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A High Proportion Reuse of RAP in Plant-Mixed Cold Recycling Technology and Its Benefits Analysis

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Abstract: The concept of the "no-waste city" has focused increasing attention on the recycling of solid waste. One such waste is reclaimed asphalt pavement (RAP), which is generated during road maintenance. The potential to reuse this resource has attracted extensive attention in recent years. This paper explores this concept via a case study of the reconstruction of two sections of the Beijing-Taipei Expressway (from Bengbu to Hefei, sections K69–K69 + 500 and K69 + 500–K69 + 900). The upper base layer of one section was paved with a novel mixture of emulsified asphalt, mixed with a high proportion of RAP made using plant-mixed cold recycling technology (EAPM-HP$_{RAP}$). For comparison, the upper base layer of the other section was paved with a conventional large-stone porous asphalt mix (LSPM). The proportions of the components of EAPM-HP$_{RAP}$ were optimized via laboratory-based proportioning design followed by proportioning verification. The results showed that the high-temperature stability, water damage resistance and pavement strength of the EAPM-HP$_{RAP}$ met the specifications of relevant engineering standards. Next, the economic and environmental benefits of this novel approach were estimated. The approach was estimated to save CNY (China Yuan) 1.5–1.8 million in engineering costs per km of road (roadbed width = 27.5 m) and CNY 158–189 million for the whole project (105 km in length). It was also estimated to reduce energy consumption equivalent to 67.41 tons of standard coal per km. Further calculations showed that every km of pavement could reduce CO_2 emissions by 176.6 tons, SO_2 emissions by 0.6 tons, NO_X emissions by 0.5 tons, ash emissions by 17.6 tons and soot emissions by 1.0 tons compared with conventional methods. For the whole road section, this is equivalent to reducing CO_2 emissions by 18,543 tons, SO_2 emissions by 60.2 tons, NO_X emissions by 52.5 tons, ash emissions by 1848 tons, and soot emissions by nearly 105 tons. In summary, it is feasible for EAPM-HP$_{RAP}$ to be used as the upper base layer in highway renovation projects. It reduces the need to mine new ores and allocate land to RAP storage, which is associated with soil and water pollution due to chemical leaching from aged asphalt. This approach provides great economic and environmental benefits compared with the use of conventional pavement technology.

Keywords: solid waste; high proportion reuse; reclaimed asphalt pavement; plant-mixed cold recycling technology; benefits analysis

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1. Introduction

Asphalt is one of the most important products of the petroleum refining industry. Road asphalt products are obtained by the distillation, solvent extraction or oxidation of the residual oil obtained after the vacuum distillation of crude oil. According to data from the National Bureau of Statistics, China's petroleum asphalt output in 2020 was more than 60 million tons; however, the domestic output does not meet the domestic demand and China imported nearly five million tons of petroleum asphalt in 2020.

Asphalt pavement is being increasingly used with the rapid development of the national economy because of its many advantages. China's total highway mileage was

5.2 million km at the end of 2021, which included 161,000 km of expressways. Due to load magnitude and load repetition associated with temperature and environmental factors, such as ultraviolet radiation, oxygen and moisture, the asphalt in pavement structures ages slowly and continuously. Its light components, such as saturated and aromatic components, are gradually converted into heavy components, such as resins and asphaltenes, resulting in increasing hardening and brittleness and reduced bonding performance. This makes asphalt pavement prone to rutting, surface aggregate loss, potholes, cracks and other problems, which, in turn, reduce poor driving comfort, safety and road usability. Hence, it is necessary to repair or re-pave degraded asphalt pavement to reduce these impacts. A huge amount of reclaimed asphalt pavement is generated during the maintenance of old asphalt pavement. This contains a large amount of aged asphalt that contains toxic and harmful substances, such as anthracene, naphthalene and pyridine, which can cause serious pollution to soil and water. Moreover, discarding RAP wastes valuable non-renewable resources, such as asphalt and mineral materials. Therefore, asphalt pavement recycling technology (APRT) that can realize the reuse of RAP has attracted increasing research attention [1–3].

APRT refers to the process of excavating, recycling, crushing, and screening old asphalt pavement, and then mixing it with new asphalt, new aggregate (when necessary), and recycling agents (when necessary). There is a complete set of processes for mixing the appropriate proportions of new asphalt mixture and re-paving and forming new pavement layers according to certain performance requirements. APRT not only recycles RAP resources but also reduces the consumption of non-renewable resources, such as asphalt, avoids land use and environmental pollution caused by RAP stacking, and can greatly reduce engineering costs [4–6]. Wang et al. used the PaLATE method (Pavement Life-cycle Assessment Tool for Environmental and Economic Effects) to estimate the energy consumption and carbon dioxide emissions of the RAP-added mixture and the new HMA (Hot Mixture Asphalt) and evaluated the environmental benefits of using RAP. The results showed that producing a mixture containing 30% RAP required only 84% of the energy and produces 80% of carbon dioxide emissions compared to using 100% primary aggregates [7].

The plant-mixed cold recycling technology using emulsified asphalt with a high proportion of RAP (EAPM-HP_{RAP}) is a kind of APRT in which a series of construction operations, such as mixing, paving and rolling, can be carried out under normal temperature conditions. Therefore, in addition to the advantages of APRT described above, it can also reduce energy consumption and pollutant emissions, and protect the health of construction workers [8–10].

This study investigated the feasibility of using EAPM-HP_{RAP} in order to improve RAP recycling efficiency. The determination of the optimal proportions of EAPM-HP_{RAP} was first carried out in the laboratory. Then, the EAPM-HP_{RAP} and large stone porous asphalt mixture (LSPM) were used as an upper pavement base to pave two test sections and conduct performance tests. The results show that the high-temperature stability, water-damage resistance and pavement strength can meet the required specifications when the EAPM-HP_{RAP} is used as a base. Finally, the economic and environmental benefits of RAP-reuse technology were estimated based on the two test sections [11].

2. Materials and Methods

2.1. Reclaimed Asphalt Pavement

The characteristics of RAP have very important impacts on the performance of the final mixture [12,13]. In this study, RAP was collected from materials milled during an overhaul of the Beijing-Taipei Expressway between Bengbu to Hefei. The RAP was sieved according to standard JTG E42 (Test Methods of Aggregate for Highway Engineering) [14] in order to understand the particle size distribution (gradation). The results are listed in Table 1.

Table 1. Particle size distribution of the studied RAP.

Screen Size (mm)	26.5	19	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
Passing rate (%)	100	97.4	80	52.2	29	18.7	11	6.3	4.1	2.6

The parameters of the RAP were tested in accordance with the requirements of *Test Methods of Aggregate for Highway Engineering* and the results are listed in Table 2.

Table 2. Aggregate properties of the studied RAP.

Aggregate Type	Parameter (%)	Result	Standard
Coarse aggregate	Asphalt content	3.8	T 0722-1993
	Needle-like content	6.6	T 0312-2005
	Crushed stone value	16.2	T 0316-2005
Fine aggregate	Asphalt content	4.9	T 0722-1993
	Needle-like content	7.6	T 0722-1993
	Angularity	33.5	T 0345-2005
	Sand equivalent	69.3	T 0334-2D05

2.2. Recycling Asphalt from the RAP

The recycled asphalt was extracted from the RAP using tetrachloroethylene solvent. The penetration of the recycled asphalt was 22 and the ductility was only 36.2 cm, which indicates that the asphalt was seriously aged after more than ten years of use. Despite this, it still had a significant impact on the diffusion process of the newly added asphalt binder [15].

2.3. Mineral Aggregate

In this study, limestone with a particle size of 10–20 mm from Zhangdian Hutian, Jinan, was used as fresh aggregate and limestone mineral powder produced in Pingyin, Jinan, as ore powder. The density, hydrophilicity coefficient (H–C) and methylene blue value (MBV) of the mineral powder were tested (Table 3).

Table 3. Properties of the mineral powder.

Parameter	Result	Standard
Density (g.cm^{-3})	2.673	T 0352-2000
H-C	0.671	T 0353-2000
MBV (g/kg)	1.00	T 0349-2005

2.4. Cement

Cement not only improves the early strength of EAPM but also promotes the demulsification of emulsified asphalt and enhances the post-demulsification interfacial bonding performance between asphalt and fresh aggregate, thereby improving the high-temperature stability of EAPM [16]. Ordinary Portland cement (PO. 32.5; Shanshui Brand, Sunnsy Group, Jinan, China) was used in this study. Its properties are shown in Table 4.

2.5. Emulsified Asphalt

The emulsified asphalt (EA) used for the APRT was produced by a colloid mill in the laboratory. Its properties are shown in Table 5.

Table 4. Properties of the Portland cement used in the EAPM.

Parameter	Requirement	Result
Fineness (80 μm, %)	≤10	0.7
Standard consistency water consumption (%)	≤28	28
Initial setting time (min)	≥90	167
Final setting time (min)	≤600	223
Specific surface area (m^2/kg)	300–450	328
3-day flexural strength (MPa)	>2.5	3.0
3-day flexural strength (MPa)	>5.5	6.4
3-day compressive strength (MPa)	>11.0	15.5
28-day compressive strength (MPa)	>32.5	34.3

Table 5. Properties of emulsified asphalt.

Parameter		Unit	Requirement	Result	Experimental Method
Demulsification speed		—	Slow or moderate	Slow crack	T 0658
Charge of the particle		—	Cationic (+)	Cationic (+)	T 0653
Engla viscosity E25		—	2–30	4	T 0622
Adhesion to coarse aggregates		—	≥2/3	Qualified	T 0654
Adhesion to fine aggregates		—	Mix well	Mix well	T 0659
Residue content by evaporation		%	≥55	62	T 0651
Sieve residue (1.18 mm)		%	≤0.1	0	T 0652
Residual asphalt	Penetration (25 °C)	0.1 mm	45–150	62	T 0604
	Ductility (15 °C)	cm	≥40	88.2	T 0605
Storage stability	1 d, 25 °C	%	≤1	0.8	T 0655
	5 d, 25 °C	%	≤5	3	T 0655

3. Results and Discussion

3.1. Proportioning Design

To determine the optimal material ratio for achieving the best pavement performance, a proportioning design was carried out in the laboratory [17,18].

3.1.1. Experimental Gradation

Based on the sieving results of RAP and mineral aggregates, and referring to the requirements of JTG F41 (*Technical Specification for Highway Asphalt Pavement Recycling*) [19] for EAPM with a medium granular-gradation range, the mixture ratio was determined to be RAP: 10–20 mm limestone: mineral powder: cement = 80:16:2:2. The experimental gradation data and corresponding curve are shown in Table 6 and Figure 1.

Table 6. Data of the experimental gradation.

Screen Size (mm)	0.075	0.15	0.3	0.6	1.18	2.36	4.75	9.5	13.2	16	19	26.5
Upper limit of grading	8	14.5	21	30.6	41.2	50	65	80	86.6	93.2	100	100
Lower limit of grading	2	2.5	3	8.6	14.2	20	35	60	70	80	90	100
Experimental gradation	3	4	6	9	15	27	50	74	85	92	97	100

3.1.2. Mixing Proportion

Referring to the conventional dosages used in actual pavement works, the amount of EA selected was 4.0%, while external water dosages of 1.5%, 2.0%, 2.5%, 3.0% and 3.5% were trialled. Specimen mixtures were prepared using the experimental gradation determined above. Then, compaction tests were performed on samples and their maximum dry density was tested in accordance with JTG E40 (*Test Methods of Soils for Highway Engineering*) [20]. Figure 2 shows the relationship between the maximum dry density and amount of external water.

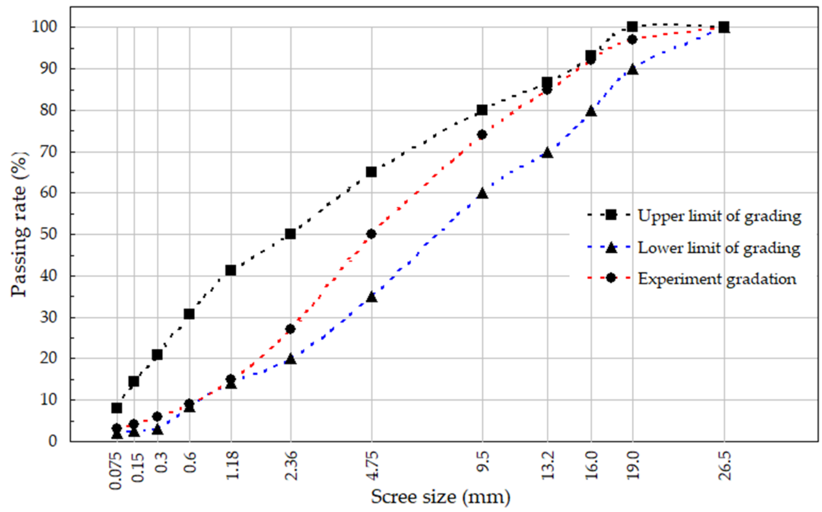

Figure 1. Grade curve of the experimental gradation.

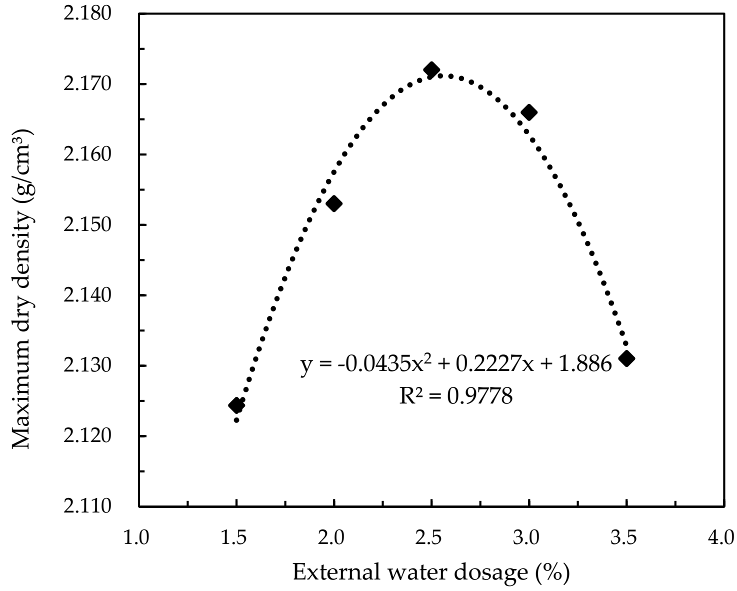

Figure 2. Influence of external water dosage on the maximum dry density of specimens.

The maximum dry density first increased and then decreased with increases in the amount of external water, reaching a peak of 2.172 g/cm^3 at an external water content of 2.5%, representing an increase of 2.2 percentage points compared to the lowest value. Therefore, the optimal external water content was determined to be 2.5% and the optimum total liquid content was 6.5%. At a total liquid content of 6.5% and cement content of 2.0%, specimen mixtures were prepared at EA contents of 3.0%, 3.5%, 4.0%, 4.5% and 5.0%. Then, relative performance tests were carried out, including bulk specific density, Marshall stability and residual Marshall stability (Table 7).

Figure 3 is based on the data in Table 7.

It can be seen that both the Marshall stability and residual Marshall stability peaked at an EA content of 4.0%. Hence, according to the analysis, the optimal content of EA was 4.0% and the optimal external water dosage was 2.5%.

Table 7. Volume Index and Marshall Stability of Specimens.

EA Content (%)	External Water Dosage (%)	Bulk Specific Density	Theoretical Maximum Relative Gravity	Void Ratio (%)	Marshall Stability (kN)	Residual Marshall Stability (kN)
3.0	3.5	2.255	2.512	9.8	12.7	14.1
3.5	3.0	2.258	2.521	10.1	14.5	17.1
4.0	2.5	2.266	2.559	10.6	14.9	18.3
4.5	2.0	2.263	2.507	9.6	14.1	17.5
5.0	1.5	2.261	2.496	9.3	12.5	13.8

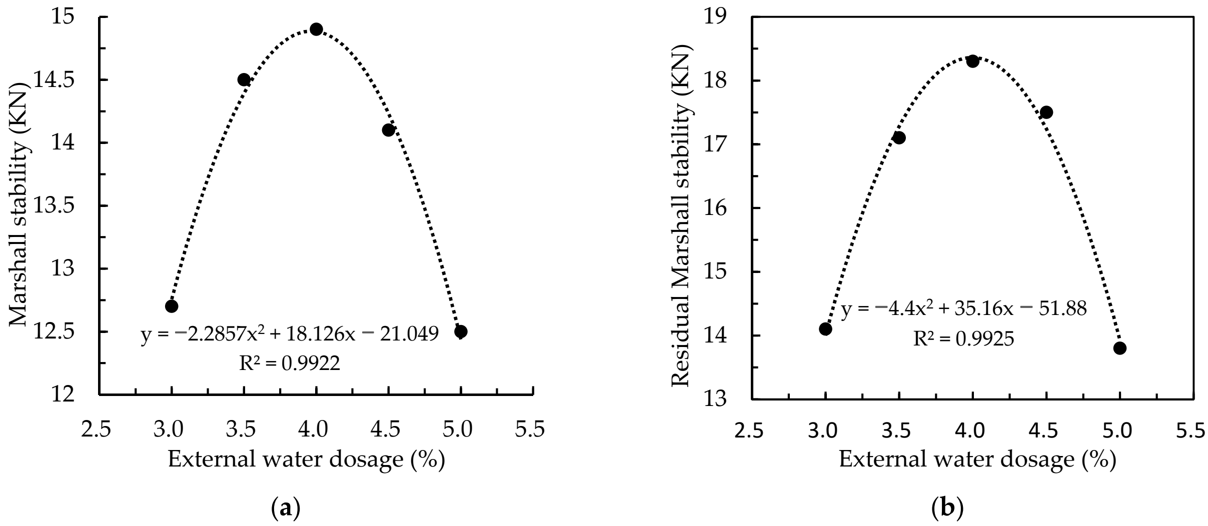

Figure 3. Relationships between external water dosage and the Marshall stability (**a**) and residual Marshall stability (**b**).

3.1.3. High-Temperature Stability

An asphalt mixture is a typical viscoelastic material that is prone to flow deformation under high-temperature conditions [21]. Therefore, the repeated loading of road vehicles, especially heavy-duty overloaded vehicles, can lead to irreversible deformation of the road surface, typically rutting damage [22]. In this paper, the dynamic stability at 60 °C was used as an index to evaluate the high-temperature stability of EAPM. *Dynamic stability* refers to the number of standard axle loads a mixture is subjected to for each 1 mm deformation under high-temperature conditions (generally selected as 60 °C). Rutting specimens (dimensions = 300 × 300 × 80 mm) were prepared in the laboratory by the wheel rolling method according to the experimental gradation and mixing proportion determined above. Rutting tests were carried out in accordance with the requirements of JTG E20 (Standard Test Methods of Bitumen and Bituminous Mixture for Highway Engineering) [23]. The test temperature was 60 °C and the wheel pressure was 0.7 MPa.

Studies have shown that rutting generally occurs on days when the average maximum temperature on the road surface is above 28 °C for seven consecutive days. The test results show that the dynamic stability of the emulsified asphalt mixed with 80% of RAP and made by the cold regeneration technique was 2320 times/mm, which meets the requirements of JTG F41 (*Technical Specification for Highway Asphalt Pavement Recycling*) and shows that the anti-rutting performance is fully qualified.

3.1.4. Water Damage Resistance

Freeze-thaw splitting tests were conducted to measure the effect of freeze-thaw cycling on the asphalt mixtures under specified conditions. The splitting strength ratios of the specimens before and after water damage were determined to evaluate the water damage resistance of the asphalt mixtures. The specimens were divided into two groups for the tests. The first set of samples was used to measure the splitting tensile strength R_{T1} without freeze-thaw cycling, and the second set was used to determine the splitting strength R_{T2} with freeze-thaw cycling. The freeze-thaw cycling was carried out in accordance with the requirements of standard JTG E20 (*Standard Test Methods of Bitumen and Bituminous Mixture for Highway Engineering*). The *TSR* (Tensile strength ratio) can be calculated by Equation (1):

$$TSR = \frac{R_{T2}}{R_{T1}} \times 100 \tag{1}$$

where R_{T1} and R_{T2} are the splitting strengths (MPa) of specimens without and with freeze-thaw treatment, respectively, and TSR is the ratio of R_{T2} to R_{T1} (%).

The test results show that the splitting strength of the specimen without freeze-thaw was 1.17 MPa, while that after freeze-thaw was 0.99 MPa. The TSR was 84.6%, which meets the requirements of standard JTG F41 (*Technical Specification for Highway Asphalt Pavement Recycling*).

3.2. Proportioning Verification

On the basis of the proportioning design, two test sections (from K69 to K69 + 500 and from K69 + 500 to K69 + 900) were paved in combination with a reconstruction project in the Bengbu to Hefei section of the Beijing-Taipei Expressway. Firstly, a 16 cm asphalt surface layer and an 18 cm upper base layer of the old road were milled off. Then, a cold regeneration technique was used to make two emulsified asphalt mixtures mixed with high proportions of RAP (EAPM-HP_{RAP}) or LSPM. The mixtures were used as the upper base layers of the two test sections, upon which the original asphalt surface structure was re-paved. Figure 4 shows the pavement structures of the two test sections.

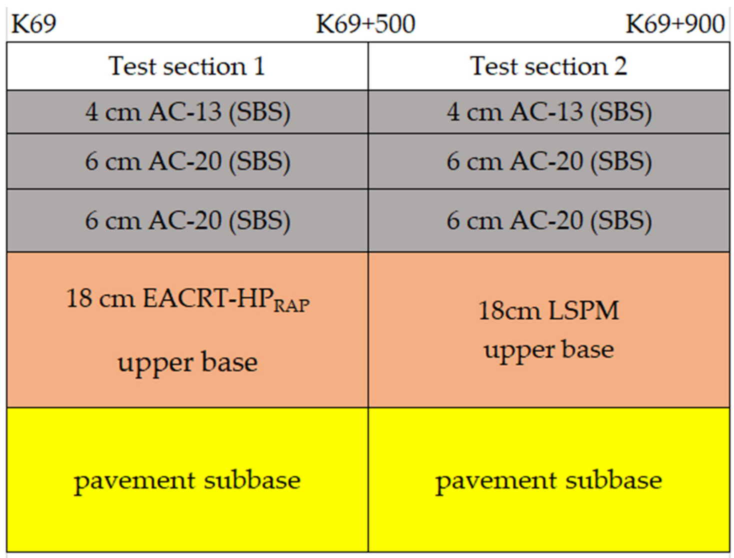

Figure 4. Schematic diagram of the pavement structures of the two test sections.

3.2.1. Compressive Strength

Preliminary specimens of the upper base layer were obtained by a core drilling machine at the four sampling points of K69 + 100 (overtaking lane), K69 + 100 (carriage lane), K69 + 200 (overtaking lane) and K69 + 200 (carriage lane) after the construction of the upper base layer was completed. Both ends of the drilled core samples were cut off to obtain a cylindrical specimen with a size of $\varphi 100 \times 100$ mm. Compression tests were carried out according to the requirements of standard JTG E20 (*Standard Test Methods of Bitumen* *and Bituminous Mixture for Highway Engineering*). The test temperature was 20 °C and the loading rate was 2 mm/min. The compressive strength is calculated by Equation (2):

$$R_c = \frac{4P}{\pi d^2} \tag{2}$$

where R_c is the compressive strength of the specimen (MPa), P is the load (N) at which the specimen fails, and d is the specimen diameter (mm). The results are shown in Table 8.

Table 8. Compressive strength of the test section.

Road Location	Maximum Load (kN)	Compressive Strength (MPa)
K 69 + 100 (overtaking lane)	26.41	3.36
K 69 + 100 (carriage way)	32.21	4.09
K 69 + 200 (overtaking lane)	29.12	3.70
K 69 + 200 (carriage way)	26.14	3.32
Average value	28.49	3.62

The results show that the compressive strength meets the specifications, which shows that it is feasible to use emulsified asphalt cold recycling technology with 80% RAP as the upper base layer in the expressway renovation project.

3.2.2. Deflection Value

The deflection values of the two sections were tested after the construction of the upper base layers was completed (Figure 5).

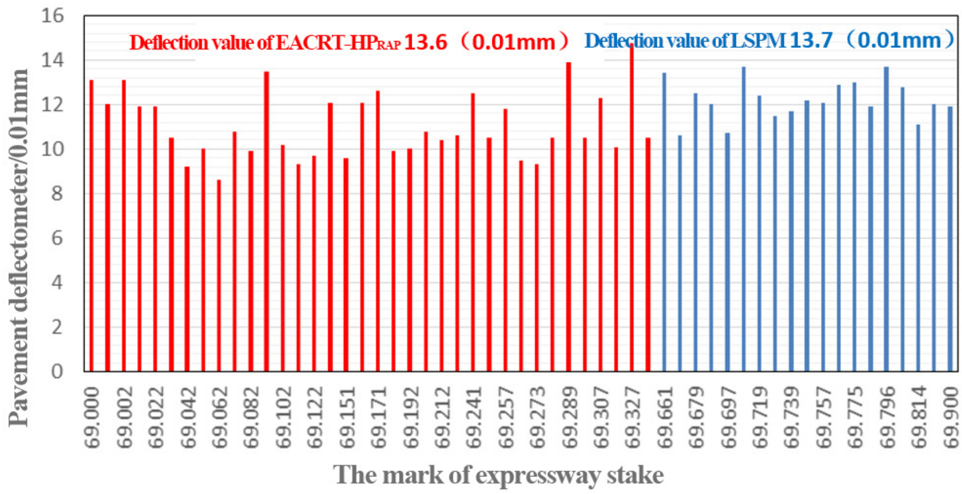

Figure 5. Comparison of the deflection values of the two test sections.

It can be seen that the deflection values of the sections with EAPM-HP$_{RAP}$ and LSPM base layers were low and similar, which indicates that the layers had the same rigidity. Hence, it is feasible to use emulsified asphalt cold recycling technology with 80% RAP as the upper base layer in the expressway renovation project.

The results show that when the EAPM-HP$_{RAP}$ was used as the upper base layer in the expressway renovation project, its high-temperature stability, water damage resistance and pavement strength met the requirements of the relevant specifications.

3.3. Benefits Analysis

Emulsified asphalt cold regeneration technology can be used in multiple construction operations, such as the mixing, paving and rolling of mixtures under normal temperature conditions, without the need to heat the aggregates and asphalt, as is required with traditional pavement construction technology. This not only reduces the amount of construction equipment needed but also greatly reduces the costs of manpower and material resources. More importantly, it can reduce energy consumption and the emissions of pollutants, such as soot, SO_2 and CO_2 [11,24,25].

3.3.1. Resource Savings

The reconstruction project was used as a case study to estimate the economic benefits of the approach. The project had a total length of 105 km and a roadbed width of 27.5 m. According to the experimental gradation and the mixing proportion, we know that the thickness of the EAPM-HP$_{RAP}$ upper base layer was 18 cm, and 80% RAP was used in the gradation during construction, which had a density of 2.2 g/cm^3 (2.2 t/m^3).

According to the above data, it can be inferred that Mz (total mass of mixture required for each 1 km of pavement base) is 27.5 × 1.0 × 0.18 × 2.2 × 1000 = 10,890 t, while the M_R (total mass of RAP reused) is 10,890 × 80% = 8712 t. Hence, using an EAPM-HP$_{RAP}$ upper base layer can save 8712 tons of mineral aggregate per km of road. According to a rough calculation, at an aggregate price of CNY 120–150 /ton, the cost saving is CNY 1.05–1.31 million of aggregate per km; such that the whole road section (105 km) would save CNY 110–138 million.

Moreover, the reuse of RAP reduces the need to mine new ore, avoids the occupation of land by RAP accumulation, and removes the pollution risks to soil and water caused by toxic and harmful substances, such as anthracene, naphthalene, and pyridine, leaching from aged asphalt [26,27].

3.3.2. Energy Savings

As RAP does not need to be heated to mix EAPM-HP$_{RAP}$, an equivalent LSPM mixture will consume more energy for aggregate and asphalt heating and to evaporate the water in the aggregates. The reconstruction project used mobile plant-mixed cold regeneration equipment (German Wirtgen KMA220). The mechanical energy consumption during the mixing process was not considered. Only the energy consumed by heating the mixture was calculated and analysed because both construction schemes require mixing of the mixture. Therefore, the energy consumption per ton of LSPM is the energy that can be saved per ton of EAPM-HP$_{RAP}$. The densities of the EAPM-HP$_{RAP}$ and LSPM were both calculated as 2.2 g/cm^3 (2.2 t/m^3).

According to the test section construction data, the oil-to-stone ratio of LSPM was 4.3% and the moisture content of the aggregate was 0.5%. The aggregate was heated from 25 °C to 160 °C and the asphalt was heated from 25 °C to 175 °C. An asphalt mixing plant was used during construction (Marini 4000 MAC320) and its fuel utilization efficiency and heat exchange efficiency were calculated as 95% and 80%, respectively.

Combining the above construction parameters and taking the production of 1 ton of LSPM as the benchmark, the energy consumption was estimated (Table 9).

Table 9. Energy consumption used to heat 1 ton of LSPM.

Parameters	Specific Heat (J/kg·K)	Mass (kg)	Initial Temperature (°C)	Discharge Temperature (°C)	Energy Required (MJ)	Standard Coal Equivalent (kg)
Dry aggregate	920	953.98	25	160	118.484	4.05
Water	2260 kJ/kg	4.79	25	100	10.825	0.37
Asphalt	1340	41.23	25	175	8.287	0.28
Total	—	1000	—	—	137.596	4.70

Note: 6.19 kg of standard coal is needed to produce 1 ton of LSPM after conversion according to the fuel utilization rate and the heat exchange efficiency of the mixing process.

According to the calculations in the previous section, the total mass of mixture required for each 1 km of pavement base is 10,890 tons. The heating energy consumption of LSPM per km is 67.41 tons of standard coal. According to the market prices of other energy sources and their equivalence to standard coal, the energy and cost savings per km of EAPM-HP$_{RAP}$ were obtained (Table 10).

Table 10. Energy consumed per km of LSPM pavement.

Energy Source	Calorific Value (MJ/kg; MJ/m^3)	Standard Coal Equivalent (kgce/kg)	Energy Saving (t)	Price (CNY/t)	Cost Saving (Thousands of CNY)
Standard coal	29.30	1.000	67.41	—	—
Diesel	42.65	1.457	46.27	8946	414
Petroleum	43.07	1.471	45.83	10,247	470
Electric	3600 kJ/(kWh)	0.123	5.48×10^5 KWh	0.7715	423

Note: The electricity price is the average of the peak and segment prices for single-system industrial and commercial electricity (≤1 kV).

From the perspective of reducing energy consumption alone, and ignoring the additional resource savings, some CNY 414,000–470,000 of energy cost can be saved per km of EAPM-HP$_{RAP}$ pavement. The whole reconstruction project (105 km) would save nearly CNY 50 million in energy costs. A comprehensive calculation of the saved ore and energy costs shows that the use of EAPM-HP$_{RAP}$ as the upper base layer saves CNY 1.5–1.8 million per km and CNY 158–189 million for the whole project (105 km). Hence, the use of EAPM-HP$_{RAP}$ can generate considerable economic benefits while also reusing RAP resources.

3.3.3. Emissions Reduction

With the intensification of the global greenhouse effect, carbon emissions have attracted increasing attention from the international community and domestic experts, scholars and governments. On 31 December 2020, the Ministry of Ecology and Environment announced the "Measures for the Administration of Carbon Emissions Trading (Trial)", which came into force on 1 February 2021.

It is reported that the combustion of 1 ton of standard coal will emit 260 kg of ash, 15 kg of soot, 2.62 tons of CO_2, 8.5 kg of SO_2 and 7.4 kg of nitrogen oxides into the atmosphere. The pollutant emissions reduction achieved by using EAPM-HP$_{RAP}$ as an upper base layer instead of conventional asphalt was calculated based on the data from the previous section. The results are shown in Table 11.

Table 11. Emission reductions achieved by using EAPM-HP$_{RAP}$ instead of regular asphalt as an upper base layer.

Emissions	CO_2 (t)	SO_2 (t)	NO_X (t)	Ash (t)	Soot (t)
1 ton of standard coal	2.62	0.0085	0.0074	0.26	0.015
1 km of EAPM-HP$_{RAP}$	176.6	0.6	0.5	17.6	1.0
Whole road section	18,543.0	60.2	52.5	1848.0	105.0

Paving 1 km of road with EAPM-HP$_{RAP}$ as the upper base layer could reduce CO_2 emissions by 176.6 tons, SO_2 emissions by 0.6 tons, NO_X emissions by 0.5 tons, ash emissions by 17.6 tons and soot emissions by 1.0 tons. Using it in the whole road section could reduce CO_2 emissions by 18,543 tons, SO_2 emissions by 60.2 tons, NO_X emissions by 52.5 tons, ash emissions by 1848 tons, and soot emissions by nearly 105 tons.

It is certain that the application and promotion of EAPM-HP$_{RAP}$ will play a very positive role in achieving carbon reduction goals under the new development philosophy. The national carbon emission rights trading market was launched on 16 July 2021, and the closing price of carbon emission allowances (CEA) was CNY 60 per ton on 22 April 2022. The power generation industry became the first industry to be included and it is foreseeable that, with the promotion, implementation and improvement of the carbon emission trading system across the country, industries such as petrochemicals and transportation will also be included in the trading market. The advantages of emissions reduction will generate considerable economic benefits with the implementation of the carbon emissions trading system.

4. Conclusions

1. Using the cold regeneration technique with emulsified asphalt mixed with a high proportion of RAP is a feasible way to pave the upper base layer of expressway renovation projects. With an experimentally optimized gradation and mixing proportion, its high-temperature stability, water damage resistance and pavement strength can meet the requirements of relevant specifications.
2. The EAPM-HP_{RAP} mixture reduces the need to mine new ore resources and allocate land for RAP storage. It also mitigates the soil and water pollution risks caused by the aged asphalt contained in RAP.
3. Compared with conventional pavement technology, EAPM-HP_{RAP} generates considerable economic benefits while reusing RAP resources. This study indicates that engineering costs of CNY 1.5–1.8 million per km of pavement can be saved, while the whole expressway renovation project (105 km) could save CNY 158–189 million by using EAPM-HP_{RAP} as the upper base layer.
4. The reuse of RAP can save energy equivalent to 67.41 tons of standard coal per km when used as the upper base layer in an expressway renovation project. Further calculations show that every km of pavement (at a roadbed width of 27.5 m) could reduce CO_2 emissions by 176.6 tons, SO_2 emissions by 0.6 tons, NO_X emissions by 0.5 tons, ash emissions by 17.6 tons and soot emissions by 1.0 tons. Using it for the whole road section could reduce CO_2 emissions by 18,543 tons, SO_2 emissions by 60.2 tons, NO_X emissions by 52.5 tons, ash emissions by 1848 tons, and soot emissions by nearly 105 tons. These energy and emissions savings are very significant, indicating that the proposed approach warrants further development.

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