applied sciences

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Study on Pavement Performance of Recycled Asphalt Mixture Modified by Carbon Nanotubes and Waste Engine Oil

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Abstract: The large amount of recycled asphalt pavement mixture (RAP) generated during renovations has a negative impact on the environment. In recent years, how to rationally recycle and reuse RAP has become a hot research direction in the field of highway construction. However, the recycled asphalt binder has some problems such as instability, easy aging and decreased adhesion. In this paper, carbon nanotubes and waste engine oil were used to modify recycled asphalt binder. Through a high-temperature rutting test, low-temperature bending test and Marshall stability test, the properties of an asphalt mixture with 40% RAP modified by carbon nanotubes and waste engine oil, an asphalt mixture with 40% RAP and an asphalt mixture without RAP were compared and analyzed. The tests showed that 1.5 wt% carbon nanotubes could improve the performance of the old asphalt binder most significantly. After adding 1.5 wt% carbon nanotubes, the high-temperature rutting resistance of the asphalt mixture was increased by 24.3%, and the bending stiffness modulus and the best crack resistance at low temperature increased significantly. In addition, after adding 1.5 wt% carbon nanotubes, the Marshall stability of the waste-engine-oil-modified RAP could be restored to the level of the new asphalt mixture. In summary, carbon nanotubes can improve the high-temperature stability, low-temperature crack resistance and Marshall stability of waste-engine-oil-modified RAP.

Keywords: asphalt mixture; regeneration; high RAP content; waste engine oil; carbon nanotubes; road performance; Marshall test

Citation: Li, W.; Yao, H.; Yang, D.; Peng, C.; Wang, H.; Chen, Z.; Zhao, Y. Study on Pavement Performance of Recycled Asphalt Mixture Modified by Carbon Nanotubes and Waste Engine Oil. *Appl. Sci.* **2023**, *13*, 10287. https://doi.org/10.3390/app131810287

Academic Editor: Laurent Daudeville

Received: 12 June 2023
Revised: 19 August 2023
Accepted: 7 September 2023
Published: 14 September 2023

1. Introduction

In the road construction in our country, asphalt pavement is becoming more and more dominant, with the advantages of safety, comfort and being easy to repair [1,2]. Most of the new and improved roads are built with asphalt mixtures. However, under the action of long-term wheel rolling and sun exposure, asphalt will gradually age, and its performance will no longer meet the requirements of relevant specifications, increasing the driving risk [3,4]. For these aged asphalt roads, in addition to the repaired part, a large amount of recycled asphalt pavement (RAP) will be generated in the subsequent pavement maintenance work. In order to reduce environmental pollution, it is very necessary to reuse the amount of RAP [5–7].

In recent years, many researchers have demonstrated that the thermal regeneration of RAP is feasible, and they used waste engine oil, waste cooking oil and other regenerants to regenerate old asphalt, trying to restore its performance to the level of new asphalt [8–12]. Hu et al. [13] evaluated the performance of asphalt pavement with RAP. The results showed that the test indexes of recycled asphalt mixture with 30% RAP meet the requirements of the specifications, except moisture content and low-temperature crack resistance. Joni et al. [14] extracted and studied old asphalt on RAP milled from pavement that was used for 6 years. By using a high-speed mixer at 150 °C and at 1300 r/min, 1–3% waste vegetable oil and waste engine oil were fully mixed with the aged asphalt. The results showed that waste oil can make the physical properties of old asphalt close to the level of new asphalt. Li et al. [15] found that the use of waste engine oil can effectively improve the three physical properties of old asphalt. Cao et al. [16] studied the regeneration effect of waste vegetable oil on aging asphalt, and the results showed that waste vegetable oil can not only improve the road performance of aging asphalt, but also ensure its safety performance and anti-aging performance. However, there is still a gap between the performance of a waste engine oil, recycled asphalt binder and new asphalt binder [17–20]. Therefore, some scholars began to modify the waste engine oil, recycled asphalt binder to improve its performance.

One of the methods to modify recycled asphalt binder is to mix some micro and nano materials. Among many micro and nano materials, carbon nanotubes are an ideal filler material for modification. Carbon nanotubes have a unique porous structure, which can adsorb oil in a regenerant and can improve the compatibility of light components of regenerant and asphalt [21,22]. At present, the effect of carbon nanotubes on asphalt modification has been widely studied [23–27]. Zheng et al. [28] studied the viscoelastic behavior of multi-walled carbon nanotubes (MWNTs) and crumb-rubber-modified asphalt. The results showed that the addition of MWNTs and crumb rubber increased the high-temperature viscosity of the substrate and reduced the temperature sensitivity of the substrate. In addition, the permanent deformation resistance, creep recovery and stress relaxation properties of asphalt significantly improved after the addition of these two modifiers. Ahmad et al. [29] studied the effect of carbon nanotubes on asphalt binders. The results showed that carbon nanotubes improved the high-temperature properties and permanent deformation resistance of binders and mixtures. Nikookar et al. [30] discussed the effects of carbon-nanofiber-modified asphalt binder and carbon-nanotube-modified aggregate on the moisture sensitivity of an asphalt mixture. The indirect tensile strength test results showed that asphalt binders and aggregates modified by carbon nanofibers and carbon nanotubes could, respectively, improve the indirect tensile strength and tensile strength ratio of the mixture. The surface free energy test results showed that the addition of carbon nanofibers and carbon nanotubes increased the adhesion free energy of the aggregate and asphalt binder system. The asphalt–aggregate bonding properties and moisture resistance also improved. Therefore, it is feasible to use carbon nanotubes to modify recycled asphalt binder. However, there are few studies on the application of carbon nanotubes in a waste engine oil, recycled asphalt binder, and the influence on the performance of a waste engine oil, recycled asphalt binder is still unknown.

On the basis of the related regeneration research carried out by the above researchers, this paper studied the improvement in the performance of a waste engine oil, recycled asphalt mixture modified by carbon nanotubes, which provide a new method for the recycling of old asphalt. This paper prepared a heat-recycled asphalt mixture without RAP, a heat-recycled asphalt mixture with 40% RAP, a waste engine oil, recycled asphalt mixture with 40% RAP, and a carbon-nanotube-modified waste engine oil, recycled asphalt mixture with 40% RAP. The road performance of the RAP heat-recycled asphalt mixture was tested using the high-temperature rutting test, low-temperature bending test and Marshall stability test, and the influence of waste engine oil and different contents of carbon nanotubes on the road performance of the RAP heat-recycled asphalt mixture was analyzed. The experimental flow chart is shown in Figure 1.

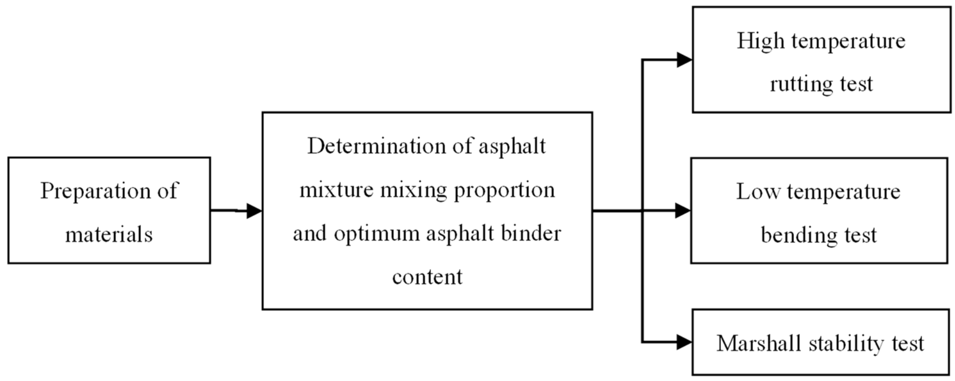

Figure 1. Experimental flow chart.

2. Materials

2.1. Aggregate

The new aggregate used in the recycled asphalt mixture was limestone. The coarse aggregate was divided into three sections of 20–30 mm, 10–20 mm and 5–10 mm, and the fine aggregate was 0–5 mm. All the aggregates were provided by Tianmen Mixing Station, and the screening results of the aggregates are shown in Table 1. The mineral powder was also provided by Tianmen Mixing Station, and the technical indexes of the mineral powder are shown in Table 2.

Table 1. Percentages of aggregate masses in different sizes.

	Scantling (mm)					
		20–30	**10–20**	**5–10**	**0–5**	**Mineral Powder**
Mass percentage of passing through the following sieves (mm) (%)	31.5	100	100	100	100	100
	26.5	95.4	100	100	100	100
	19	3.7	95.5	100	100	100
	16	0.6	72.4	100	100	100
	13.2	0.5	50.1	100	100	100
	9.5	0.4	15.9	98.3	100	100
	4.75	0.4	0.8	17.7	100	100
	2.36	0.4	0.4	1	74.5	100
	1.18	0.4	0.4	1	46.9	100
	0.6	0.4	0.4	0.9	25.8	100
	0.3	0.4	0.4	0.9	13.9	100
	0.15	0.4	0.4	0.9	7.7	94.6
	0.075	0.4	0.4	0.9	3.6	86.8

Table 2. Technical indexes of mineral powder.

Test Item		**Experimental Data**	**Technical Requirements**
Performance density (t/m^3)		2.688	≥2.50
Water content (%)		0	≤1
Particle size range	<0.6 mm (%)	100	100
	<0.15 mm (%)	94.6	90~100
	<0.075 mm (%)	86.8	75~100
Appearance		No clumps or lumps	No clumps or lumps
Plasticity index (%)		2	<4

2.2. RAP and Waste Engine Oil, Recycled Asphalt Binder

The RAP used in this paper was provided by Hubei Road and Bridge Maintenance Co., Ltd. (Wuhan, China), Shandong Expressway Group, and came from the middle and bottom milling materials generated by the maintenance of the Tianmen section of Wujing Expressway. The large crushing and screening machine in Tianmen Mixing Station divided the RAP into two sections (0–13 mm and 13–30 mm). The asphalt binder contents of RAP's 0–13 mm section and 13–30 mm section were detected using T0735 in "Test Regulations for Highway Asphalt Binder and Asphalt Mixtures" (JTG E20-2019).

The waste engine oil used in this paper was HX8 5W-40 automobile waste engine oil. The processing process of the waste engine oil regenerant was as follows: The waste engine oil was placed into the oven for 2 h to remove excess water. Then, a funnel and filter paper were used to filter out the excess impurities and metal particles in the waste oil, and the filtered product was the waste engine oil regenerant. The waste engine oil regenerant was dark brown and slightly transparent with a slightly pungent smell, and its viscosity was low. The basic physical indexes of the waste engine oil regenerant are shown in Table 3.

Table 3. Basic physical indexes of waste engine oil.

Index	Unit	Testing Result	Test Specification
Flash point	°C	216	GB/T 3536
Impurity	%	0.06	GB/T 511
Oxidation stability	Min	33	SH/T 0193
Kinematic viscosity (40 °C)	mm^2/s	42.3	GB/T 265

2.3. Carbon Nanotubes

The waste engine oil, recycled asphalt binder was modified by carbon nanotubes. The carbon nanotubes were provided by Jiangsu Xianfeng Nanomaterials Technology Co., Ltd. (Nanjing, China). The specific property parameters of the carbon nanotubes are shown in Table 4.

Table 4. Specific parameters of carbon nanotubes.

Property	Units	Numerical Value	Characterization Method
External diameter	nm	30–50	HRTEM, Raman
Inner diameter	nm	5–12	HRTEM, Raman
Length	µm	<10	TEM
Purity	wt%	>95	TGA and TEM
Specific surface area	m^2/g	>60	
Bulk density	g/cm^3	0.14	

3. Experimental Method

3.1. Preparation of Recycled Asphalt Binder Modified by Carbon Nanotubes

The method of preparing the waste engine oil, recycled asphalt binder was as follows: The waste engine oil was gradually mixed into the old asphalt binder at a speed of 1000 r/min. Then, the recycled asphalt binder was obtained by stirring it at a high speed at 160 °C for 30 min.

The method of preparing carbon-nanotube-modified, waste engine oil, recycled asphalt binder was as follows: The prepared RAS and carbon nanotubes were mixed in a high-speed shear mixer at a speed of 3000 r/min and at a temperature of 170 °C for 30 min; then, the carbon-nanotube-modified, waste engine oil, recycled asphalt binder was obtained.

3.2. Preparation of Asphalt Mixture

3.2.1. The Mixing Proportion of Asphalt Mixture

According to the results of RAP crushing and screening in the asphalt mixing station, fine aggregate will be more than coarse aggregate. In order to maximize the efficiency of RAP recovery and utilization, the proportion of the 0–13 mm section should be greater than the 13–30 mm section during the RAP content design. In this paper, the ratio of the 0–13 mm segment to the 13–30 mm segment was 5:3. This paper prepared an AC-25 heat-recycled asphalt mixture used for renovating the underside of Wujing Expressway. In order to optimize the on-site process, the preparation process for the RAP heat-recycled asphalt mixture with high content was studied in this paper, and the content of RAP was increased to 40%. The resulting grading curve is shown in Figure 2. At the same time, an asphalt mixture without RAP was prepared as a blank control group, and the grading curve of this group is shown in Figure 3.

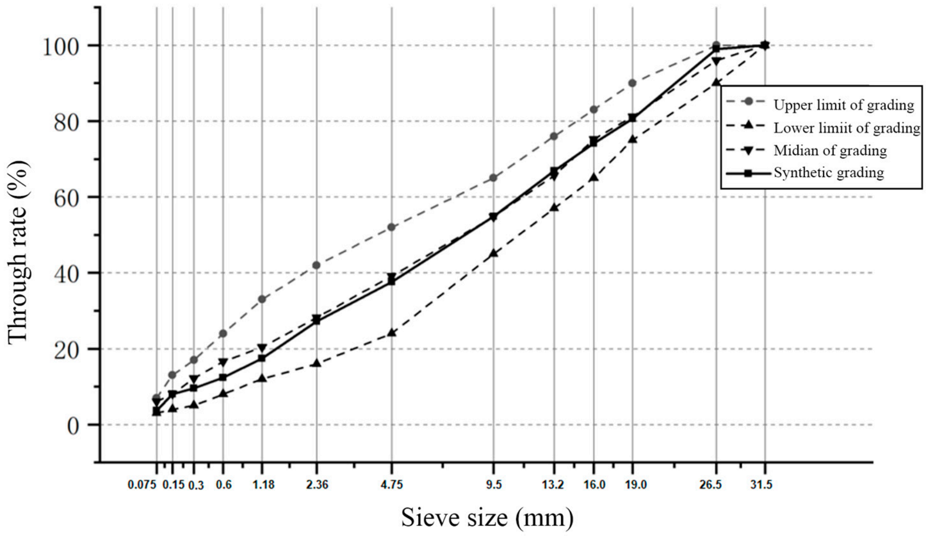

Figure 2. Gradation curve of AC-25 heat-recycled asphalt mixture with 40% RAP.

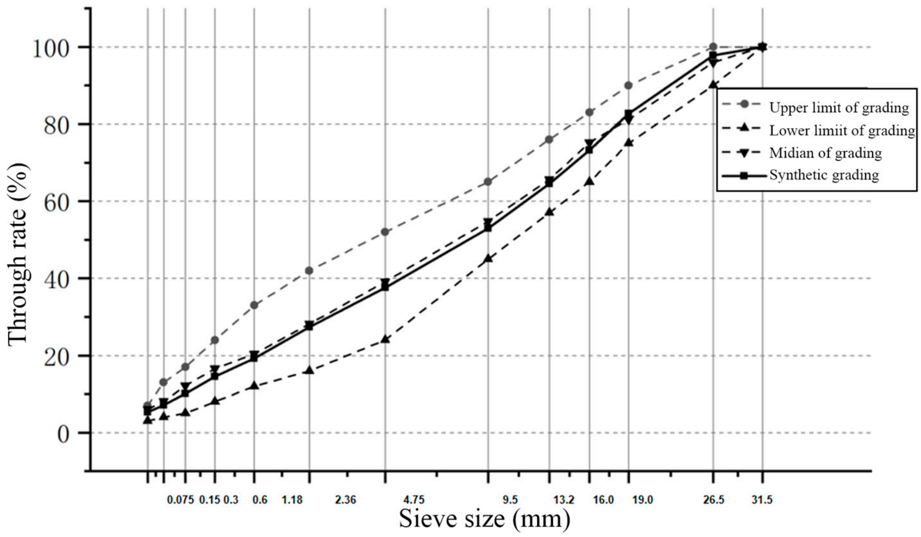

Figure 3. Gradation curve of AC-25 heat-recycled asphalt mixture without 40% RAP.

3.2.2. The Optimum Asphalt Binder Content

The Marshall test method is commonly used to determine the optimum asphalt binder content of asphalt mixtures. The optimum asphalt binder content can be calculated using the parameters of the Marshall test with different asphalt–aggregate ratios. In this paper, the optimum asphalt binder content was determined by the matching ratio that all the indexes above met the requirements for.

3.3. Pavement Performance Test

The pavement performance evaluation of an asphalt mixture is an important step before its application in actual construction. In this paper, three test methods were used to evaluate the road performance. The test standard adopted in this paper was "Field Test Regulations for Road Subgrade and Pavement" (JTG 3450-2019).

3.3.1. High-Temperature Rutting Test

A rutting plate of 300 mm × 300 mm × 50 mm was made of the asphalt mixture using an LBCX-1 hydraulic rutting sample forming machine. After placing the asphalt mixture in it for one day, the rutting test was carried out under the constant temperature of 60 °C. The deformation depth of the rutting plate in 45 min and 60 min was recorded via the rutting tester, and the dynamic stability of the mixture was calculated according to the deformation. The equation for calculating the dynamic stability of the specimen of the heat-recycled asphalt mixture is shown in Equation (1).

$$DS = \frac{(t_2 - t_1) \times N}{d_2 - d_1} \times C_1 \times C_2 \tag{1}$$

DS—Dynamic stability of asphalt mixture (times/mm);
d_1—Deformation of asphalt mixture at t_1 = 45 min (mm);
d_2—Deformation of asphalt mixture at t_2 = 60 min (mm);
C_1—Coefficient corresponding to the rutting tester;
C_2—Coefficient of the rutting specimen. This experiment is 1.0 as required by the specification;
N—The rate of round-trip tire rolling in a rutting test. It is usually 42 times/min.

3.3.2. Low Temperature Bending Test

The 300 mm × 300 mm × 50 mm rutting plate made using the LBCX-1 hydraulic rutting sample forming machine was cut into 250 mm × 30 mm × 35 mm trabecular samples. Then, these samples were placed into a −10 °C incubator for refrigeration for 45 min. After cooling, the UTM-100 multi-function material testing system was used for testing. The maximum load and mid-span disturbance of the trabecular specimen during the test were recorded. The flexural tensile strength R_B, maximum flexural strain ε_B and modulus of flexural stiffness S_B were calculated by analyzing the test results. The flexural tensile strength, maximum flexural strain and modulus of bending stiffness when the specimen was damaged were calculated as shown in Equations (2)–(4):

$$S_B = \frac{R_B}{\varepsilon_B} \tag{2}$$

$$R_B = \frac{3 \times L \times P_B}{2 \times b \times h^2} \tag{3}$$

$$\varepsilon_B = \frac{6 \times h \times d}{L^2} \tag{4}$$

S_B—Modulus of bending stiffness when the specimen is damaged (MPa);
R_B—Flexural tensile strength when the specimen is damaged (MPa);
ε_B—Maximum flexural strain when the specimen is damaged (με);
b—Width of cross section at the middle span of the specimen (mm);
h—Height of cross section at the middle span of the specimen (mm);
L—Span of the trabecular specimen (mm);
P_B—Maximum load value of the specimen when it is damaged (N);
d—Deflection value of specimen at the middle span when it is damaged (mm).

3.3.3. Marshall Stability Test

Four standard Marshall specimens were prepared and randomly divided into two groups. The specimens were cooled at room temperature for 12 h before being demolded and tested. The two groups of test blocks were immersed in a 60 °C constant-temperature water tank at the same time, and the stability MS_1 and MS_2 were measured, respectively, after 30 min and 48 h of immersion. The ratio of stability between two groups of test blocks is the Marshall stability (MS). The calculation formula is as follows:

$$MS = \frac{MS_2}{MS_1} \tag{5}$$

4. Results and Analysis

4.1. Results of Optimal Asphalt Binder Content

The stability, flow value, gross volume relative density, void ratio (VV), voids in mineral aggregate (VMA) and voids filled with asphalt (VFA) corresponding to five kinds of asphalt–aggregate ratios of the heat-recycled asphalt mixture with 40% RAP content were calculated, and the calculation results are shown in Figure 4.

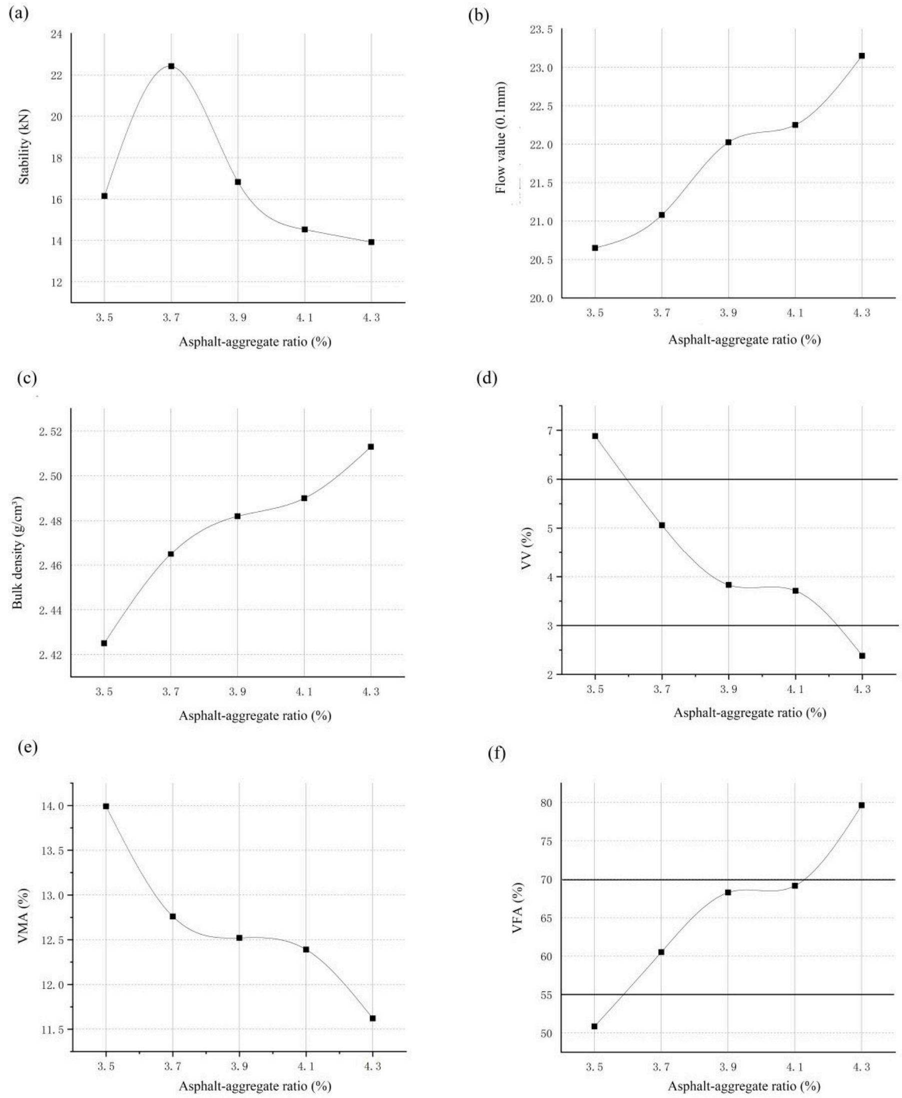

Figure 4. (**a**) Stability results of 40%HMA; (**b**) flow value results of 40%HMA; (**c**) gross volume density results of 40%HMA; (**d**) void ratio results of 40%HMA; (**e**) voids in mineral aggregate results of 40%RHMA; (**f**) voids filled with asphalt results of 40%HMA.

According to the asphalt binder content of RAP sections and the mix ratio of RAP sections, it could be calculated that the content of the old asphalt was about 1.7%. Therefore, the optimal content of the new asphalt in the heat-recycled asphalt mixture with 40% RAP content was 2.24%.

Next, we calculated the stability, flow value, gross volume relative density, VV, VMA and VFA corresponding to the five asphalt–aggregate ratios of the waste engine oil, recycled asphalt mixture with 40% RAP. The calculation results are shown in Figure 5.

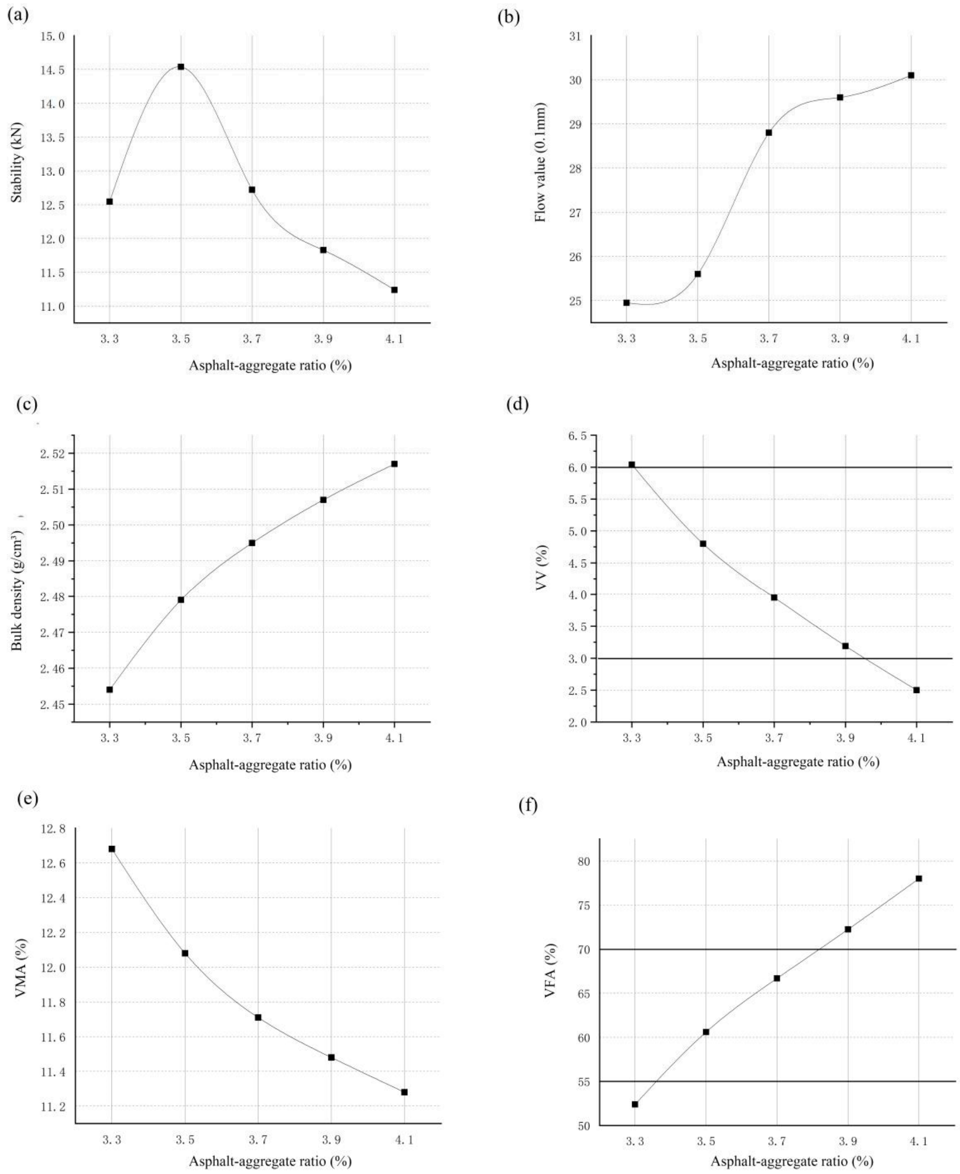

Figure 5. (**a**) Stability results of 40%RHMA; (**b**) flow value results of 40%RHMA; (**c**) the gross volume density results of 40%RHMA; (**d**) void ratio results of 40%RHMA; (**e**) voids in mineral aggregate results of 40%RHMA; (**f**) voids filled with asphalt results of 40%RHMA.

According to the asphalt binder content of the RAP sections and the mix ratio of the RAP sections, it could be calculated that the content of the old asphalt binder was about 1.7%. Therefore, the optimal content of the new asphalt binder in the waste engine oil, recycled asphalt mixture with 40% RAP was 1.98%.

Carbon nanotubes have adsorption effects on light oil, so they also affected the optimal asphalt content in the carbon-nanotube-modified, waste engine oil, recycled asphalt mixture. We calculated the stability, flow value, gross volume relative density, VV, VMA and VFA corresponding to five asphalt–aggregate ratios of the carbon-nanotube-modified, waste engine oil, recycled asphalt mixture with 40% RAP. The calculation results are shown in Figure 6.

According to the mix ratio of the RAP sections and the asphalt binder content of the RAP sections, it could be calculated that the old asphalt binder content was about 1.7%.

Therefore, the optimum new asphalt binder content in the carbon-nanotube-modified, waste engine oil, recycled asphalt mixture with 40% RAP was 2.25%. It could be seen that the carbon nanotubes could adsorb part of the oil in the waste engine oil, recycled asphalt binder, resulting in a slight increase in the amount of new asphalt in the recycled asphalt mixture.

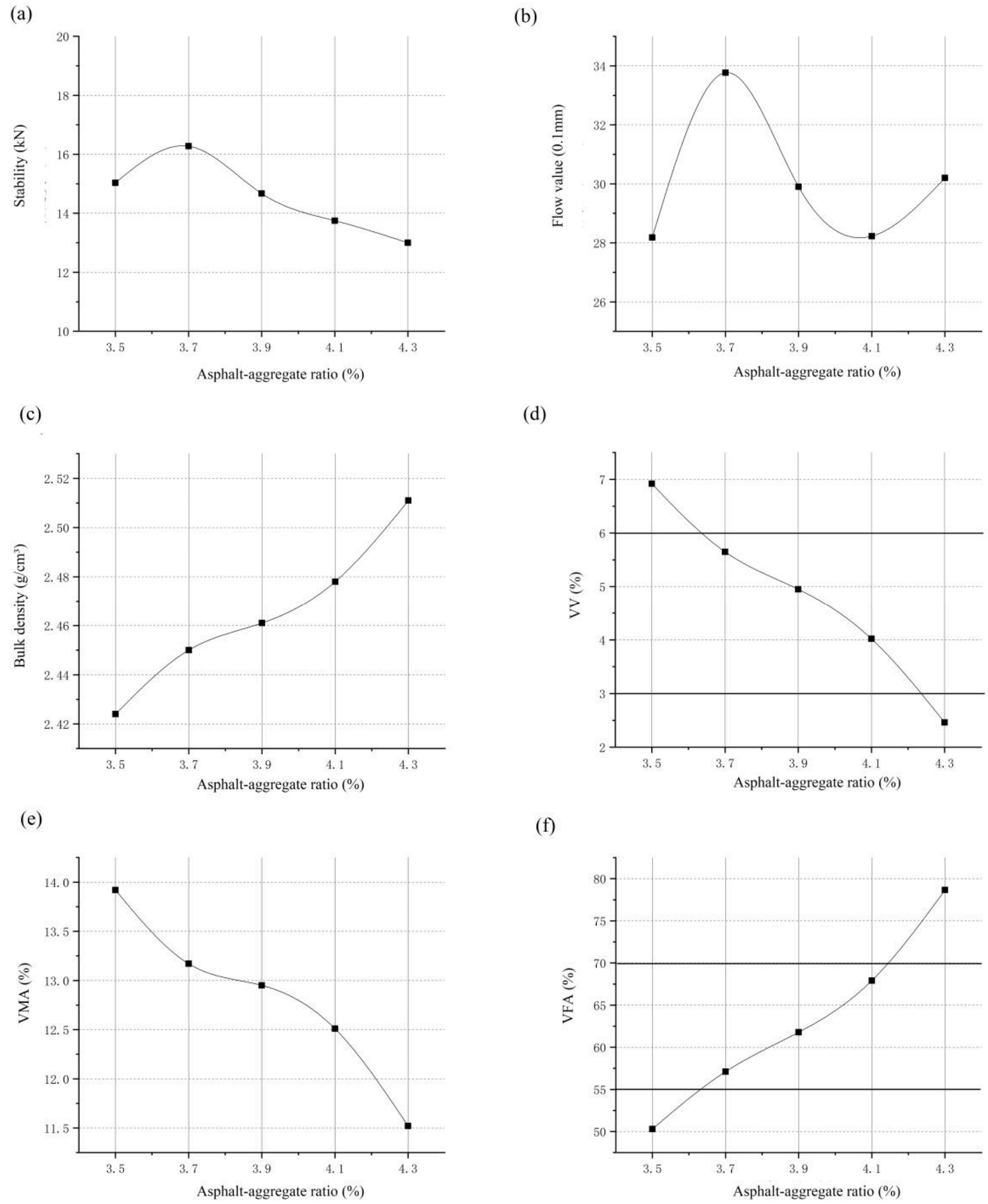

Figure 6. (**a**) Stability results of 40%RHMA-1.5C; (**b**) flow value diagram of 40%RHMA-1.5C; (**c**) gross volume density of 40%RHMA-1.5C; (**d**) void ratio results of 40%RHMA-1.5C; (**e**) voids in mineral aggregate results of 40%RHMA-1.5C; (**f**) voids filled with asphalt results at 40%RHMA-1.5C.

4.2. Results of High-Temperature Rutting Test

High-temperature rutting tests were carried out on the heat-recycled asphalt mixture without RAP (NHMA); the heat-recycled asphalt mixture with 40% RAP (40%HMA); the waste engine oil, recycled asphalt mixture with 40% RAP (40%RHMA), and the carbon-nanotube-modified, waste engine oil, recycled asphalt mixture with 40% RAP (40%RHMA-1C, 40%RHMA-1.5C and 40%RHMA-2.5C). The results are shown in Table 5.

Table 5. Results of high-temperature rutting test.

Sample	d_1 (mm)	d_2 (mm)	DS (times/mm)
NHMA	3.5	3.9	1575
40%HMA	1.9	2.09	3204
40%RHMA	2.33	2.48	2440
40%RHMA-1C	2.28	2.53	2515
40%RHMA-1.5C	1.94	2.15	3034
40%RHMA-2.5C	2.14	2.38	2633
Specification	-	-	≥1000

As can be seen from Table 5, the *DS* of 40%HMA was much larger than that of NHMA. This is because the old asphalt binder in RAP increased the hardness of the recycled asphalt mixture, thus improving the high-temperature performance of 40%HMA. After adding the waste engine oil to 40%HMA, the waste engine oil restored some of the rheological properties of the old asphalt binder. The waste engine oil softened the old asphalt binder and thus reduced the high-temperature stability of 40%RHMA and made it more similar to NHMA. Due to the good mechanical strength of carbon nanotubes, the addition of carbon nanotubes to 40%RHMA increased the high-temperature deformation resistance of the recycled asphalt binder between aggregates. Carbon nanotubes played a "reinforcing" role" between the waste engine oil, recycled asphalt binder and could effectively enhance the high-temperature stability of the waste oil, recycled asphalt mixture. Among them, 40%RHMA-1.5C showed the greatest improvement in high-temperature rutting resistance, which increased by 24.3% compared with 40%RHMA. However, the high-temperature stability of the waste engine oil, recycled asphalt mixture would have been adversely affected if too many carbon nanotubes were added. The rutting plate samples after the high-temperature rutting test are shown in Figure 7.

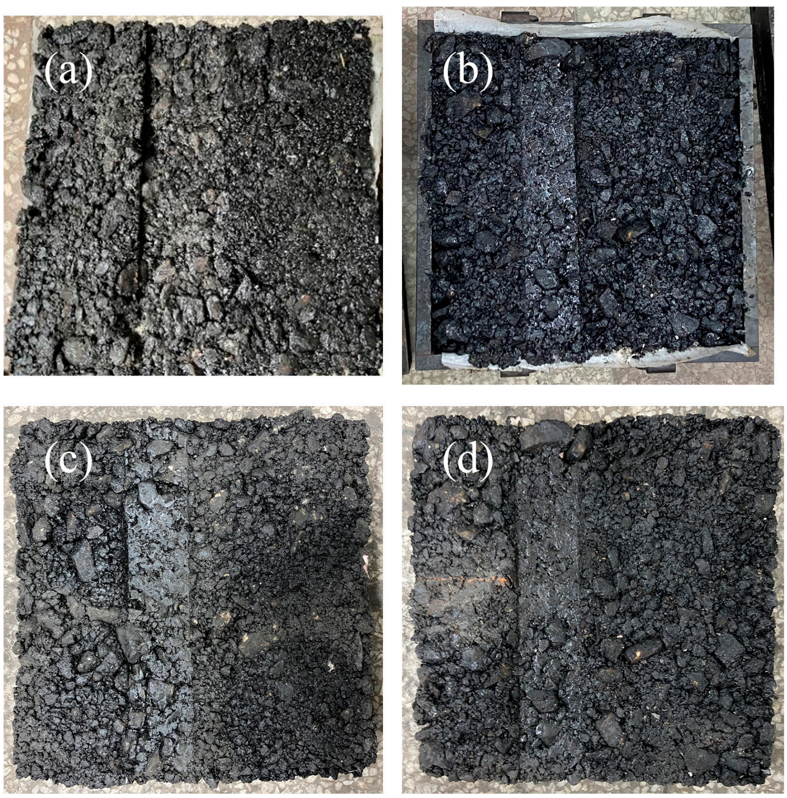

Figure 7. (**a**) NHMA rutting plate sample after high-temperature rutting test; (**b**) 40%HMA rutting plate sample after high-temperature rutting test; (**c**) 40%RHMA rutting plate samples after high-temperature rutting tests; (**d**) 40%RHMA-1.5C rutting plate samples after high-temperature rutting test.

4.3. Results of Low-Temperature Bending Test

According to the low-temperature bending test method, three-point bending tests were carried out on NHMA, 40%HMA, 40%RHMA, 40%RHMA-1C, 40%RHMA-1.5C and 40%RHMA-2.5C. The results are shown in Table 6. It can be seen that 40%HMA had greater flexural tensile strength than NHMA. This is because the old asphalt binder was harder and had a smaller penetration than the new asphalt binder, resulting in the higher strength of 40%HMA. After adding waste engine oil regenerant to 40%HMA, the flexural tensile strength became smaller, even smaller than NHMA. After adding carbon nanotubes into 40%RHMA, the flexural tensile strength increased, which was close to that of NHMA. Moreover, the flexural tensile strength of 40%RHMA increased with the increasing content of carbon nanotubes.

Table 6. Results of low-temperature bending test.

Sample	R_B (MPa)	ε_B (με)	S_B (MPa)
NHMA	9.13	2850	3203.51
40%HMA	12.16	2234	5443.15
40%RHMA	8.78	2346	3742.54
40%RHMA-1C	9.01	2554	3527.8
40%RHMA-1.5C	9.23	2882	3202.64
40%RHMA-2.5C	10.34	3018	3426.11
Specification	-	≥2000	-

Because of the poor elongation of the old asphalt binder, brittle fractures occurred easily. The deformation capacity of 40%HMA was poor, and the maximum flexural strain was much smaller than that of NHMA. After the addition of the waste engine oil regenerant, the maximum flexure strain of 40%RHMA rose, but there was still a big difference between it and NHMA. The maximum flexural tensile strain required in the specifications should be no less than 2000 με for common areas and no less than 2600 με for some cold areas. Obviously, the performance of 40%RHMA would not be up to standard in cold regions. The ε_B increased significantly after the addition of carbon nanotubes to 40%RHMA, reaching 3018 με.

The bending stiffness modulus reflects the ability of an asphalt mixture to resist bending deformation within the elastic limit. The greater the modulus of bending stiffness, the smaller the ability of an asphalt mixture to resist bending deformation within the elastic limit. Therefore, a larger bending strain of an asphalt mixture corresponds to smaller the flexural tensile strength and bending stiffness modulus, as well as better low-temperature cracking resistance. The bending stiffness modulus of 40%HMA was the largest, indicating that RAP can greatly reduce the low-temperature cracking resistance of recycled asphalt mixtures. The loss of low-temperature cracking resistance caused by the addition of RAP was recovered by adding waste engine oil regenerant. This is because the waste engine oil regenerant restored part of the performance of the old asphalt binder in RAP and enhanced the flow performance of the old asphalt binder. In this way, brittle damage did not easily occur in 40%RHMA, but at the same time, the waste engine oil reduced the strength of the recycled asphalt mixture, resulting in the low-temperature crack resistance being improved, but it still could not reach the level of NHMA. With the addition of carbon nanotubes to 40%RHMA, the bending stiffness modulus decreased first and then increased with the increase in carbon nanotubes. This means the low-temperature cracking resistance increased first and then decreased. Due to the excellent viscoelastic properties of 40%RHMA modified by carbon nanotubes, the asphalt mixture was less prone to cracking. However, with the increase in the carbon nanotube content, the increasing hardness hindered the elastic deformation of 40%RHMA. 40%RHMA-1.5C had excellent viscoelastic properties and low hardness. Therefore, 40%RHMA-1.5C had the smallest bending stiffness modulus and the best crack resistance at low temperature, even better than NHMA.

4.4. Results of Marshall Stability Test

Marshall stability tests were carried out on NHMA, 40%HMA, 40%RHMA, 40%RHMA-1C, 40%RHMA-1.5C and 40%RHMA-2.5C, and the results are shown in Table 7. As can be seen, the residual stability of 40%HMA was the smallest, only 73.2%, which did not even meet the standard requirements. This is because the adhesion performance between the old asphalt binder and aggregate in RAP was poor. Water easily invaded the gap between the asphalt binder and aggregate and gradually produced cracks and asphalt stripping. This weakened the anti-deformation ability of the recycled asphalt binder, and the Marshall stability decreased significantly. After adding waste engine oil regenerant into 40%HMA, the adhesive property of the recycled asphalt binder obviously improved, and the residual stability increased by 13.9%. But there was still a difference between the Marshall stability of 40%RHMA and that of NHMA. After adding carbon nanotubes into 40%RHMA, carbon nanotubes strengthened the adhesion between the waste engine oil, recycled asphalt binder and aggregate. Therefore, the waste engine oil, recycled asphalt binder fell off the asphalt surface less easily. Carbon nanotubes also increased the ductility of the waste engine oil, recycled asphalt binder, making cracks between 40%RHMA less likely to occur via water invasion. The residual stability of 40%RHMA-1.5C was restored to the level of the new asphalt mixture, and the Marshall stability significantly improved.

Table 7. Results of Marshall stability test.

Sample	MS_1 (kN)	MS_2 (kN)	MS (%)
NHMA	14.4	13.6	94.4
40%HMA	17.53	12.8	73.2
40%RHMA	11.83	10.3	87.1
40%RHMA-1C	13.3	12.19	91.6
40%RHMA-1.5C	14.63	13.85	94.4
40%RHMA-2.5C	15.05	13.51	89.7
Specification	-	-	$\geq$80

5. Conclusions

This paper presents a new economical and effective method for the recovery and utilization of old asphalt binder. In this paper, the preparation method of a carbon-nanotube-modified, waste engine oil, recycled asphalt mixture was studied, and the road performance of the high-temperature stability, low-temperature cracking resistance and Marshall stability of a carbon-nanotube-modified, waste engine oil, recycled asphalt mixture was studied through a high-temperature rutting test, a low-temperature bending test and the Marshall stability test. By adding waste engine oil and carbon nanotubes to the old asphalt binder, the high-temperature rutting resistance, low-temperature bending resistance and Marshall stability of the waste-engine-oil-modified RAP could be greatly improved, and it could be restored to the level close to or even better than the new asphalt mixture. The conclusions are as follows:

Carbon nanotubes can improve the high-temperature stability of waste-engine-oil-modified RAP. The results of the high-temperature rutting test show that RAP could increase the hardness of asphalt binder in recycled asphalt mixtures, improve the softening point and then increase the high-temperature performance of 40%HMA. The waste engine oil could restore some of the physical properties of the old asphalt binder, which reduced the high-temperature performance of 40%RHMA to close with that of NHMA. Carbon nanotubes play a role of "reinforcing" between waste engine oil regenerant and asphalt binder and effectively enhance the high-temperature stability of 40%RHMA. Among them, 40%RHMA-1.5C showed the greatest improvement in high-temperature rutting resistance. However, too many carbon nanotubes had adverse effects on the high-temperature stability of the waste-engine-oil-modified RAP.

Carbon nanotubes can improve the low-temperature crack resistance of waste-engine-oil-modified RAP. The results of the low-temperature bending test show that RAP could greatly reduce the low-temperature crack resistance of 40%HMA. The addition of waste engine oil regenerant could restore the fluidity of part of the old asphalt binder and make 40%RHMA not prone to brittle failure, thus improving its low-temperature cracking resistance. However, it still could not reach the level of NHMA. When carbon nanotubes were added into 40%RHMA, the low-temperature cracking resistance first increased and then decreased with the amount of carbon nanotubes. The 40%RHMA-1.5C sample had excellent high-temperature deformation resistance and low-temperature crack resistance, even better than NHMA.

Carbon nanotubes could improve the Marshall stability of the waste-engine-oil-modified RAP. The addition of waste engine oil regenerant could significantly improve the Marshall stability of 40%HMA. However, there was still a gap between 40%RHMA and NHMA. After adding carbon nanotubes to 40%RHMA, the MS of 40%RHMA-1.5C was restored to the level of the new asphalt mixture.

Author Contributions: Data curation, D.Y.; formal analysis, H.W.; investigation, W.L. and H.Y.; methodology, H.W. and Z.C.; project administration, C.P.; supervision, C.P.; writing—original draft, C.P. and D.Y.; writing—review and editing, Y.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China (52108425), China University of Geosciences (Wuhan) (CUGL150412, G1323531606 and G1323519261), National College Student Innovation and Entrepreneurship Training Program (S202010491065), Anhui Road and Bridge Engineering Group Co., Ltd. (2021056235) and Shandong Highway and Bridge Maintenance Co., Ltd. (2021056502).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: This research was completed at the Faculty of Engineering in China University of Geosciences, Wuhan, China. Yaode Li provided test resources for this research.

Conflicts of Interest: The authors declare no conflict of interest.

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