

Design of Mix Proportions and Evaluation of Road Performance for High-RAP Hot-Mix Asphalt Recycled with Central Plant

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Keywords: Central Plant Hot Recycling; High-RAP Content; Rejuvenator; Mix Proportion Design; Road Performance; Asphalt Mixture

Abstract: To achieve efficient resource utilization of reclaimed asphalt pavement (RAP), this study aims at a 60% RAP content and employs a self-developed composite rejuvenator for waste oil to investigate the mix proportion design and road performance of AC-13 hot-mix recycled asphalt mixture. The optimal rejuvenator dosage was determined as 12% by weight of recovered old asphalt based on asphalt aging recovery tests. Using the Marshall design method, the optimal new asphalt content was identified as 1.87%, corresponding to an asphalt-to-aggregate ratio of 5.11%. Comprehensive evaluations were conducted on high-temperature stability, moisture stability, low-temperature cracking resistance, and Marshall mechanical properties. Results indicate that the dynamic stability reaches 4,866 cycles/mm, the residual Marshall stability after immersion is 99.2%, the freeze-thaw splitting strength ratio is 107.1%, the low-temperature bending strain at -10 °C is 2,131.5 $\mu\epsilon$, and the Marshall stability is 15.58 kN. All indicators meet specification requirements, demonstrating excellent high-temperature performance, outstanding moisture resistance, adequate low-temperature resistance, and sufficient mechanical strength. This research confirms the technical feasibility of recycling asphalt mixtures with 60% RAP content, providing reliable support for large-scale RAP utilization and green, low-carbon road development.

1. Introduction

As of 2024, China's total highway mileage has exceeded 5.5 million kilometers, with over 90% of the road surface being asphalt pavement, marking a comprehensive transition into a phase where construction and maintenance are equally emphasized [1]. The annual volume of reclaimed asphalt pavement (RAP) generated from maintenance, repair, and expansion projects exceeds 300 million tons. Without efficient recycling, this material not only consumes valuable land resources but also causes severe environmental pollution and resource waste. Due to its mature technology, convenient quality control, and reliable pavement performance, plant-mixed hot recycling has become the mainstream method for large-scale RAP reuse[2]. However, traditional plant-mixed hot recycling typically limits RAP content to below 30% to ensure compaction effectiveness and final

performance, thereby restricting further improvements in resource utilization efficiency. When RAP content increases to 60%, the proportion of aged asphalt in the mixture significantly rises, leading to a sharp decline in penetration, an increase in softening point, and a dramatic reduction in ductility. This results in varying degrees of deterioration in low-temperature crack resistance and fatigue performance of recycled mixtures, forming a key technical barrier to high-RAP applications. Restoring aged asphalt properties through appropriate rejuvenators, combined with scientific mix design, is thus critical to achieving high-RAP recycling[3]. This study focuses on 60%-RAP plant-mixed hot-recycled asphalt mixtures, systematically conducting mix design and pavement performance evaluation, aiming to provide theoretical foundations and technical support for large-scale engineering applications of high-RAP recycling technologies, which holds significant practical implications for promoting green and low-carbon development in the road industry.

Extensive research has been conducted by scholars worldwide on plant-mixed hot recycling technology. Regarding RAP content limits, conventional studies generally agree that mix performance remains controllable at RAP contents below 30%. However, recent research has gradually expanded toward higher RAP levels, with preliminary validation showing feasibility even at 60% or above[4]. On the mechanism of rejuvenator action, it is widely accepted that light fractions in rejuvenators effectively replenish the lost aromatic and saturated components in aged asphalt, reducing the relative concentration of asphaltenes and restoring the colloidal system from "gel-like" to "sol-like," thereby recovering penetration and ductility. In terms of pavement performance evaluation, high-temperature stability and Marshall mechanical properties often perform well—sometimes even better than those of virgin mixtures—under high-RAP conditions; however, low-temperature crack resistance and moisture stability tend to deteriorate with increasing RAP content, becoming focal points of ongoing research and debate[5]. Most existing studies focus on specific projects or single performance indicators, lacking systematic and in-depth analysis on the synergistic control mechanisms between rejuvenator dosage and RAP content, the unique gradation design requirements under high-RAP conditions, and the balanced optimization of multiple performance indicators.

Current research still faces several limitations: the determination of optimal rejuvenator dosage often relies solely on restoring three key indicators within specification ranges, without fully considering the higher demand for low-temperature flexibility associated with high-RAP mixtures; gradation design frequently follows conventional asphalt mixture methods, lacking targeted analysis of the relationships among RAP grading, synthetic gradation, and skeleton interlocking structure; pavement performance evaluation is mostly limited to single-indicator verification, lacking comprehensive assessment integrating high-temperature stability, moisture resistance, low-temperature behavior, and mechanical properties. This study targets a 60% RAP content, employing a self-developed composite rejuvenator derived from waste oil, to conduct mix design for AC-13 recycled asphalt mixtures. Through rutting tests, immersed Marshall tests, freeze-thaw splitting tests, low-temperature beam bending tests, and Marshall tests, the pavement performance is systematically evaluated, and the engineering applicability of high-RAP recycled mixtures under different climatic zones and traffic loading conditions is explored.

2. Raw Material Properties and Regeneration Mechanism

2.1 Characterization and Variability Analysis of RAP Material

The RAP material used in this study was sourced from milled urban road pavement. After removing impurities, crushing, and screening, it was divided into two size fractions: 0–8 mm and 8–15 mm, which were stored separately to minimize segregation between coarse and fine particles that could affect the accuracy of mix design. The asphalt content of the two fractions was determined by

combustion method at 5.94% and 4.88%, respectively. Asphalt content increased with decreasing particle size, consistent with the trend that finer particles have larger surface area and higher asphalt coating. Aged asphalt was recovered through extraction, exhibiting a penetration of 33.1 (0.1 mm) at 25 °C, a ductility of 7.8 cm at 10 °C, and a softening point of 62.9 °C. Compared to the baseline 70-grade binder asphalt (penetration: 65.8 (0.1 mm), ductility: 36.6 cm, softening point: 49.1 °C), the aged asphalt showed approximately 50% lower penetration, nearly 80% reduced ductility, and over 13 °C higher softening point—typical characteristics of thermal-oxidative aging and hardening—making it no longer compliant with the basic requirements for 70-grade asphalt as specified in current standards. Gradation analysis indicated that the original mixture type was AC-13, and the combined gradation curve closely matched the standard median, providing an accurate gradation basis for subsequent regeneration design. Variability in RAP material mainly arises from fluctuations in milling depth, differences in original pavement materials, and inconsistencies in crushing and screening processes[6]. This study controlled these effects through separate storage of graded fractions and repeated parallel extraction tests, ensuring that the dispersion of asphalt content and gradation parameters remained within acceptable limits.

2.2 Evaluation of New Asphalt and Aggregate Properties

The new asphalt used in this study is grade 70 A-level road petroleum asphalt. Its indicators such as penetration, softening point, and elongation all meet the requirements of JTG F40—2004 specification, and can meet the performance requirements for high-grade road construction. The new aggregates are limestone crushed stones (10-15mm, 5-10mm), manufactured sand, and mineral powder. The limestone is hard and evenly distributed, and its main indicators such as crushing value, abrasion value, and adhesion all meet the specification requirements, providing a stable framework structure and filling effect for the mixture. The mineral powder is obtained by grinding the same type of limestone, with fine particle size that conforms to the standard, and does not contain harmful impurities. It can effectively fill the voids in the asphalt mixture and improve the adhesion between asphalt and aggregates. The performance differences between the new aggregates and the old aggregates in RAP materials mainly lie in the surface texture and asphalt coating state. The residual aged asphalt on the surface of the old aggregates reduces the interfacial bonding activity with the new asphalt, which poses potential adverse effects on the interface strength and water stability of the recycled mixture. This characteristic needs to be compensated by the interface strengthening effect of the recycling agent.

2.3 Selection of Recycled Agent Type and Working Principle

The recycled agent used in this study is a self-developed waste oil composite recycled agent, mainly composed of waste engine oil, waste edible oil, furfural extract oil, and C9 petroleum resin. During the long-term service of asphalt, it is subjected to the combined effects of heat, oxygen, light, and vehicle loads, resulting in a chemical composition imbalance, an increase in the proportion of asphaltic matter, and a transformation from "soluble type" to "gel type" in the colloid system. Macroscopically, this is manifested as a decrease in penetration, an increase in softening point, and a reduction in elongation. The asphalt becomes harder and more brittle, and its adhesion and plasticity decrease. The light oil fraction (aromatic fraction and some saturated fraction) in the recycled agent, when mixed with aged asphalt, can effectively replenish the lost oil fraction, reduce the relative concentration of asphaltic matter, and make the chemical composition approach the balanced state of fresh asphalt. The functional components in the recycled agent further enhance the comprehensive performance of aged asphalt: C9 petroleum resin enhances the high-temperature adhesion and rut resistance of asphalt, avoiding the risk of high-temperature flow dispersion after

the addition of light oil fraction; furfural extract oil improves the low-temperature ductility and elastic recovery ability of asphalt, alleviating the problem of brittleness and cracking; the polar components in waste engine oil and waste edible oil strengthen the interface adhesion between asphalt and aggregates, and delay the secondary aging of recycled asphalt. According to the JTG/T5521—2019 specification evaluation, this recycled agent belongs to RA-5 type, with a viscosity of 495.4 mm²/s at 60°C, a flash point of 231°C, and the viscosity ratio and mass change before and after the film oven test are at a relatively low level, having appropriate viscosity and good aging resistance, which can effectively replenish the lost light components in aged asphalt, improve its rheological properties, restore its road performance, and achieve the dual effect of "component repair + performance enhancement".

3. Design of the mix proportion for high-concentration recycled asphalt mixture

3.1 Determination of the optimal dosage of the recycled agent

The dosage of the recycled agent is calculated based on the recycled old asphalt content in the RAP material. Five dosage levels of 6%, 8%, 10%, 12%, and 14% are set, and their respective needle penetration, 10 °C elongation, and softening point are measured after being mixed with recycled aged asphalt. Without adding the recycled agent, the needle penetration of the aged asphalt is only 33.1 (0.1mm), the elongation is 7.8cm, and the softening point is as high as 62.9°C, showing significant hardening characteristics. As the dosage of the recycled agent increases, the needle penetration gradually rises, the softening point gradually decreases, and the elongation significantly improves, which is consistent with the mechanism of the recycled agent replenishing light components and regulating the balance of the colloid system. When the dosage is 10%, the needle penetration returns to 63.7 (0.1mm), the elongation increases to 70.9cm, and the softening point drops to 52.1°C, and the three indicators have entered the range of the 70# asphalt specification. When the dosage is increased to 12%, the needle penetration is 73.4 (0.1mm), the 10 °C elongation exceeds 100cm, the softening point is 50.8°C, and the elongation increases by more than 40% compared to the 10% dosage. The low-temperature ductility improvement is particularly significant. When the dosage continues to increase to 14%, the needle penetration rises to 82.6 (0.1mm), the 10°C elongation exceeds 100cm, and the softening point is 48.9°C. The indicators have exceeded the reasonable range of the 70# asphalt, and excessive introduction of light components may lead to a decrease in high-temperature bonding performance and a weakening of anti-deformation ability. Considering that the target RAP dosage is as high as 60%, and the proportion of recycled aged asphalt in the mixture is large, higher requirements are imposed on the low-temperature ductility of the binder. At a dosage of 12%, it is significantly better than the low-temperature performance of 10% dosage while ensuring the high-temperature performance is within the reasonable range. Therefore, the optimal dosage of the recycled agent is determined to be 12% of the recycled old asphalt content.

3.2 Aggregate Gradation Design and Optimization

The gradation type designed in this study is AC-13. According to the JTG/T5521—2019 specification, the synthetic gradation calculation is conducted based on the screening results of each grade of RAP and new aggregates. The RAP grades are 0-8mm and 8-15mm, and the new aggregates include 10-15mm crushed stones, 5-10mm crushed stones, mechanically graded sand, and mineral powder. The final determined aggregate mix ratio is: 20% 10-15mm crushed stones, 10% 5-10mm crushed stones, 9% mechanically graded sand, 1% mineral powder, 40% 8-15mm old materials, and 20% 0-8mm old materials. The total RAP content is 60%. The synthetic gradation

curve is completely within the median range of the AC-13 specification gradation, with a 93.7% pass rate at 13.2mm sieve, 77.6% at 9.5mm, 51.4% at 4.75mm, 37.9% at 2.36mm, 28.4% at 1.18mm, 20.2% at 0.6mm. The measured gradation is in good agreement with the designed gradation. The particularity of gradation design under high RAP content lies in: the old aggregates in RAP are coated with aged asphalt, and their effective particle size is larger than that of new aggregates. When calculating the synthetic gradation, the contribution of aged asphalt to the sieve passing rate needs to be considered; the fine RAP grade (0-8mm) accounts for 20%, and its higher asphalt content and fine aggregate proportion have a direct impact on the void characteristics and optimal asphalt content of the mixture; the coarse RAP grade (8-15mm) accounts for 40%, and as the skeleton of the mixture, it has a reduced edge angle and surface roughness due to the coating of aged asphalt, which needs to be compensated by the filling effect of new aggregates. The smoothness of the synthetic gradation curve and the conformity with the specification range indicate that this mix ratio ensures the skeleton filling structure while achieving the reasonable filling of coarse and fine aggregates.

3.3 Determination of the Optimal Asphalt Content

Based on the formula in JTG/T5521—2019, the total asphalt content was estimated. It was calculated that the total asphalt content was 5.40%. After deducting the contribution of the old asphalt in RAP, the estimated new asphalt content was 2.26%. Five new asphalt content levels (corresponding to oil-stone ratios of 4.5%, 5%, 5.5%, 6%, and 6.5%) were used to conduct Marshall tests to measure the bulk density, void ratio, void ratio of aggregates, saturation, stability, and flow value of each group of specimens[7]. As the new asphalt content increased, the bulk density showed a trend of increasing first and then decreasing, while the void ratio and void ratio of aggregates first decreased and then increased. The stability reached its peak around an oil-stone ratio of 5.11%. Combining the volume indicators with the mechanical indicators, the optimal oil-stone ratio was determined to be 5.11%, corresponding to the optimal new asphalt content of 1.87%. This new asphalt content was significantly lower than the conventional content of ordinary AC-13 mixture, and the contribution rate of the old asphalt in RAP exceeded 60%. This achieved significant savings in new asphalt materials while ensuring performance. The void ratio was controlled at around 4%, the void ratio of aggregates met the minimum requirements of the specification, the saturation was within a reasonable range, indicating that this mix ratio had good balance in volume characteristics.

3.4 Reliability Test of the Design Mix Ratio Results

The stability of the designed mix ratio was verified through multiple parallel Marshall tests. The coefficient of variation of the bulk density, void ratio, and stability of each group of specimens was at a low level, indicating that the design mix ratio results had good repeatability. The leakage and dispersion tests were conducted on the recycled mixture to test its anti-leakage and anti-dispersal capabilities. The results all met the specification requirements, proving that the mix ratio had reliable guarantees in terms of construction workability and durability. The stacking of RAP materials in different grades and multiple parallel tests effectively controlled the influence of raw material variability on the mix ratio accuracy. The collaborative optimization of the recycled agent dosage and new asphalt content achieved a good balance between the high-temperature, water stability, and low-temperature performance of the mixture, laying a reliable mix ratio foundation for the subsequent systematic evaluation of road performance.

4. Comprehensive Evaluation of the Road Performance of Recycled Asphalt Mixtures

4.1 High Temperature Stability

The high-temperature stability of the recycled mixtures was evaluated using the rutting test. The test temperature was 60 °C, the wheel pressure was 0.7 MPa, and the specimen size was 300mm × 300mm × 50mm. The dynamic stability test result of the high-renewal asphalt mixture was 4866 times/mm, which far exceeded the requirement of not less than 2000 times/mm in the JTG F40—2017 specification. Although this value was lower than the reported values of some low-renewal asphalt mixtures or new materials, it still demonstrated excellent high-temperature rutting resistance under 60% RAP content conditions. The aged asphalt in RAP has a relatively high hardness and rich asphalt content, and its glass transition temperature shifts upward, enabling the binder to maintain a high elastic modulus at high temperatures, effectively enhancing the overall shear deformation resistance of the mixture. The self-developed recycled agent not only restores the low-temperature ductility of the aged asphalt but also enhances the high-temperature bonding force through the C9 petroleum resin component. This avoids the risk of high-temperature flow dispersion that may occur after adding light oil. The new and old asphalt and aggregates formed a stable and dense spatial network structure, enabling the mixture to still have strong resistance to flow deformation under high-temperature conditions. The excellent performance in high-temperature stability confirms the rationality of the design of the "component repair + performance enhancement" dual effect of the recycled agent, and also provides performance guarantee for the engineering application of high-renewal asphalt mixtures in high-temperature areas and heavy-load traffic sections[8].

4.2 Water Stability

The water stability was evaluated through the combined assessment of the water immersion Marshall test and the freeze-thaw splitting test. The residual stability measured by the water immersion Marshall test was 99.2%, which was much higher than the requirement of not less than 85% in the specification, indicating that the mixture had minimal strength loss under water immersion conditions and excellent resistance to water stripping. The TSR measured by the freeze-thaw splitting test was as high as 107.1%, exceeding 100%. The cause of this phenomenon can be attributed to two aspects: the epoxy soybean oil and other active components in the self-developed recycled agent continue to undergo slow cross-linking and curing reactions under the water and heat conditions during the specimen formation and freeze-thaw cycles, enhancing the internal cohesion of the binder; the sufficient integration of the recycled agent and the aged asphalt significantly improved the adhesion between the asphalt and aggregates, resulting in an increase in interface strength after freeze-thaw cycles. The presence of aged asphalt on the surface of RAP partially reduced the fresh activity of the aggregate surface, but the polar components in the recycled agent effectively compensated for the loss of interface adhesion, while the original mineral powder and fine aggregates in RAP filled the mixture voids, reducing the water ingress channels. Although the TSR exceeding 100% is a favorable result, it also indicates that the continuous reaction of the active components of the recycled agent during the freeze-thaw cycles may bring uncertainty to the long-term performance stability, which needs to be verified through multiple freeze-thaw cycle tests in subsequent studies.

4.3 Low-temperature Crack Resistance Performance

The low-temperature crack resistance of the mixture was evaluated through the -10°C small

beam bending test, with the maximum flexural strain being used to characterize its stress relaxation ability and flexibility under low temperatures. The measured failure flexural strain of the specimens was 2131.5 $\mu\epsilon$, which met the requirements of cold-region roads for the low-temperature strain capacity of asphalt mixtures (the specification requires no less than 2000 $\mu\epsilon$). This value was lower than that of the ordinary new material, reflecting the deteriorating effect of the insufficient toughness of aged asphalt under high RAP content on the low-temperature deformation capacity. The 12% RAP content effectively supplemented the lost light components in the aged asphalt, partially restoring its low-temperature ductility and flexibility, enabling the high RAP content mixture to still maintain sufficient stress relaxation capacity at low temperatures and avoiding brittle failure. Compared with the 10% RAP content, the 10°C elongation of the aged asphalt in the 12% RAP content mixture increased from 70.9 cm to over 100 cm, significantly improving the low-temperature performance, verifying the key role of the optimized RAP content in low-temperature crack resistance. The climate zone of the project location requires a minimum low-temperature ultimate flexural strain of 1200 $\mu\epsilon$ for AC-13 type mixtures. The measured value of this recycled mixture has a safety margin of approximately 78%, indicating its good low-temperature adaptability in cold or seasonally frozen areas.

4.4 Marshall Mechanical Properties and Volume Characteristics

The Marshall test measured the stability of AC-13 (RAP 60%) to be 15.58 kN, the flow value to be 35.7 (0.1 mm), and the void ratio to be around 4.0%, all meeting the specification requirements. The stability value was much higher than the specification requirement value and significantly higher than that of conventional asphalt mixtures, confirming its good overall strength and bearing capacity. The high stability was attributed to the hardening effect of aged asphalt in the RAP, the good gradation design, and the effective restoration of the overall performance of the binder system by the recycled agent. The flow value was within a reasonable range, indicating that the mixture retained appropriate deformation coordination ability while maintaining a high bearing capacity. The void ratio was controlled at around 4%, ensuring the durability of the mixture and providing a reasonable working space for compaction. Compared with the ordinary new material, the recycled mixture showed higher stability and slightly lower flow value, with increased rigidity. This is consistent with the brittle increase trend observed in the low-temperature test. The balance between volume characteristics and mechanical indicators indicates that through reasonable mix proportion design and selection of recycled agents, high RAP recycled mixtures can meet or even exceed the mechanical performance requirements of conventional asphalt mixtures.

4.5 Comprehensive Evaluation of Road Performance and Discussion on Engineering Applicability

The high stability in high temperatures, water stability, low-temperature crack resistance, and Marshall mechanical properties were incorporated into a unified evaluation system. The high-replacement-content recycled mixture exhibited a comprehensive performance feature of "excellent in high temperatures, outstanding in water stability, meeting standards in low temperatures, and abundant in mechanical properties". The high-temperature dynamic stability of 4866 times/mm and the water immersion residual stability of 99.2% were at a relatively high level. The low-temperature flexural strain of 2131.5 $\mu\epsilon$ had a safety margin of approximately 78%, and the Marshall stability of 15.58 kN was significantly higher than that of conventional mixtures. No significant performance conflicts were observed among the various indicators, indicating that the collaborative optimization of the recycled agent dosage and the new asphalt usage achieved a balanced performance across multiple objectives. In terms of engineering applicability, this mix

ratio scheme is particularly suitable for high-temperature regions and heavy-traffic sections. Its excellent high-temperature rutting resistance can effectively extend the pavement service life. For cold regions or seasonally frozen areas, although the safety margin of the low-temperature flexural strain meets the specification requirements, it is recommended to further optimize the recycled agent formula in combination with regional climate characteristics to enhance the redundancy of low-temperature crack resistance. When used in rainy areas, the water stability is excellent, and no additional anti-peeling agent dosage is required, but attention should be paid to the potential impact of the long-term reaction of the recycled agent active components on water stability. The large-scale application of high-replacement-content RAP recycled mixtures can significantly absorb milling materials, reduce the consumption of new asphalt and new aggregates, and has significant environmental and economic benefits, providing a reliable technical path for promoting the green and low-carbon development of the road industry.

5. Conclusion

This study aimed to achieve a 60% RAP content and used waste oil as the composite reclamation agent to complete the mix design and performance evaluation of AC-13 type high-concentration plant-mixed hot recycled asphalt mixture. The optimal reclamation agent content was 12% of the recycled old asphalt mass, and the optimal new asphalt usage was 1.87%, corresponding to an asphalt-to-aggregate mass ratio of 5.11%. The road performance tests showed that the dynamic stability reached 4866 times/mm, the water immersion residual stability was 99.2%, the freeze-thaw splitting strength ratio was 107.1%, the -10°C low-temperature flexural strain was 2131.5 $\mu\epsilon$, and the Marshall stability was 15.58 kN. All indicators met the specification requirements, presenting comprehensive performance characteristics of excellent high-temperature performance, outstanding water stability, meeting low-temperature standards, and sufficient mechanical strength. The study confirmed the technical feasibility of 60% high-concentration RAP recycling, providing a reliable basis for the large-scale utilization of milling materials and the green and low-carbon development of roads.

Acknowledgment

This work was sponsored by Fundamental Research Project of the Educational Department of Liaoning Province (LJKMZ20222050). The support is gratefully acknowledged.

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