between bottom-layer strain and number of loading cycles in the small accelerated loading test

Table 3. Components and parameters of the fatigue life–temperature equivalence equation

Types	Parameters			
	y_0	A_1	t_1	R^2
AC-16	538.7	2.8×10^6	5.4	1
AC-20	452.5	2.2×10^6	5.5	1

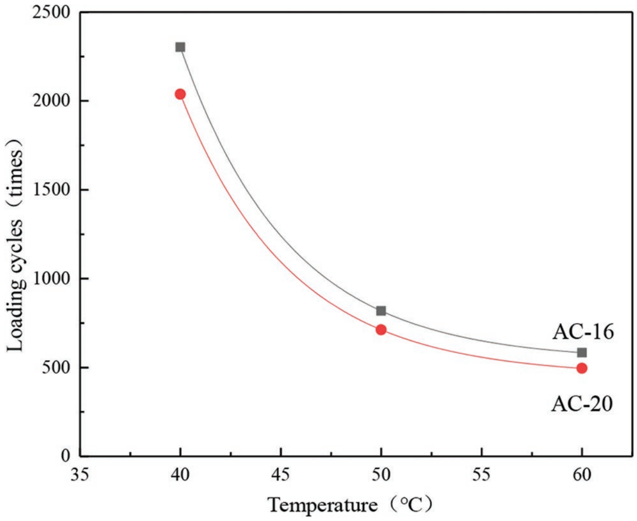

Figure 8. Fatigue life–temperature equivalence curve of the triaxial repeated creep test

equivalent curve of temperature. Based on Equation (1), it can be predicted that the number of load cycles for the AC-16 graded triaxial repeated creep test at 25℃ is approximately 27,862, and the fatigue life obtained from the small accelerated loading test is approximately 10.5 times greater than that of the triaxial repeated creep test. Using the AC-20 gradation to verify this relationship, the number of triaxial repeated creep test load cycles at 25℃ was approximately 21,920, whereas the actual fatigue life from the small accelerated loading test, defined based on the rebound modulus, was approximately 242,500 cycles. This value is approximately 11 times greater than the triaxial repeated creep test load cycles for the AC-20 gradation at 25℃ and is consistent with the fatigue life relationship established for the AC-16 gradation.

Based on these findings, it can be deduced that, for asphalt mixtures of the same gradation subjected to triaxial repeated creep testing, the fatigue life obtained from the small accelerated loading test is approximately 11 times greater than the number of triaxial repeated creep test load cycles. Considering the conservativeness of the test, 12 times the number of triaxial repeated creep test load cycles under the same conditions can be used as the termination criterion for the small accelerated loading test. This criterion can also serve as a reference for determining the fatigue failure of asphalt mixtures under these test conditions.

4. Conclusion

Based on the triaxial repeated creep test, the resilient modulus of the asphalt mixture under different testing conditions was determined. Using the termination criteria of the triaxial repeated creep test, the residual resilient modulus of the asphalt mixture was proposed as the stopping criterion for the three-pump repeated creep test. These findings were validated through experiments conducted under multiple loading stages and temperatures, and are applicable to testing results obtained in different moisture environments.

Based on the small accelerated loading test, the macroscopic failure behavior and stress characteristics were analyzed. Combined with the findings from the triaxial repeated creep test, it was concluded that vertical cracking occurs earlier than horizontal cracking at the bottom of the specimen. An increase in moisture content intensifies the water-induced damage of the asphalt mixture; therefore, both air humidity and the mixture's moisture content should be carefully controlled during the test.

The fatigue life–temperature equivalence curve of the triaxial repeated creep test was established using the ExpDec1 model. The relationship between the number of load cycles in the triaxial repeated creep test and the fatigue life of the small accelerated loading test was predicted. The fatigue life obtained from the small accelerated loading test was found to be approximately 12 times greater than that of the triaxial repeated creep test under identical conditions. This relationship is applicable to test results under different moisture conditions; however, an increase in the specimen's moisture content leads to a reduction in fatigue life.

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Conflict of interest

The authors declare they have no competing interests.

Author contributions

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Investigation: Yu Wang
Methodology: Yu Wang, Peng Wang
Writing–original draft: Yu Wang, Peng Wang
Writing–review & editing: Yu Wang, Jiangsan Hu

Availability of data

Data are available upon reasonable request to the corresponding author.

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