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Long-Term Performance of Recycled Asphalt Pavement with Recycled Engine Oil Bottom Based on Accelerated Loading Test

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Abstract: The practical performance of recycled asphalt obtained from recycled engine oil bottom (REOB) was evaluated by paving a test road of base asphalt and REOB-recycled asphalt mixture in a laboratory, where accelerated loading tests with 700,000 cycles were conducted. During accelerated loading, pavement temperature, layer bottom strain, pavement skid resistance, and rutting were monitored. The performance of pavement core material was tested after loading to analyze the index change of binder and the compaction degree of the mixture. The results show that the long-term anti-rutting ability of REOB-recycled asphalt pavement is approximately 10% higher than that of the base asphalt pavement, although the long-term anti-sliding force and anti-fatigue performance are poor. A developed model of rut with loading time can better predict the development trends of these parameters with loading cycles. The performance test of the pavement material after loading shows that 700,000 cycles can only degrade the performance of the test pavement, not damage it. The recycled asphalt pavement with 7% REOB has basically the same performance as the base asphalt under 700,000 cycles, indicating that REOB-recycled asphalt pavement can ensure basic road performance, while providing economic and environmental advantages. These results provide a reference for the application and form optimization of REOB-recycled asphalt pavement.

Keywords: recycled engine oil bottom; accelerated loading test; long-term performance; secondary aging

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1. Introduction

As a secondary by-product of engine oil, recycled engine oil bottom (REOB) presents a similar homology and compatibility with asphalt in production. The feasibility of using REOB as an asphalt modifier has previously been effectively verified [1–3]. Moreover, its product features, such as those related to economy and environmental protection, excellent performance, and waste treatment, have attracted global attention.

Golalipour et al. [4] studied ten types of oil-modified asphalt, including two kinds of recycled asphalt with REOB, and they found that both REOB blends that they tested were the least susceptible to aging among all of the oil blends they used. In addition, compared with the other eight kinds of oil, REOB most effectively improved the low-temperature performance of the binder. As early as 1998, Herrington et al. [5] paved a test road with a hot-recycled asphalt mixture produced by waste oil disintegration bottoms (WODB). After 57 months of testing, they found that all parts performed well, and the surface did not deteriorate, crack, or rut. Rostyslav et al. [6] used REOB-regenerated aging asphalt from different sources, before designing a mixture. They found that the permanent deformation and dynamic modulus of the REOB-modified asphalt mixture and the base asphalt mixture were similar when the performance grade (PG) of the mixture was consistent. Cooper et al. [7] designed five 12.5 mm asphalt mixtures for high-, medium-, and low-temperature performance tests using two base asphalts and three different REOB contents for recycled asphalt, and they established that the use of REOB can increase the temperature performance of the mixture.

REOB can effectively restore the performance of old asphalt, but during use, the low-temperature performance is often poor. Li et al. [8] tested the turning point temperature, freezing fracture temperature, and failure strength of asphalt mixtures mixed with 0%, 2.5%, 6.0%, and 15% REOB using the thermal stress restrained specimen test, and found that a high REOB content can have adverse effects on the low-temperature crack resistance of the asphalt mixture. Zaumanis et al. [9] studied aged REOB-recycled asphalt and discovered that its penetration index usually increases, which indicates that it is a more structural and brittle material and hence is easier to crack.

Related research has been conducted by means of basic indoor tests of materials. However, to date, no studies have been performed on the operation of REOB-recycled asphalt pavements owing to the long on-site test period required and high costs. In recent years, the simulated accelerated loading test method has received significant attention and is considered to be an important method for designing pavement based on service performance. This method is closest to simulating an actual traffic load in current research on road engineering.

In the history of pavement structural design, the AASHO full-scale pavement accelerated loading test is the most representative test method. By establishing the relationship between the service performance of a pavement structure and the cumulative number of axle loads in traffic, the AASHO test verified the mechanical design of pavement structure. This method also opened up new ways to study asphalt pavement. Sirin et al. [10] conducted tests on five test sections using a heavy vehicle simulator to predict pavement rutting in Florida. The five test sections adopted different running directions and different combinations of loading wheels. The results showed that when evaluating the rutting resistance of pavement under the traffic and climate conditions in Florida, driving the loading wheels in one direction is more effective than two-way driving. Choubane et al. [11] used accelerated loading test equipment to evaluate the long-term performance of high-performance asphalt pavement with either coarse or fine aggregate gradation. They found that fine aggregate asphalt pavement provides superior rutting resistance than coarse aggregate material. Theys et al. [12] proposed a semi-empirical–semi-mechanical subgrade design model using subgrade deflection as a road design standard instead of the generally accepted vertical stress by conducting a large number of heavy-duty simulator (HVS) tests in California, USA. Hugo [13], a researcher in South Africa, developed the fourth generation of the previous pavement accelerated loading simulation systems of MLS and MMLS and successfully applied it to evaluate pavement fatigue performance. Accelerated loading tests were carried out on cement- and lime-stabilized sandy soil base in Mozambique. During the test, indexes such as surface cracks, grooves, pits, dynamic deflection, pavement flatness, and rutting were examined. At the same time, the long-term performance of asphalt pavement was investigated by testing the mechanical properties of materials using indoor tests, and the fatigue performance laws of the asphalt mixtures were obtained. Clearly, accelerated loading tests can provide many useful conclusions to guide the design of pavement structures and materials.

In this study, pavement performance is compared and analyzed on the basis of the material and structural form by paving base asphalt and REOB-recycled asphalt roads. Accelerated loading equipment was used to quickly accumulate load on the test section to simulate the real service environment of pavement. Pavement performance in the loading process was monitored, which provides the basis for the research and application development of REOB-recycled asphalt pavement.

2. Materials and Methods

2.1. REOB Regenerant

The Recycled Engine Oil Bottom (REOB) selected in this test comes from a qualified recycled oil treatment plant in Zibo, Shandong Province. Its main treatment process is: filter waste oil—membrane distillation—uronic refining—clay process.

The United States of America state the requirements for REOB quality control in the "Standard specification for refined engine oil bottoms/vacuum tower asphalt extender (VTAE)" promulgated in 2017 [14]. Based on this specification, as well as the similarity between REOB and asphalt compatibility, the related physical indicators and components of REOB were tested, and the results are shown in Table 1.

Table 1. Basic technical properties of REOB.

Physical Properties	Ash Content/%	Relative Density	60 °C Viscosity/Cst	Flash Point/°C	Thin Film Oven Test	
					Viscosity Ratio	Quality Change/%
	3.7	0.911	484	247	1.69	−1.284
Four-component analysis		Asphaltene/%	Colloid/%	Aromatics/%	Saturation/%	
		0.2	17.7	81.2	0.9	

In this study, a representative REOB from factory machinery was selected. According to the results of testing the performance of this REOB shown in Table 1, it meets the following functions and characteristics of a regenerant:

(1) Security. The flash point index reflects its construction safety. If this value is too low, it is a fire hazard under high-temperature operation. After testing, the flash point value of REOB is 247 °C, and the flash point value as asphalt regeneration agent meets the requirements of construction safety standards shall not be less than 220 °C.

(2) Components. Aromatic components mainly play the role of dissolving and dispersing asphaltene in aged asphalt; thus, regenerants require a large amount of aromatic components. The four-component analysis revealed that the aromatic content of the REOB regenerant is high at 81.2%, which can supplement the aromatic content missing in the asphalt aging process, while the saturated content also meets the specification requirements of $\leq$30% regenerant.

(3) Anti-aging properties. The viscosity ratio and mass change reflect the increase in viscosity and the decrease in mass after the film is heated, respectively. The smaller these two values, the better the anti-aging properties of the material. Owing to the high content of light components in REOB, it easily volatilizes at high temperature. Certain amounts of mass loss and viscosity increase are inevitable, but they are within the specification and controllable ranges, namely, a viscosity ratio $\leq$3 and a mass loss from −4% to 4%.

2.2. Asphalt

This test design required two kinds of asphalt: base asphalt and recycled asphalt. The conventional base binder was A-grade 70# petroleum asphalt with a performance classification of PG64-28. Recycled asphalt was prepared by adding the REOB regenerant to the aged asphalt. The aged asphalt was prepared as follows: The base asphalt was weighed to 600 g and poured into a 40 cm × 30 cm × 4.8 cm iron plate. The iron plate with the base asphalt was transferred into a 163 °C oven and stirred every 2 h to ensure even heating and aging of the asphalt. The aging time was prolonged to 48 h. In this way, one oven could perform the aging test of at least 3.6 kg asphalt, thereby significantly improving the efficiency of aging asphalt preparation [15]. The results of our previous research showed that the ideal regeneration effect was obtained when the REOB content was approximately 7% [16]. The specific preparation method of recycled asphalt is as follows: 7% REOB was added to the aged base asphalt at 160 °C for mixing, followed by shearing at 3000 r/min at 165 ± 5 °C for 30 min. Thereafter, it was placed in an oven at 160 °C for 1 h. The performance of the different types of asphalt used in the test is shown in Table 2.

Table 2. Asphalt test parameters.

Test Index		Unit	Base Asphalt	Aged Asphalt	7% REOB-Recycled Asphalt
			Test Parameters		
Penetration (25 °C)		0.1 mm	72.7	29	71
Softening point		°C	49.7	68	51.9
Ductility (10 °C, 5 cm/min)		cm	56.4	0.6	50.0
Relative density (25 °C)		/	1.024	1.036	1.022
Viscosity (135 °C)		Cst	338.2	1651.5	391
RTFOT (163 °C, 5 h)	Mass loss	%	−0.17	−0.09	−0.18
	Residual Penetration ratio	%	79.1	67.0	80.2
	Residual ductility (10 °C)	cm	21.2	0	16.2

Taking the three index values of base asphalt as a reference, the penetration, softening point, and ductility of the aged asphalt could be restored to 97.7%, 104.4%, and 88.7%, respectively, after adding 7% REOB, which could achieve the complete regeneration of the aged asphalt.

2.3. Asphalt Mixture

The AC-13 and AC-20 asphalt mixtures were used for the upper and lower layers of the test road, respectively, and the use of the binder is shown in Figure 1. The new coarse and fine aggregates used in the mixture were all obtained from the Zhang Qiu limestone quarry in Jinan. Among the components, the recycled asphalt surface is made of REOB-recycled asphalt and new asphalt as the binder, which was then mixed with the new and old aggregate to yield a mixture. The Reclaimed Asphalt Pavement (RAP) in the recycled pavement was taken from the asphalt concrete surface course of an expressway in Shandong, in which the content of RAP was 40%. Calculations using the Marshall design method indicated that the oil–stone ratio was 5.0%, and the gradation designs are shown in Figures 1 and 2.

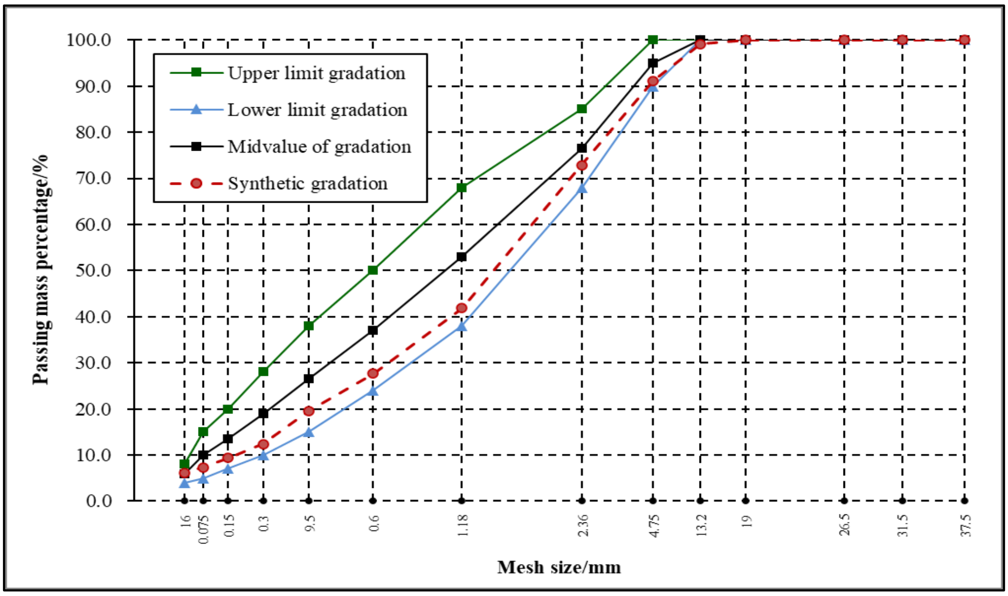

Figure 1. AC-13 aggregate gradation curve.

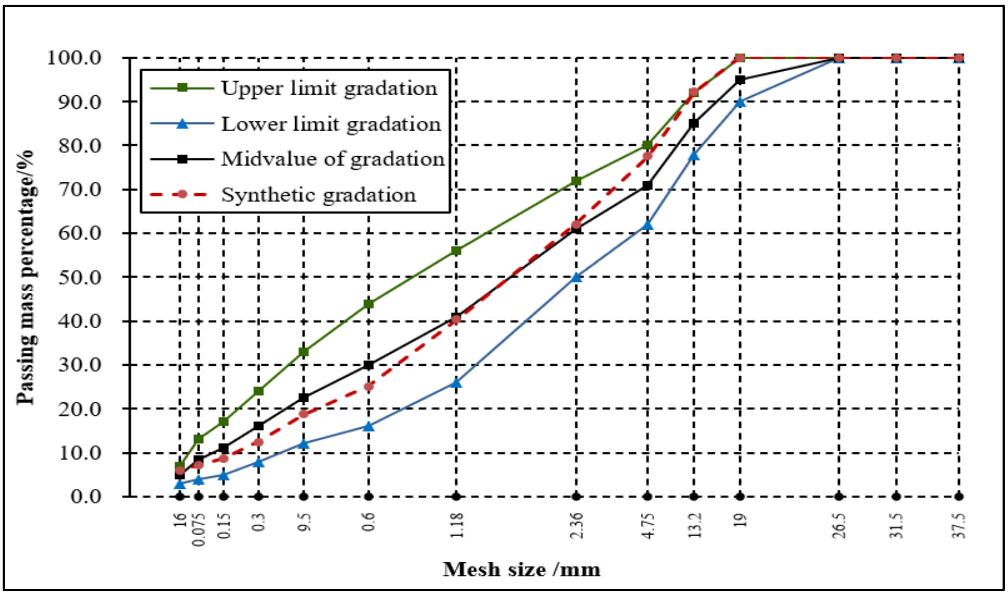

Figure 2. AC-20 aggregate gradation curve.

2.4. Test Plan

An accelerated loading test of the three pavement structures was conducted to compare the performance of different combinations of pavement. Five mixing pots of Shandong Provincial Key Laboratory of Asphalt Pavement Structure were used for mixing the mixture, and each mixing pot mixed 20 kg asphalt mixture each time. After research, it was decided that the temperature of the mixture that gets mixed from the completion to the paving stage be maintained by a large tray oven containing 1000 kg hot material in the Key laboratory of Asphalt Pavement structure in Shandong Province for hot material insulation process. The insulation temperature was uniformly set to 150 °C, which is conducive to the paving work of the test section.

This study was carried out according to the following flow chart, as shown in Figure 3. It involved two parts: (1) testing the pavement performance under loading and (2) extracting asphalt materials from the pavement after loading to examine changes in the properties of REOB-recycled asphalt.

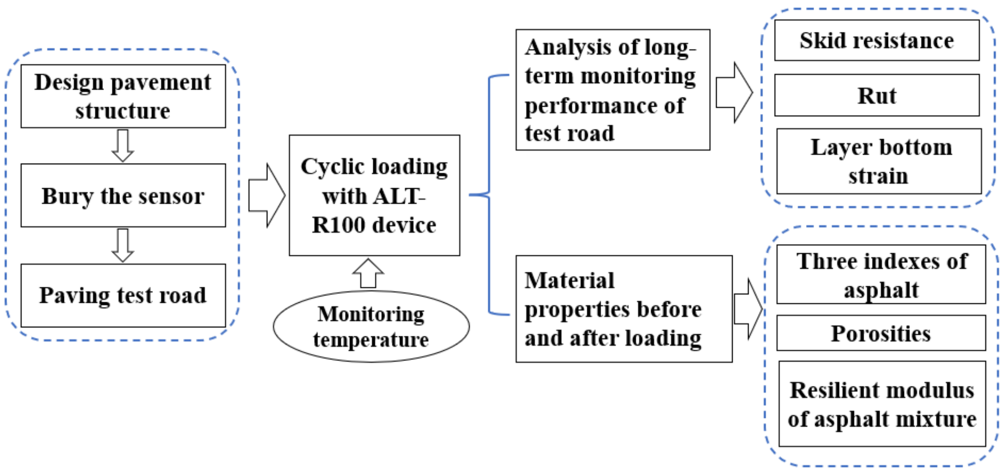

Figure 3. Flow chart of the accelerated loading test.

As shown in the paving plan in Figure 4, the upper and lower layers of the test pavement were made of dense-graded asphalt concrete. Fine-grained AC-13 gradation was selected for the upper layer, and medium-grained AC-20 gradation selected for the lower layer. The base layer cement stabilized the macadam base. The width and length of the pavement were designed to be 100 and 400 cm, respectively. To accelerate the destruction of the test road, the upper and lower layers were designed to be 4 and 6 cm thick, respectively. The lower layers of Pavements I and II were both an AC-20 base asphalt mixture However, the asphalt binders in their respective upper layers were different, namely, base asphalt and REOB-recycled asphalt, respectively. Using these materials in the upper layer enabled studying the performance difference between the REOB-recycled asphalt mixture and ordinary base asphalt concrete pavement. Meanwhile, Pavements II and III used base asphalt and REOB-recycled asphalt in the lower layer, respectively, which allowed investigating the long-term performance of pavement with REOB-recycled asphalt mixture in the underlying layer.

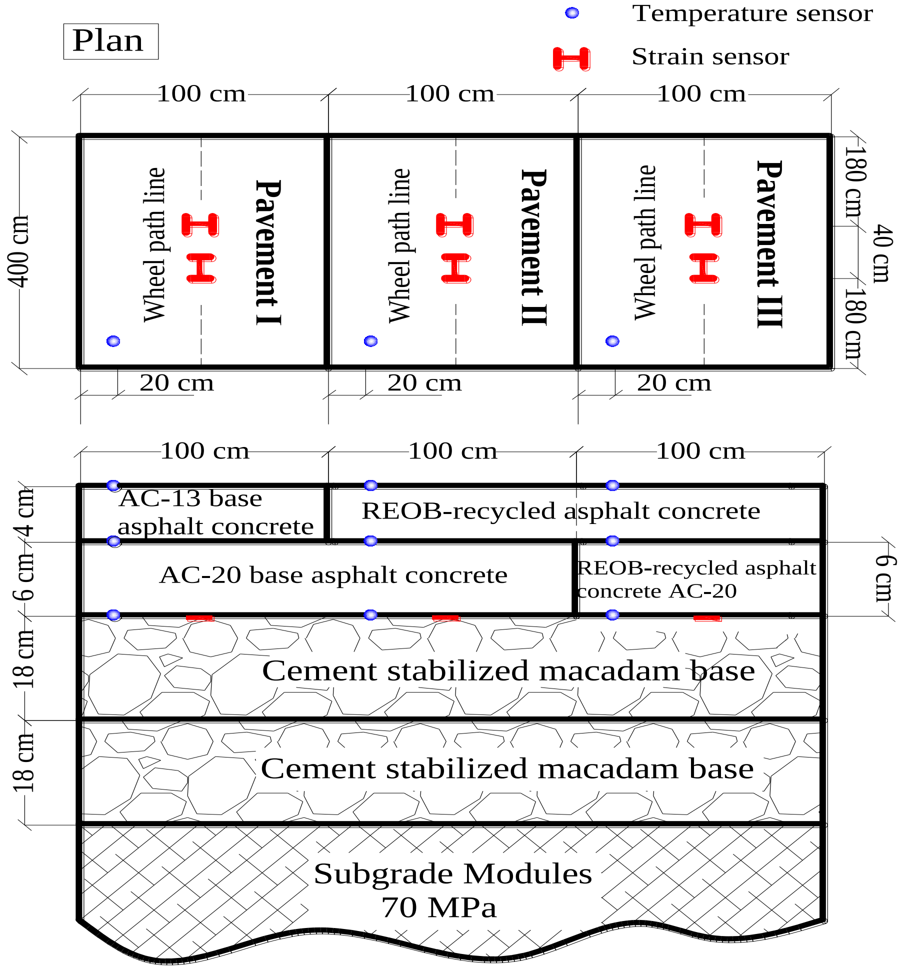

Figure 4. Road structure and sensor location map.

The equipment used in this model test was a small rotary road acceleration loading system (ALT-R100) independently developed by Shandong Jiaotong University. The equipment could be used in a three-wheel unidirectional cycle loading method, and the maximum loading speed reached 35 km/h (15,000 cycles/h). This approach was convenient to use and could quickly simulate the actual traffic load and environmental damage to the road surface in a short time. The reasonable structure and damage mechanism in the life cycle of a road could be effectively and accurately analyzed by monitoring the road conditions and test parameters during the loading process.

To accelerate the destruction speed of the test road, the upper and lower layers were designed to be 4 and 6 cm thick, respectively. The full-scale asphalt test pavement structure was paved with a 100 KN cyclic loading mode with a driving speed of 22 km/h, and the effective loading length of the equipment was 100 cm. To reduce the impact of environmental factors during the loading process, a reciprocating cyclic loading method was adopted: Pavement I was loaded for 50,000 cycles, translated to the loading area of Pavement II and loaded for 50,000 cycles, and then translated to the loading area of Pavement III and loaded for 50,000 cycles. This was the reciprocating cycle loading method. During the loading process, the pavement temperature, layer bottom strain, pavement friction coefficient, and rut depth were monitored regularly and at fixed points.

(1) Pavement temperature: Temperature monitoring was conducted using an embedded thermocouple temperature sensor with a measurement range able to reach −200–500 °C, while the accuracy reached 0.002 °C. A temperature sensor was embedded at the top of the upper layer, the bottom of the upper layer (the top of the lower layer), and the bottom of the lower layer of the three pavements of the test road in the form of pre-burying, which recorded temperature values every 1 h. The layout position is shown in Figure 4. Meanwhile, the indoor temperature of the corresponding time was recorded using a mercury thermometer.

(2) Layer bottom strain: After comparison, the layer bottom strain monitor was used to select the KM-100HAS "I"-shaped resistance strain gauge produced by Japan's TML company, which provided superior comprehensive performance. The three-dimensional position where the strain sensor was buried was located between the top of the cement-stabilized gravel layer and the bottom of the lower layer along the direction of the wheel track belt, and between the bottom of the upper layer and the top of the lower layer. The strain response data were collected every 10,000 cycles with a 100 Hz acquisition frequency, and the acquisition time was approximately 2 min/12 loading cycles. The strain data acquisition system included a DC-004P dynamic strain gauge that was made by Tokyo Measuring Instruments Lab in Japan, and visual log DC-7004P control software to collect and analyze the strain data.

(3) Anti-sliding performance: Each wheel of the loading equipment was rolled for 5000 cycles, and the friction coefficient data were collected once by a pendulum friction meter, which was the British Pendulum Number (BPN) condition value, representing the anti-sliding ability of the pavement. The friction coefficient of the asphalt pavement was monitored by setting three detection points along the wheel trace direction, as shown in Figure 5a.

(4) Anti-rutting performance: A laser car that was independently developed by Shandong Jiaotong University was used for the rutting test at points A and B in Figure 5. The test range of the laser car was 1 m^2. The rutting data were collected after every 5000 loading cycles, and the rutting of a cross-section was tested every 0.2 m, as shown in Figure 5b.

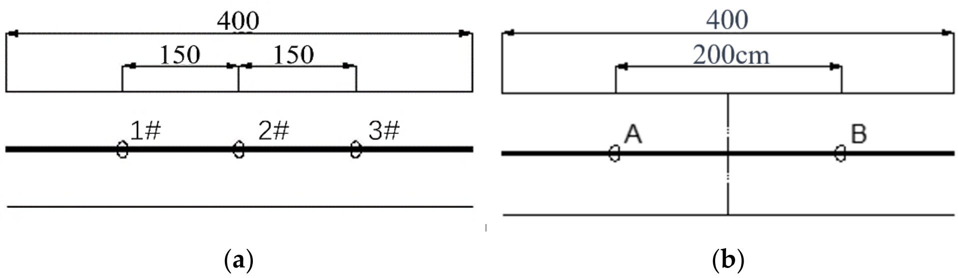

Figure 5. Layout of monitoring points. (**a**) Layout of friction coefficient monitoring points; (**b**) Layout of track monitoring points.

3. Results and Discussion

3.1. Analysis of Long-Term Monitoring Performance of Test Road

3.1.1. Temperature

The relationship curve between the loading cycles and temperature of the three types of pavements is shown in Figure 6, with 20,000 loading cycles as a statistical unit. Owing to the reciprocating loading mode of the three pavements, the difference in pavement temperature among the pavements was relatively small. However, owing to the large time span from summer to autumn, the overall temperature showed a downward trend with decreasing room temperature (15–35 °C), and the temperature dropped sharply after loading for 420,000 cycles. Therefore, the experiment was divided into two stages based on the temperature gradient.

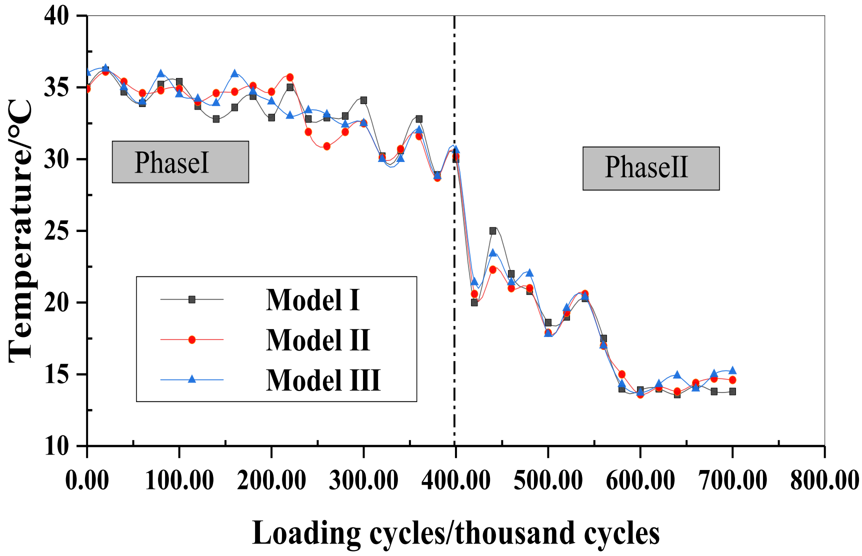

Figure 6. Temperature curve during loading.

Stage I: The average temperature of asphalt pavement was 33.3 °C, and the total number of loading cycles was 400,000.

Stage II: The average temperature of asphalt pavement was 17.4 °C, and the total loading number of loading cycles was 300,000.

3.1.2. Skid Resistance

The measured BPN values were all obtained for conventional dry road, and the thickness of the upper layer of the test road was 4 cm; thus, the measured values did not require temperature correction. The decay law of the friction coefficient of the three types of asphalt pavement structures under accelerated loading was obtained using a statistical method, as shown in Figure 7.

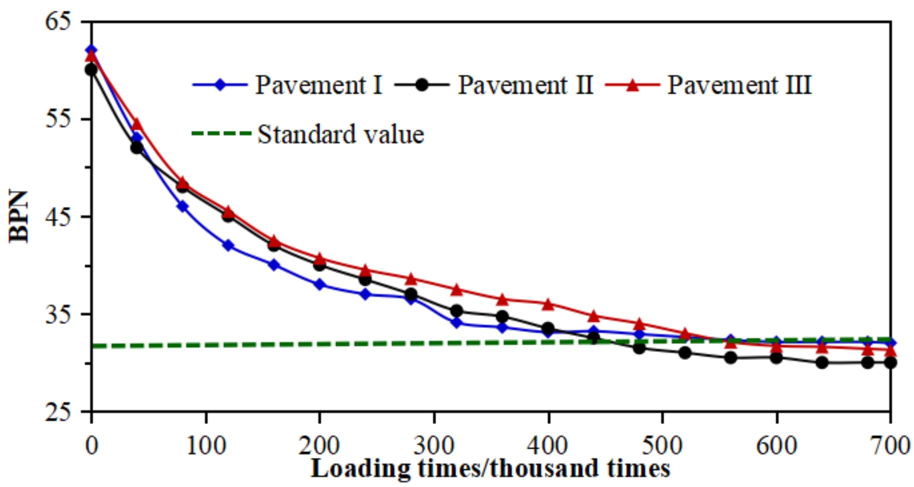

Figure 7. Variation law of pavement friction coefficient.

The initial friction coefficients of the three accelerated loading test sections were all above 60. The friction coefficient decreased gradually with increasing loading cycles and decreased rapidly in the early stage of loading. After loading for 400,000 cycles, the pendulum value dropped below 40, which is below 60% of the initial value, and Pavement I exhibited the fastest rate of decrease, falling to approximately 55% of the initial value. The difference in the skid-resistance performance of the three types of pavement was small, which indicates that REOB-recycled asphalt will not reduce the skid-resistance performance of asphalt pavement, which is mainly controlled by the characteristics of the aggregate and gradation. The pendulum value decreased slowly and tended to gradually stabilize after 400,000 loading cycles until the end of the test. The skid-resistance performance of Pavements II and III decayed rapidly. Their BPN values were lower than those of Pavement I at 440,000 and 560,000 loading cycles, respectively, and lower than the required value of 32 for class 2. Further, these were below highway maintenance specifications at 600,000 and 480,000 loading cycles, respectively.

Therefore, the skid-resistance performance of conventional asphalt mixture pavement is inferior to that of REOB-recycled asphalt mixture pavement in the short term because of the high viscosity of recycled asphalt, which will also cause a more serious degree of rutting in Pavement I compared to other pavements. With the increasing number of loading cycles, from the perspective of long-term pavement service, the anti-sliding performance of conventional asphalt mixture pavement is better than that of REOB-recycled asphalt mixture pavement.

3.1.3. Rut

The rut formed on the test road is typically unstable (flow type), owing to the reciprocating rolling action of the ALT-R100 system. Deformation curve of wheel rut section after 700,000 times of loading is shown in Figure 8a. Figure 8b shows the overall evolution of the road ruts of the three different pavement structures under the action of loading and rolling at room temperature.

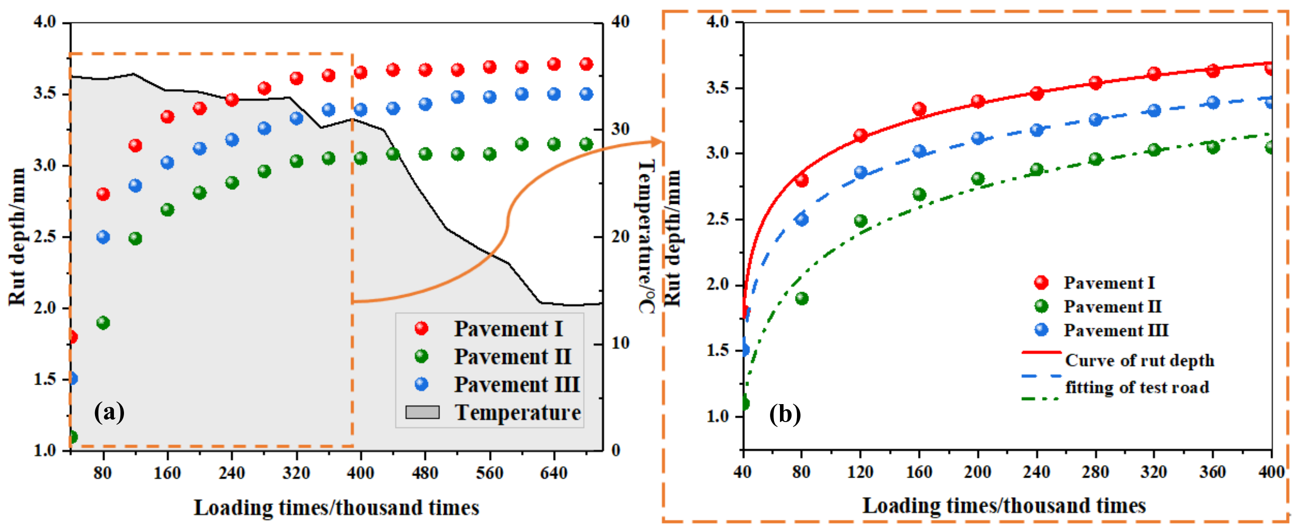

Figure 8. Variation law of pavement rutting. (**a**) Deformation curve of wheel rut section after 700,000 times of loading; (**b**) The overall evolution of the road ruts of the three different pavement structures under the action of loading and rolling at room temperature.

The tests reveal several results:

(1) The overall rutting shapes of the three pavement structures are similar after cycle loading, as shown in Figure 9. The rutting depths of the three types of pavement structures developed rapidly before 220,000 loading cycles with the acceleration loading system; at 160,000 loading cycles, the first inflection point appears in the

rutting development, and the second inflection point appears at 220,000 loading cycles. However, after 220,000 loading cycles, the rutting depth tended to increase at a slower rate and remained almost unchanged after 400,000 loading cycles. Because the compaction of the aggregate and the discharge of air were relatively fast, the pavement could be in the stage of aggregate compaction before 220,000 loading cycles.

(2) The gray area shown in Figure 8 is the change in room temperature; hence, higher room temperature and road temperature also played a certain role in promoting the generation of rutting, causing a greater change in the early rutting depth. At the end of 700,000 loading tests, the rutting depths of the first, second, and third structural pavements were 3.7, 3.2, and 3.5 mm, respectively.

(3) Compared with structural Pavements I and II, which had the same form of their lower layer, the anti-rutting ability of recycled Pavement II was approximately 13% better than that of conventional pavement "Pavement I," when the upper layer of asphalt mixture is comprised of 4 cm of base asphalt AC-13 and REOB-recycled asphalt AC-13, respectively. The upper and lower layers of Pavement III contained the recycled mixture, whereas Pavement II only contained the recycled mixture in the upper layer and showed better anti-rutting performance than Pavement III. Comprehensive analysis shows that the REOB-recycled asphalt mixture has good anti-rutting performance when used in the upper layer.

(4) At high temperature conditions, above 30 °C, damage is related to rutting but not fatigue. At intermediate temperature conditions, below 20 °C, damage is related to fatigue, and the ruts change slightly and gradually flatten out. According to the above test data results and relevant research data, the rutting changes with the loading cycles in a logarithmic form [17], and the regression curve above 30 °C (the first 400,000 loads) is shown in Figure 8b. The fitting model is shown in Table 3. The correlation coefficient R^2 of the fitted logarithmic curve is over 0.98, indicating that the fitted function is reliable.

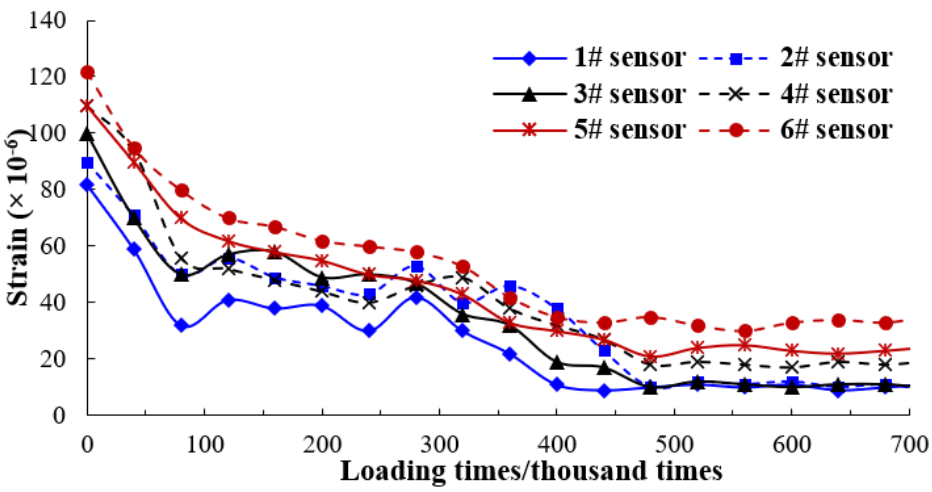

Figure 9. Relationship between layer bottom strain of each sensor and loading cycles.

Table 3. Rutting prediction Pavements of three pavement structures.

Pavement Structure Model	Rutting Prediction Model	R^2
Structural Pavement I	rut = 0.38959 ln(N − 3.71988) + 2.9481	0.99598
Structural Pavement II	rut = 0.41277 ln(N − 3.65412) + 1.94652	0.99743
Structural Pavement III	rut = 0.52695 ln(N − 3.27094) + 1.25467	0.98152

Where: rut is rutting depth, N is the number of loading cycles.

3.1.4. Layer Bottom Strain

An effective method to study the stress and fatigue of asphalt pavement is to analyze the layer bottom strain, as many problems with pavement are closely related to the layer bottom strain [18].

During the accelerated loading test, sensors No. 1, No. 3, and No. 5 were transverse strain sensors of Pavements I, II, and III, respectively, and sensors No. 2, No. 4, and No. 6 were longitudinal strain sensors. According to the monitoring results, the relationship between the layer bottom strain and loading time is shown in Figure 9.

(1) As seen in Figure 9, the change trends of the transverse and longitudinal sensors of each pavement structure are consistent, whereas the numerical values differ. The initial strain values of Pavements I, II, and III are above 80×10^{-6}, 100×10^{-6}, and 110×10^{-6}, respectively. After 80,000 loads, these values drop to approximately 40×10^{-6}, 50×10^{-6}, and 70×10^{-6}, respectively. At this time, the strain changes are related to the high temperature and compaction of the mixture. As there is only a limited number of load cycles for intermediate temperatures, fatigue does not occur yet, and thereafter, the strain is only related to the temperature conditions.

(2) The strain change during the entire loading process may be divided into three stages. In the initial stage of loading, the temperature is relatively high, in which the layer bottom strain is also high. In the middle stage of loading, the temperature drops sharply from 350,000 to 500,000 loading cycles. With the long-term effect of the load, the strain decreases gradually. Before the end of loading, from 500,000 to 700,000 loading cycles, the temperature drops, causing a halt in the change in strain value.

(3) In the later stage of loading (from 500,000 to 700,000 cycles), the strain values of Pavements I, II, and III are stable at $9–11 \times 10^{-6}$, $10–19 \times 10^{-6}$ and $21–33 \times 10^{-6}$, respectively. The strain at the bottom of the third layer of the pavement is at a relatively high level compared to other pavements. This result shows that the pavement using REOB-recycled asphalt mixture on both the upper and lower layers has less sufficient mechanical properties than the pavement using this asphalt mixture only in the upper layer and the conventional asphalt pavement in the lower one. Excessive strain could directly cause pavement damage, and the anti-fatigue performance of the third layer of the pavement is poor.

Studies have been conducted on the fatigue performance of asphalt mixtures in different ways, and different fatigue pavements of asphalt mixtures have been proposed.

The British Transport and Road Research Institute has proposed fatigue design standard Formulas (1) and (2) [19,20] for asphalt pavement, with a reliability of 85% and an equivalent temperature of 20 °C.

$$N_f = 1.66 \times 10^{-10} \times (\varepsilon_t)^{-4.32}(\mathrm{AC}) \tag{1}$$

and

$$N_f = 4.169 \times 10^{-10} \times (\varepsilon_t)^{-4.16}\ (\mathrm{AM}). \tag{2}$$

Elliot and Thomson established a relationship between the tensile strain and pavement fatigue life. For a typical Illinois dense graded I asphalt mixture, the following fatigue pavement Formula (3) can be adopted [21]:

$$N_t = 5 \times 10^{-6} \times (\varepsilon_t)^{-3.0}. \tag{3}$$

The fatigue test results of different asphalt mixtures show that the resilient modulus plays an important role in the fatigue performance of materials. Monismith et al. established the following general Formula (4) [22]:

$$N_f = K(\varepsilon_t)^{-n}(S_{min})^{-m}. \tag{4}$$

Wang Xudong et al. conducted constant stress bending fatigue tests, combined with load transverse distribution, load intermittent time, and adverse season days. They modified the indoor fatigue model as follows [23]:

$$N_e = N_f \times 7 \times 40 \times \frac{365}{60} \times 2 = 13.7 \times A_a A_g / A_C \sigma^{-4.17} \quad (5)$$

where N_f is the laboratory fatigue life, $N_f = 4025 A_a A_g / A_C \sigma^{-4.17}$; ε_t is the tensile strain; A_a is the coefficient of asphalt type; A_b is the gradation coefficient of asphalt mixture; A_c is the coefficient of highway grade coefficient; and σ is stress.

In the actual service process of pavement, its stress and strain are constantly changing and uncertain under vehicle loads. Most of the above fatigue models were obtained by testing under the stress control and strain control modes, which differ from the actual situation of real pavement. For an unstable variable stress, damage accumulation hypothesis should be used to estimate the fatigue failure life of the road. Cyclic loading is adopted in this test, and the loading times are sufficient. A comparative analysis of the transverse and longitudinal tensile strains is performed by the Wohler equation, and load action cycles of Pavement III are used as an example, by which the relationship between tensile strain and load action cycles is established, as shown in Figure 10.

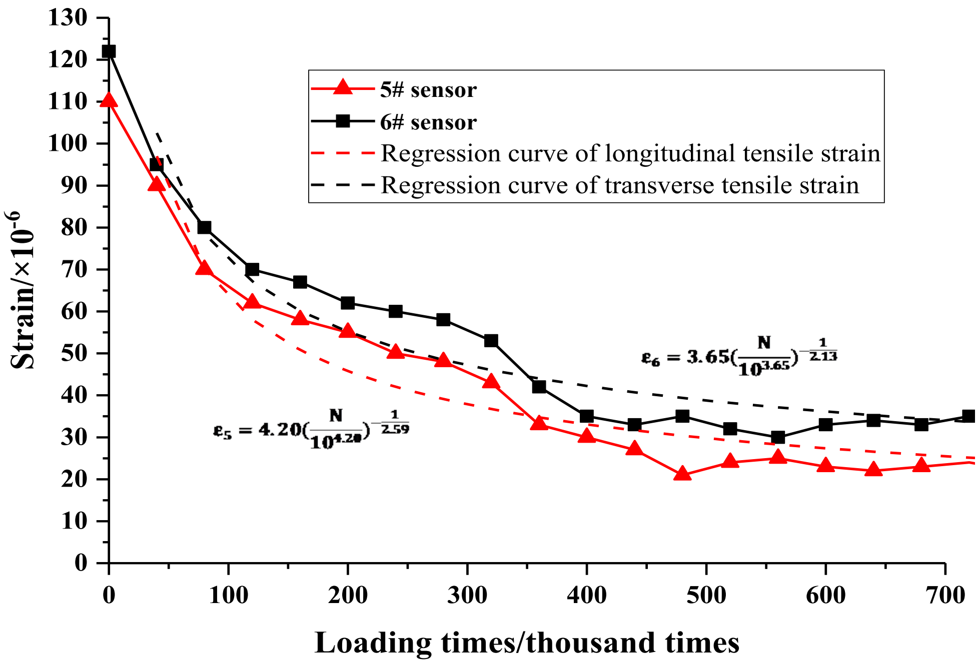

Figure 10. Relationship between strain and the number of loading cycles.

3.2. Material Properties before and after Loading

After 700,000 times of loading, cores were taken from the loading areas (including rutting pits and uplifts) and unloaded areas of the three pavements. Three index tests were performed on the extracted asphalt, and the mixture porosity test and resilience modulus test were performed on the core samples. Based on the original test data, the physical properties of the recovered binder and the porosity and modulus of the mixture of each group are shown in Figures 11 and 12 and Table 4.

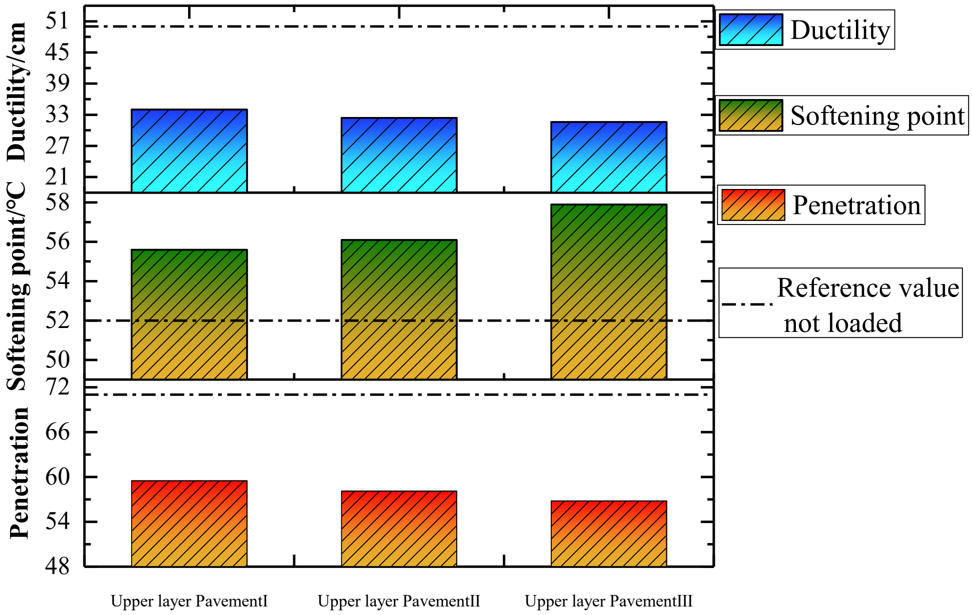

Figure 11. Three indexes of asphalt binder for each pavement.

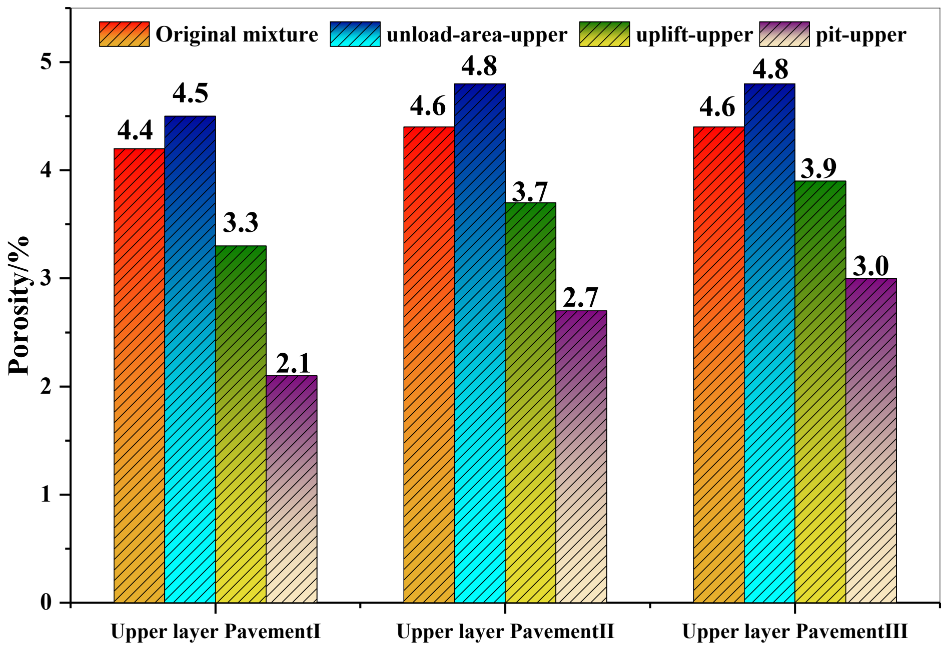

Figure 12. Porosities of cores taken from different pavements.

Table 4. Resilience modulus of cores taken from different pavements.

Coring Position	Resilience Modulus/MPa			
	Mixture	Unload-Area-Upper	Uplift-Upper	Pit-Upper
Upper layer Pavement I	673	666	785	826
Upper layer Pavement II	679	671	792	807
Upper layer Pavement III	679	670	788	801

The comparison of physical performance of the binder on the upper layer of each structural pavement after loading shows that among the three indexes, the degree of change in the softening point is the smallest, i.e., less than 6 °C, whereas the ductility changes to greatest degree, by more than 27 cm. Thus, the performance metrics of the asphalt binder decrease in varying degrees after mixing, paving, and wheel loading. The performance of the recycled asphalt of Pavement III decreases the most. The softening point of Pavement III is the most prominent; it is 6 °C and 1.2 °C higher than that of original asphalt and Pavement II with the same material, respectively. Pavement III has a penetration of 14.2 mm lower than original asphalt. In the rut fitting function $y = a - b \ln(x + c)$, b represents the slope of the curve. Model III has the largest b, and the rut develops the most rapidly, which verifies that the faster the asphalt performance declines, the faster the rutting resistance degrades.

Figure 12 shows the porosity comparison of materials at different positions in the upper layer of each pavement structure. Porosity index can reflect the compaction of pavement materials of each structure. The porosities of pavement II, III, and I are the highest, second highest, and lowest, respectively. The porosities of pit- and uplift-upper of pavement I are 53.3% and 26.7% lower than that of the unloaded area, respectively, whereas those corresponding to pavements II and III are 43.7% and 22.9% lower and 37.5% and 18.7% lower, respectively. The degree of wheel load compaction of pavement I is greater than that of other pavements. If the increase in porosity is attributed to the lateral flow of material, pavement I has more lateral material flow and is more affected by rutting. REOB-recycled asphalt is used as the mixture in the upper layer, which has obvious advantages over the base asphalt in terms of the rutting resistance of the whole asphalt layer. The porosity changes of Pavements II and III are basically equal, indicating that REOB-recycled asphalt can also provide satisfactory rutting resistance when used in the lower layer.

There is no significant difference in the modulus of compressive rebound between the new base asphalt Pavement I and the REOB-recycled asphalt Pavements II and III, as shown in Table 4. After 700,000 cycles, the modulus appreciations of uplift-upper of Pavements I, II, and III are 119 MPa, 121 MPa, and 118 MPa, respectively, and those of pit-upper are 160 MPa, 136 MPa, and 131 MPa, respectively. The moduli of Pavements II and III in the unload-area-upper and the uplift-upper remain large, and the possibility of damaging the pavement is greater under sufficient load. In addition, the moduli do not reach the attenuation stage, indicating that the pavement performance is only degraded under 700,000 cycles, but does not reach the damage stage. The performance of REOB-recycled asphalt pavement is basically equivalent to that of base asphalt surface under 700,000 loads.

To study the fatigue resistance of the material, loading times should be increased further.

4. Conclusions

In this study, REOB is used as an asphalt modifier in the field of aging asphalt recycling, which offers a certain amount of economic and environmental protection. To explore the practical long-term application performance of REOB-recycled asphalt pavement, the rotary accelerated loading test system (ALT-R100) independently developed by our university is used to carry out cyclic loading tests on three sections of REOB-recycled asphalt pavement, to simulate the long-term load behavior of service pavement in a short time. The following conclusions may be drawn:

(1) After using the ALT-R100 accelerated loading system to perform 700,000 loading cycles, the anti-skid performance and anti-rutting performance of concrete pavement with REOB-recycled asphalt and conventional asphalt are basically consistent, both meeting use requirements.

(2) The pavement with the REOB-recycled asphalt mixture in the upper and lower layers enters the compaction stage sooner; thus, it is prone to rutting damage earlier, and the asphalt binder is more prone to aging. This problem does not occur when REOB-recycled asphalt mixture is only used in the upper layer.

(3) A logarithmic model for predicting rutting and a Wohler-equation-based strain prediction model of the three-section test road under ALT-R100 accelerated loading were obtained, revealing the development laws for rutting and bottom strain within the applied loading times.
(4) The rutting depth, BPN value, and bottom strain of the pavement gradually stabilized after loading for 400,000 cycles. When ALT-R100 is used to evaluate the high-temperature rutting resistance and anti-skid performance of asphalt mixtures, the standard test can be performed for 400,000 to 500,000 loading cycles.

With sufficient time and funds, we can continue to conduct accelerated loading tests involving REOB-recycled asphalt pavement by constructing a field test road in the future to study the performance characteristics of base asphalts having different structures with REOB-recycled asphalt layers.

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References

1. Jia, X.; Huang, B.; Bowers, B.F.; Zhao, S. Infrared spectra and rheological properties of asphalt cement containing waste engine oil residues. *Constr. Build. Mater.* **2014**, *50*, 683–691. [CrossRef]
2. Hesp, S.A.; Shurvell, H.F. X-ray fluorescence detection of waste engine oil residue in asphalt and its effect on cracking in service. *Int. J. Pavement Eng.* **2010**, *11*, 541–553. [CrossRef]
3. Hesp, S.A.M.; Shurvell, H.F. Waste Engine oil Residue in Asphalt Cement. In Proceedings of the Seventh International Conference on Maintenance and Rehabilitation of Pavements and Technological Control, Thessaloniki, Greece, 12–17 June 2019.
4. Golalipour, A. Investigation of the Effect of Oil Modification on Critical Characteristics of Asphalt Binders. Ph.D Thesis, The University of Wisconsin—Madison, Madison, WI, USA, 2013.
5. Herrington, P.R.; Hamilton, P.G. *Recycling of Waste Oil Distillation Bottoms in Asphalt*; Transfund New Zealand Research Report; California Transit Association: Sacramento, CA, USA, 1998.
6. Bennert, T.; Ericson, C.; Pezeshki, D.; Haas, E.; Shamborovskyy, R.; Corun, R. Laboratory performance of refined engine oil bottoms (REOB) modified asphalt. *J. Assoc. Asph. Paving Technol.* **2016**, 163–207.
7. Cooper, S.B., Jr.; Mohammad, L.N.; Elseifi, M.A. Laboratory Performance of Asphalt Mixtures Containing Recycled Asphalt Shingles and Re-Refined Engine Oil Bottoms. *J. Mater. Civ. Eng.* **2017**, *29*, 04017106. [CrossRef]
8. Li, X.; Gibson, N.; Andriescu, A.; Arnold, T.S. Performance evaluation of REOB-modified asphalt binders and mixtures. *Road Mater. Pavement Des.* **2017**, *18*, 128–153. [CrossRef]
9. Zaumanis, M.; Mallick, R.B.; Frank, R. Evaluation of rejuvenator's effectiveness with conventional mix testing for 100% reclaimed asphalt pavement mixtures. *Transp. Res. Rec. J. Transp. Res. Board* **2013**, *2370*, 17–25. [CrossRef]
10. Sirin, O.; Tia, M.; Roque, R.; Choubane, B. Evaluation of performance characteristics of the heavy vehicle simulator in Florida. *Build. Environ.* **2007**, *42*, 1270–1277. [CrossRef]
11. Choubane, B.; Gokhale, S.; Sholar, G.; Moseley, H. Evaluation of coarse and fine graded superpave mixtures under accelerated pavement testing. *Transp. Res. Rec. J. Transp. Res. Board* **2006**, *1974*, 120–127. [CrossRef]
12. Theyse, H.L.; Hoover, T.P.; Harvey, J.T.; Monismith, C.L.; Coetzee, N.F. A mechanistic-empirical subgrade design model based on heavy vehicle simulator test results. *Pavement Mech. Perform.* **2006**, *154*, 195–202.

13. Hugo, F.; De Vos, E.R.; Tayob, H. Aspects of cement stabilized mozambique sand base material performance under MMLS3 and MLS10 APT trafficking. *SATC* **2007**. Available online: http://hdl.handle.net/10019.1/43003 (accessed on 6 April 2022).
14. *ASTM D8125-2017*; Standard Specification for re-Refined Engine Oil Bottoms (REOB)/Vacuum Tower Asphalt Extender (VTAE). American Society for Testing and Materials: West Conshohocken, PA, USA, 2017.
15. Yu, M.Z. Design and Road Performance Test of Recycled Asphalt Mixture with REOB. Ph.D. Thesis, Shandong Jiaotong University, Shandong, China, 2019. (In Chinese).
16. Li, J.; Yu, M.; Cui, X.; Wang, W. Properties and Components of Recycled Engine Oil Bottom Rejuvenated Asphalt and Its Grey Relationship Analysis. *Adv. Mater. Sci. Eng.* **2019**, *2019*, 1–11. [CrossRef]
17. Wang, P.C.; Hao, X.W.; Zhang, Y. Long term performance of warm mix asphalt mixture based on accelerated loading test. *J. Shenyang Jianzhu Univ.* **2020**, *36*, 860–869. (In Chinese)
18. Coutinho, R.P.; Babadopulos, L.F.A.L.; Freire, R.A.; Branco, V.T.F.C.; Soares, J.B. The use of stress sweep tests for asphalt mixtures nonlinear viscoelastic and fatigue damage responses identification. *Mater. Struct.* **2013**, *47*, 895–909. [CrossRef]
19. Luo, S.; Qian, Z.D.; Harvey, J. Fatigue decay characteristics test of epoxy asphalt mixture. *Chin. J. Highw.* **2013**, *26*, 20–25. (In Chinese)
20. Powell, W.D.; Potter, J.F.; Mayhew, H.C.; Nunn, M.E. The structural design of bituminous roads. *Transp. Road Res. Lab.* **1984**, *1132*, 1984.
21. Elliot, R.P.; Thompson, M.R. Mechanistic design concepts for conventional flexible pavement. *Transp. Eng. Ser. Urbana: Univ. Ill.* **1986**. Available online: https://www.researchgate.net/publication/269090247 (accessed on 6 April 2022).
22. Monismith, C.L.; Deacon, J.A. Fatigue of asphalt paving mixtures. *Transp. Eng. J.* **1969**, *95*, 122–131. [CrossRef]
23. Wang, X.D.; Sha, A.M.; Xu, Z.H. *Dynamic Characteristics and Dynamic Parameters of Asphalt Pavement Materials*; People's Communications Press: Beijing, China, 2002.