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Research Article

Antiageing Performance Evaluation of Recycled Engine Oil Bottom Used in Asphalt Rejuvenation

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To comprehensively evaluate the antiageing performance of recycled engine oil bottom (REOB) used in asphalt rejuvenation, ageing performance studies were carried out on REOB, REOB-rejuvenated asphalt, and REOB-rejuvenated asphalt mixture. The thin film oven test (TFOT) results of REOB and a professional regenerant, RA5, were compared to verify the ageing resistance of REOB as an asphalt regenerant. The quality and viscosity of REOB-rejuvenated asphalt, RA5-rejuvenated asphalt, and base asphalt were measured after extended TFOT (ageing times for 5 h, 10 h, 15 h, 20 h, and 25 h), and the low-temperature performance of three aged asphalts was evaluated by bending beam rheological tests. The corresponding three kinds of asphalt mixtures were used to design and pave surface layers of a full-scale indoor test road. The long-term fatigue performance of indoor asphalt pavement was investigated by a self-developed rotary accelerated loading test (RALT) system. The results show that when used as an asphalt regenerant, REOB meets the antiageing requirements listed in the technical specification. The short-term (TFOT ageing time less than or equal to 10 h) ageing resistance of REOB-rejuvenated asphalt is better than that of RA5-rejuvenated asphalt but worse than that of base asphalt, whereas the long-term (TFOT ageing time greater than or equal to 15 h) ageing resistance of REOB-rejuvenated asphalt is the worst among the three tested asphalts. After long-term ageing, REOB-rejuvenated asphalt is prone to cracking at low temperatures because of its rapid increase in stiffness and sharp decrease in stress relaxation performance. Increasing temperatures increases the deflection value of asphalt pavement as the number of loading cycles increase. High-temperature ageing significantly aggravates the increase of the deflection value of REOB-rejuvenated asphalt pavement under RALT long-term loading, which makes it most prone to fatigue failure among the three pavements. Therefore, the above test results show that REOB used in asphalt pavement rejuvenation is prone to premature and excessive damage.

1. Introduction

At present, the development of asphalt pavement in China has entered the stage of both construction and maintenance. Asphalt pavement recycling technology has become a popular research area for roads because of the ability to recycle large amounts of reclaimed asphalt pavement (RAP) materials generated in the maintenance and repair of asphalt pavement, save ore and asphalt resources, and reduce construction costs. The key to recycling RAP materials is adding appropriate regenerants to rejuvenate the aged asphalt in RAP materials. In the market, professional regenerants are not only generally expensive but also consume many resources and even cause environmental pollution, which is contrary to the concept of green and sustainable development of asphalt pavement recycling technology. Therefore, the development of new economical and green asphalt regenerants is urgently needed.

China's transportation industry produces 25 to 30 million tons of recycled engine oil (REO) every year [1]. Generally, 70–80% of REO can be effectively recycled through regeneration processes, such as distillation-clay refining or distillation-hydrogenation [2, 3]. However, the remaining residue (accounting for 20–30%) cannot be effectively recycled due to the presence of many impurities; this residue is called recycled engine oil bottom (REOB).

Currently, REOB is mostly treated by discarding, burying, or burning, which causes substantial environmental pollution. To realize the resource reutilization of REOB, based on the similarity and compatibility between REOB and asphalt, research on the use of REOB in asphalt materials has begun at home and abroad. Many relevant patents have been reported on the use of REOB in different asphalt structural layers [4, 5]. However, Hesp and Shurvell [6, 7] found that REOB resulted in premature and excessive cracking of asphalt pavement in northern Ontario, Canada, based on X-ray fluorescence (XRF) analysis. Ding et al. [8, 9] used REOB to modify or rejuvenate asphalt and found through laboratory tests that REOB was unfavourable to the anti-ductile fracture performance and low-temperature cracking resistance of asphalt. The reason may be that paraffin in REOB precipitates asphaltenes, and iron, copper, chromium, and other metals accelerate the oxidation of asphalt. It is considered that the deterioration of performance in the above studies is closely related to the ageing of REOB and asphalt. Therefore, to explore the long-term stability and drawbacks of REOB as an asphalt regenerant, it is necessary to conduct a comprehensive and systematic study on the antiageing performance of REOB used for asphalt regeneration.

In this paper, REOB is used as a regenerant for simulated aged asphalt. By comparing and analysing the ageing performance of REOB, REOB-rejuvenated asphalt, and an REOB-rejuvenated asphalt test road, the effect of ageing on the road performance of REOB used as asphalt regenerant is evaluated comprehensively, which provides an improvement basis for REOB used in asphalt pavement.

2. Materials and Methods

2.1. Test Materials

2.1.1. Recycled Engine Oil Bottom. REOB, which cannot be distilled from REO after pretreatment and atmospheric and vacuum distillation in a large REO treatment plant, was selected in this paper. And a professional regenerant RA5 developed with mineral oil as the base oil on the market was selected for comparative study. Four components of REOB and RA5 were analysed using rod-thin-layer chromatography/hydrogen flame ionization detection (TLC-FID), which was produced by Zibo Shanfen Analytical Instrument Co., Ltd. The specific testing steps are described in the following section of experimental methods. The properties and components of REOB and RA5 are shown in Table 1.

2.1.2. Asphalt Binders. The original asphalt is 70-A base asphalt with a performance grade (PG) of 70–28. The simulated aged asphalt was prepared from base asphalt by a thin film oven test (TFOT) and a pressure ageing vessel (PAV) according to the Chinese test standard [10]. The REOB-rejuvenated asphalt and RA5-rejuvenated asphalt, which exhibited good performance recovery, were prepared by adding 7% (mass ratio of aged asphalt) REOB and 5% RA5 to the aged asphalt, respectively, at 150°C and shearing for 10 minutes at 4000 r/min. The performance indexes of different asphalt binders are shown in Table 2.

2.1.3. Asphalt Mixture. AC-20 dense-graded asphalt concrete was selected as the surface layer of the indoor test road. The aggregate is made of limestone. Mineral powder is the filler obtained by mechanical grinding of limestone. The gradation design is shown in Figure 1. To accurately compare the influence of three kinds of asphalt on the performance of the asphalt mixture, REOB-rejuvenated asphalt, RA5-rejuvenated asphalt, and 70-A base asphalt were used as binders of AC-20 dense-graded asphalt concrete, and the Marshall design method was used to determine the optimum asphalt-aggregate ratio of the three kinds of asphalt mixtures; three optimum ratios were 4.4%, respectively.

2.2. Experimental Methods

2.2.1. Four-Component Analysis. Four-component analysis was carried out on REOB and RA5 by using the TLC-FID. Specifically, the samples were first dissolved in toluene to prepare in solutions of 30 mg/mL. Next, samples 0.8–1.0 μL in volume were placed into the 15 mm chromatographic rod. Then, the chromatographic frame was placed into three types of mixtures composed of *N*-heptane, toluene, and toluene/ethanol (volume ratio 55 : 45) and expanded in sequence on the expansion table. After each expansion, the chromatographic frame was dried, kept warm, and moisturized until the next expansion. Finally, after three rounds of expansion, the chromatographic frame was tested and analysed by a rod-thin-layer chromatography analyser.

2.2.2. Extended Thin Film Oven Test. The TFOT protocol can only simulate the short-term ageing of the original asphalt mixture during mixing and paving. The PAV protocol can only simulate the long-term ageing of an asphalt pavement in service for 5 years, but the asphalt at this time has not reached sufficient ageing [11]. Therefore, the modified extended TFOT (ageing time for 5 h, 10 h, 15 h, 20 h, and 25 h) is used to rapidly simulate the ageing of asphalt in long-term use process [12]. The specific test procedure refers to Chinese test standard [10]. Note that the asphalt in the sample dish should be stirred with glass rods every 5 hours during TFOT ageing to avoid the formation of a skin that slows oxygen entering the asphalt [7, 13].

2.2.3. Brookfield Viscosity Test and Bending Beam Rheological Test. The viscosity tests were performed with a Brookfield rotary viscometer (model NDJ-1C, Changji Geological Instrument Co., Ltd). The rheological tests were performed with a bending beam rheometer (BBR) (model TE-BBR-F, CANNON Equipment Company). Brookfield viscosity tests used a No. 21 rotor with a rotational speed of 20 RPM. BBR test temperatures were −18°C. The tests were carried out in

Table 1: Basic properties and chemical components of REOB and RA5.

Type	Colour	Density (25°C, g/cm^3)	Asphaltenes (%)	Resins (%)	Aromatics (%)	Saturates (%)
REOB	Reddish brown	0.904	0.2	15.5	83.5	0.8
RA5	Black	1.08	1.7	12.1	62.7	23.5

Table 2: Performance indexes of different asphalt binders.

Type	Penetration (25°C, 0.1 mm)	Softening point (°C)	Ductility (10°C, 5 cm/min, cm)	Viscosity (135°C, Pa·s)	PG
Base asphalt	71	48.7	22	0.397	70–28
Aged asphalt	24	66	0.4	2.352	76–10
REOB-rejuvenated asphalt	72	50	21.6	0.433	70–28
RA5-rejuvenated asphalt	68	51.3	24.2	0.417	70–28

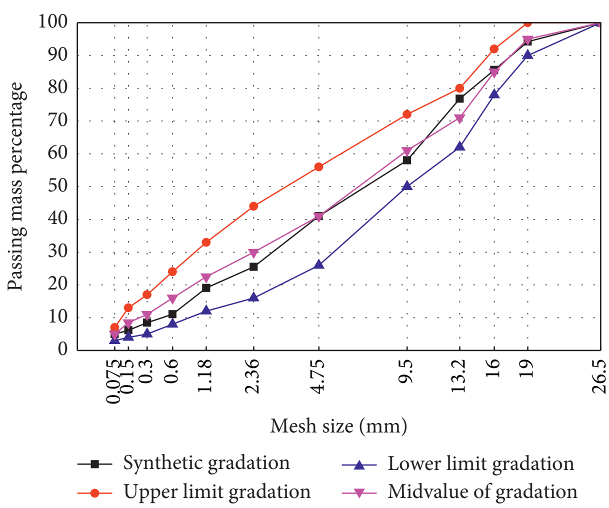

Figure 1: AC-20 aggregate gradation curve.

accordance with the relevant methods of Chinese test standard [10].

2.2.4. Rotary Accelerated Loading Test. To rapidly simulate the damage to pavement caused by actual traffic loads, our university independently developed the rotary accelerated loading test (RALT) system, as shown in Figure 2. The dimensions of the RALT system are 3360 mm × 2120 mm × 2526 mm. The RALT system can simulate the equivalent axle loads of vehicles less than or equal to 100 kN at rolling speeds of 10~35 km/h (3000–15000 cycles/h). The RALT system has a temperature regulation system that can adjust the temperature from −15°C to 60°C. The effective loading length of the RALT system is 1 m.

2.2.5. Falling Weight Deflectometer. A falling weight deflectometer (FWD) can accurately capture the actual deformation of pavement under actual dynamic loads, calculate the modulus of the pavement structure layer, and scientifically evaluate the bearing capacity of pavement [14]. In this paper, PRIMAX 1500 FWD produced by Grontmij Company in the Netherlands is used to test the deflection of the pavement structure layer.

3. Results and Analysis

3.1. Antiageing Performance of REOB. When REOB is used as a regenerant, its own ageing resistance is directly related to the antiageing and durability of asphalt rejuvenated with REOB. In the process of thermal oxygen ageing, the mass of the regenerant will increase due to oxidation and polymerization; on the contrary, a mass loss will be caused by the volatilization of light components. However, considering that the regenerant is rich in aromatics, the mass loss of the regenerant will dominate during the thermal ageing process [15]. Therefore, the mass losses and viscosity ratios of REOB and RA5 were measured after a 5 h TFOT, and the results are shown in Table 3.

Table 3 shows that the mass losses and viscosity ratios of REOB and RA5 meet the technical requirements of Chinese technical specification [16], indicating that both regenerants exhibit good thermal stability and ageing resistance, and the feasibility of REOB as a regenerant has been preliminarily verified. Moreover, it can be seen that both the mass loss and viscosity ratio of REOB are less than those of RA5 after a 5 h TFOT, indicating that the antiageing performance of REOB is better than that of RA5. At this time, there is no phenomenon of poor thermal stability and antiageing performance of waste mineral oil as regenerant which has been concerned by predecessors [17, 18].

3.2. Antiageing Performance of REOB-Rejuvenated Asphalt. Because short-term simulated ageing (5 h TFOT) cannot evaluate the long-term performance of asphalt [19], the physical and rheological properties of asphalt were tested and analysed after extended TFOT (ageing times for 5 h, 10 h, 15 h, 20 h, and 25 h); hence, the antiageing performance of REOB-rejuvenated asphalt was evaluated in long-term use process [12].

3.2.1. Mass Loss. Similar to the above TFOT of REOB, the evaporation loss of rejuvenated asphalt is much greater than the weight gain of oxygen absorption due to the addition of

(a) (b)

Figure 2: The rotary accelerated loading test (RALT) system. (a) Front view of the RALT, (b) console, and (c) temperature control system.

Table 3: Ageing indexes of REOB and RA5 after a 5 h TFOT.

Test objects	Mass loss (%)	Viscosity ratio (%)
REOB	2.48	1.75
RA5	2.75	1.87
Technical requirements	−4 to 4	≤3

either REOB or RA5. So the mass losses of REOB-rejuvenated asphalt, RA5-rejuvenated asphalt, and base asphalt were measured under the extended TFOT ageing times. The results are shown in Figure 3.

As shown in Figure 3, the mass losses of the three asphalts are less than 0.8% after the 5 h TFOT, which meets the standard requirements. In addition, the mass loss of REOB-rejuvenated asphalt is less than that of RA5-rejuvenated asphalt when the TFOT is less than 10 h, indicating that the antiageing property of REOB-rejuvenated asphalt is better than that of RA5-rejuvenated asphalt at this time, which is consistent with the antiageing performance of REOB. However, when the TFOT is 15 h or longer, the mass loss of REOB-rejuvenated asphalt is greater than that of RA5-rejuvenated asphalt, and the gap between the two increases as the TFOT ageing time increases, indicating that the weakness of poor thermal stability and ageing resistance of REOB as a regenerant is gradually revealed under long-term high-temperature ageing.

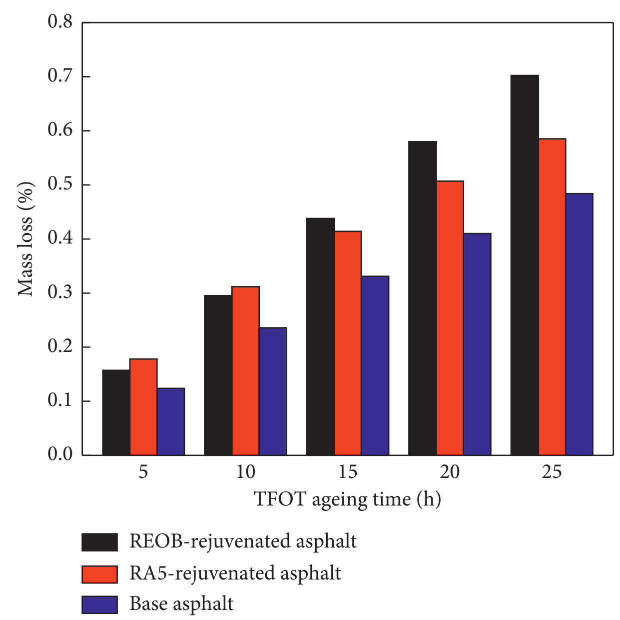

Figure 3: Relations between mass loss and TFOT ageing time for three kinds of asphalt.

3.2.2. Viscosity Ageing Index. Asphalt viscosity can accurately reflect the degree of colloidal solubility of asphaltenes in asphalt components [20]. Asphalt ageing increases the asphaltene content due to component migration, and the increase in asphaltenes results in a continuous increase in asphalt viscosity. Therefore, the viscosity change can accurately reflect the ageing process and ageing degree of asphalt. Under extended TFOT ageing times, the dynamic viscosities of the three asphalts at 60°C were measured, and the results are shown in Table 4.

Table 4: Viscosities of the three kinds of asphalt at 60°C under different extended TFOT ageing times (MPa·s).

Asphalt type	TFOT ageing time (h)					
	0	5	10	15	20	25
REOB-rejuvenated asphalt	503	972	1785	2949	4491	5862
RA5-rejuvenated asphalt	475	961	1726	2553	3454	4046
Base asphalt	446	880	1392	2026	2665	3125

According to the data in Table 4, the antiageing performance of the different asphalts can be characterized by the viscosity ageing index C. The formula for C is as follows:

$$C = \lg\lg\eta_2 - \lg\lg\eta_1, \quad (1)$$

where C is the viscosity ageing index, η_2 is the viscosity under different TFOT ageing times (MPa·s), and η_1 is the viscosity before ageing (MPa·s). Therefore, the relationships between the viscosity ageing index C and ageing time for the three kinds of asphalt are obtained, as shown in Figure 4.

Figure 4 shows that the viscosity ageing indexes C of the three kinds of asphalt increase as the TFOT ageing time increases, indicating a decrease in the ageing resistance of the three asphalts. After a 5 h TFOT, the order of the viscosity ageing index is RA5-rejuvenated asphalt > base asphalt > REOB-rejuvenated asphalt, which indicates that REOB-rejuvenated asphalt has the best ageing resistance among the three. After a 10 h TFOT, the order of the viscosity ageing index is RA5-rejuvenated asphalt > REOB-rejuvenated asphalt > base asphalt. At this time, the ageing resistance of REOB-rejuvenated asphalt is not as good as that of base asphalt but is still better than that of RA5-rejuvenated asphalt. As the TFOT ageing time increases, the viscosity ageing index of REOB-rejuvenated asphalt becomes greater than that of the other two asphalts, and the gap between REOB-rejuvenated asphalt and the other two asphalts increases as the ageing time increases, indicating that REOB-rejuvenated asphalt has the worst long-term (at TFOT ageing times greater than or equal to 15 h) antiageing performance. The reason may be that the paraffin in REOB accelerates asphaltene precipitation and that iron, copper, chromium, and other metals in REOB are easily oxidized at high-temperature for a long time, thus intensifying the ageing and hardening of asphalt.

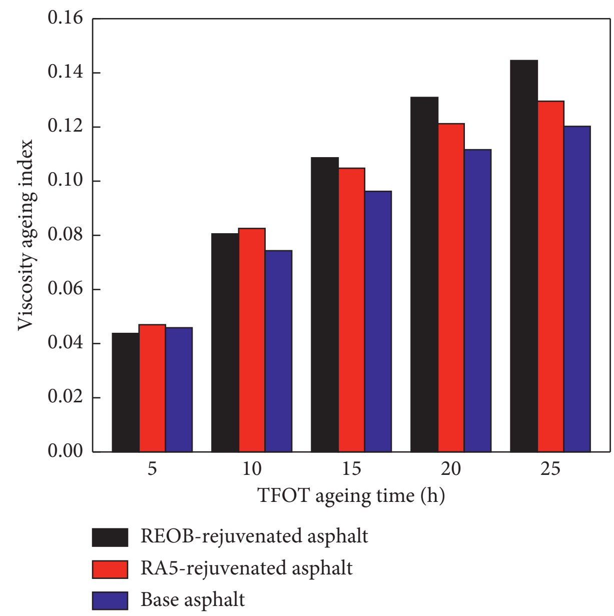

Figure 4: Relations between viscosity ageing index and TFOT ageing time for the three kinds of asphalt.

3.2.3. Creep Stiffness and Creep Rate.

3.2.3. Creep Stiffness and Creep Rate. The ageing of asphalt pavement makes the asphalt hard and brittle, wherein the asphalt stiffness increases, and the stress relaxation and ultimate tensile strain decrease; these changes easily result in the low-temperature cracking of asphalt pavement, which shortens the service life of asphalt pavement [21]. Therefore, a low-temperature bending creep test can be carried out using a BBR, as proposed by the Strategic Highway Research Program (SHRP), to evaluate the effect of extended TFOT ageing on the low-temperature crack resistance of asphalt. After the extended TFOTs, the creep stiffnesses and creep rates of the three asphalts at −12°C are shown in Figures 5 and 6, respectively.

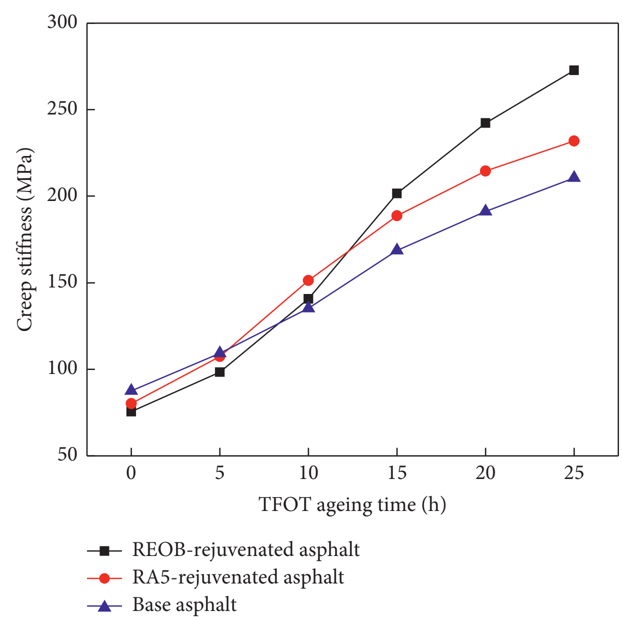

Figure 5: Relation between creep stiffness rate and TFOT ageing time.

Figure 5 shows that the creep stiffnesses of the three kinds of asphalt increase with increasing TFOT ageing time, which shows that the asphalt hardens continuously and that the low-temperature performance gradually decreases after ageing. After 5 h and 10 h TFOTs, the increased levels of creep stiffness of the three asphalts are ranked as follows: RA5-rejuvenated asphalt > REOB-rejuvenated asphalt > base asphalt; these results demonstrate that the hardening rate of RA5-rejuvenated asphalt is the highest among the three asphalts and the short-term (TFOT ageing time less than or equal to 10 h) ageing resistance of REOB-rejuvenated asphalt is better than that of RA5-rejuvenated asphalt but worse than that of base asphalt. When the TFOT ageing time is 15 h or longer, the increased levels of creep stiffness of REOB-rejuvenated asphalt are greater than those of RA5-rejuvenated asphalt and base asphalt, indicating that REOB-rejuvenated asphalt has the worst long-term (TFOT ageing time greater than or equal to 15 h) ageing resistance, which is consistent with the mass loss and viscosity ageing index trends shown above.

Figure 6 shows that the creep rates of three asphalts decrease with increasing TFOT ageing time, which indicates that the stress dissipation ability of asphalt at low temperature gradually weakens. After 5 h and 10 h TFOTs, the creep rate of REOB-rejuvenated asphalt falls below that of base asphalt. When the TFOT ageing time is 15 h or longer, the

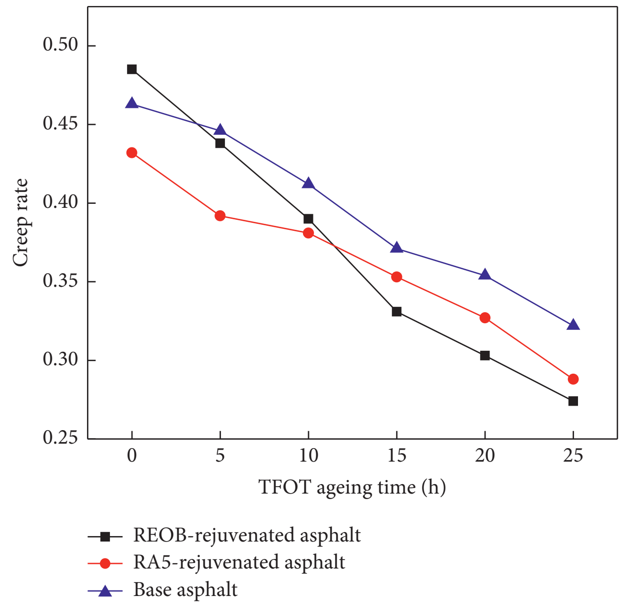

Figure 6: Relation between creep and TFOT ageing time.

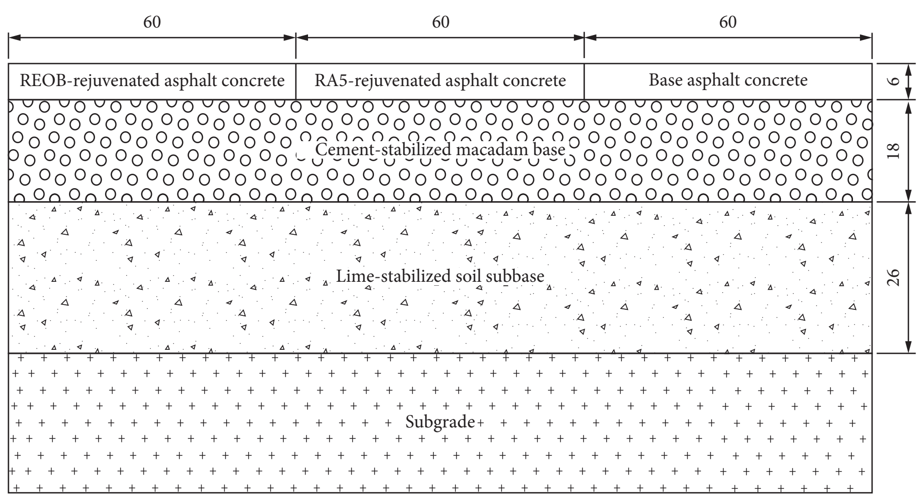

Figure 7: Structural sketch of full-scale indoor test road (cm).

creep rate of the REOB-rejuvenated asphalt substantially drops to a point less than that of RA5-rejuvenated asphalt, indicating that the stress relaxation ability of REOB-rejuvenated asphalt decreases to the worst among the three asphalts; therefore, the corresponding asphalt pavement would easily crack when the temperature sharply decreases.

3.3. Antiageing Performance of an REOB-Rejuvenated Asphalt Mixture Test Road. Another aspect of the reduction in the service life of asphalt pavement caused by ageing is the attenuation of fatigue resistance. Ageing increases the stiffness of the asphalt mixture, decreases the ultimate failure strain of traffic fatigue and temperature stress fatigue, and reduces the number of loading actions of fatigue damage [21], which ultimately leads to fatigue failure of asphalt pavement.

To study the effects of ageing on the fatigue resistance and service life of asphalt pavement and to explore the practical feasibility of REOB used in rejuvenated asphalt pavement, REOB-rejuvenated asphalt concrete, RA5-rejuvenated asphalt concrete, and base asphalt concrete were used to design and pave surface layers of a full-scale indoor test road (Figures 7 and 8) in this study. Using the RALT system independently developed by our university, the three pavement structures were loaded at normal temperature and high temperature (60°C) with a 100 kN axle load and a 15 km/h loading speed. For every 50,000 loads by the RALT system, the deflection values of the three pavement structures were measured using an FWD. The relationship between loading cycles and deflection values is shown in Figure 9.

Figure 9 shows that the deflection values of the three asphalt pavement structures increase but the growth rates

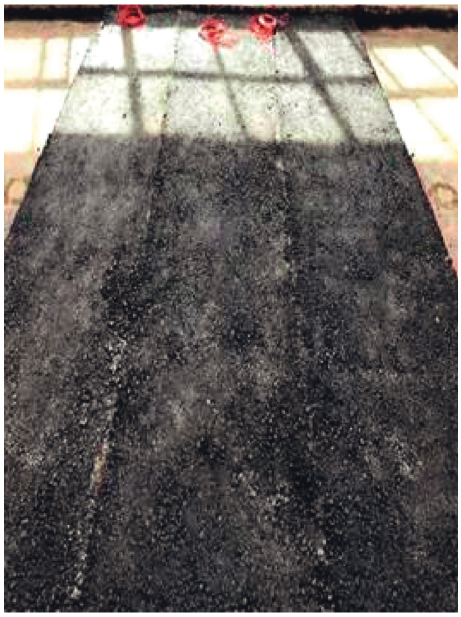

Figure 8: Field map of full-scale indoor test road (from left to right in the field map: REOB-rejuvenated asphalt concrete, RA5-rejuvenated asphalt concrete, and base asphalt concrete).

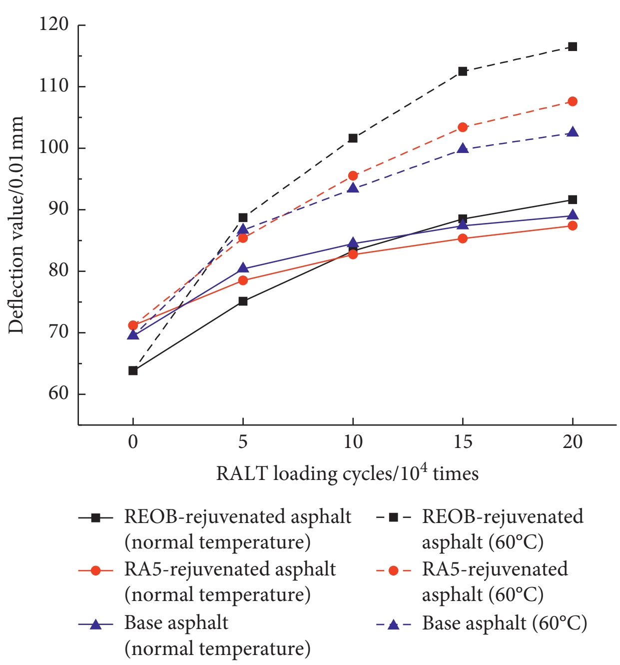

Figure 9: Relation between pavement deflection value and RALT loading cycles.

slow as the number of RALT loading cycles increases, indicating that the structural bearing capacity and service life of the asphalt pavement gradually decrease [18]. In addition, the increase in temperature substantially increases the deflection value of asphalt pavement because the deformation resistance and structural modulus of asphalt pavement decrease with increasing temperature. Moreover, according to the time-temperature equivalence principle [22], increasing the temperature is equivalent to increasing the number of loading cycles; therefore, the deflection values of asphalt pavement are further increased at higher temperatures.

The growth rate of the deflection value of REOB-rejuvenated asphalt pavement is obviously greater than those of RA5-rejuvenated asphalt pavement and base asphalt pavement. After the high temperature accelerates the ageing of the three asphalt pavements, the growth of the deflection value of REOB-rejuvenated asphalt pavement becomes more substantial, which indicates that high-temperature ageing exacerbates the decrease in bearing capacity of asphalt pavement during long-term loading processes and makes REOB-rejuvenated asphalt pavement more prone to fatigue failure than RA5-rejuvenated asphalt pavement and base asphalt pavement.

4. Conclusions

(1) REOB meets the technical requirements of mass loss and viscosity ratio of asphalt regenerants listed in the technical specification. Moreover, at a TFOT ageing time of 5 h, REOB exhibits a better antiageing performance than professional regenerant RA5.

(2) At a TFOT ageing time less than or equal to 10 h, the short-term antiageing performance of REOB-rejuvenated asphalt is better than that of RA5-rejuvenated asphalt evaluated by the mass loss and viscosity ageing index. But the long-term antiageing performance of REOB-rejuvenated asphalt is worse than that of RA5-rejuvenated asphalt and base asphalt when the TFOT ageing time is greater than or equal to 15 h.

(3) The evaluation of creep stiffness for antiageing performance is consistent with the law of mass loss and viscosity ageing index; that is, REOB-rejuvenated asphalt exhibits better short-term antiageing performance and the worst long-term antiageing performance. Moreover, the creep rate of REOB-rejuvenated asphalt is substantially attenuated during extended TFOT ageing, which shows that REOB-rejuvenated asphalt is prone to thermal cracking.

(4) The full-scale indoor test road shows that both increasing loading cycles and increasing temperatures can increase the deflection value of asphalt pavement and reduce the bearing capacity of pavement. Compared with RA5-rejuvenated asphalt pavement and base asphalt pavement, high-temperature ageing decreases the bearing capacity of REOB-rejuvenated asphalt pavement more substantially in the long-term loading process, which makes REOB-rejuvenated asphalt pavement more prone to fatigue failure.

Data Availability

The experimental data in this paper are from the pavement material laboratory of Shandong Jiaotong University, which is the provincial key laboratory. The experimental data in this paper are real and reliable.

Conflicts of Interest

The authors declare no conflicts of interest.

Acknowledgments

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Supplementary Materials

The video records an actual wheel loading process simulated by the rotary accelerated loading test (RALT) system independently developed by our university on the full-scale indoor test road. The RALT system can rely on temperature control system to set the temperature (–15°C to 60°C) of pavement under loading cycles and accelerates and loads pavement under certain axle loading (less than or equal to 100 kN) and speed (10~35 km/h). Each time the pavement is loaded, the console records the times of loading. (*Supplementary Materials*)

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