Research on Recycling and Utilization Technology of Old Asphalt Mixtures from Road Surfaces and Their Performance

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Abstract: To address the issue of recycling and reusing the waste asphalt mixtures (RAP) generated from highway maintenance, a systematic study was conducted on the mix design and performance regulation of hot recycling, cold recycling, and semi-rigid base recycling mixtures. The optimal scheme for hot recycling was 60% RAP content, 12% recycling agent content, and 1.87% new asphalt content, with a dynamic stability of 4866 times/mm and a freeze-thaw splitting strength ratio of 107.1%, and a -10℃ flexural strain of 2131.5 με. For cold recycling, the reasonable scheme was 90% RAP content, 4.3% emulsified asphalt, and 1.5% cement, with a dynamic stability of 2425 times/mm and a freeze-thaw splitting strength ratio of 82%. For semi-rigid base RAP, the reasonable content was 30% to 50%, with a cement content of 4.5% to 5.0%, and the 7-day unconfined compressive strength met the requirement of not less than 3.5 MPa. Fine separation of RAP can reduce the grading variation coefficient to 6.2% and control the false particle content within 10%. Intelligent construction and full-process quality monitoring effectively guarantee the quality of recycled pavement. The engineering application saves material costs by approximately 20%, shortens the construction period by about 30%, and has significant economic and ecological benefits.

Keywords: Waste asphalt mixture; Hot recycling; Cold recycling; Mix design; Road performance; RAP content

1. Introduction

Under the "dual carbon" strategy and the resource conservation orientation, the recycling and reuse of waste asphalt mixtures (RAP) has become a key path for the green and sustainable development of road transportation. Currently, the three mainstream technologies for RAP recycling - hot recycling, cold recycling, and warm-mix recycling - each have their own applicable conditions and performance limitations: hot recycling mixtures have stable quality but suffer from the secondary aging of old asphalt and high energy consumption; cold recycling has a high RAP utilization rate but poor water stability; warm-mix recycling can reduce the mixing temperature but requires higher requirements for mix design. The problems of large performance variation of recycled mixtures, limited RAP dosage, and lagging technical specifications are intertwined, restricting the large-scale application of recycling technology in high-grade roads. Conducting systematic research on the technology and performance of RAP recycling utilization is of great practical significance for breaking through the bottleneck of high RAP dosage application, improving the long-term durability of

recycled road surfaces, and promoting the low-carbon transformation of the road industry.

Domestic and foreign scholars have formed rich research results on RAP recycling technology. In terms of hot recycling, the anti-deformation, anti-fatigue, and water stability of recycled mixtures improve with the increase of RAP dosage within a reasonable range, but the upper limit of thermal efficiency of traditional heating methods and the aggregation phenomenon of "false particles" in RAP restrict the further increase of dosage. In cold recycling, emulsified asphalt and foamed asphalt technologies can achieve a 80% or higher RAP dosage, and normal temperature construction significantly reduces energy consumption, but the RAP dosage and the frost heave splitting strength ratio are negatively correlated, and water stability becomes a bottleneck for application. In semi-rigid base layers, the 7-day unconfined compressive strength of cement-stabilized RAP mixtures decreases with the increase of RAP dosage, and when the dosage exceeds 60%, the cement dosage needs to be increased to meet the strength requirements, and the strength variation coefficient also increases. In performance prediction, regression analysis, neural networks, and grey theory models have been introduced into the evaluation of pavement usage performance, and the PCI regression model, after parameter correction, can better reflect the actual road conditions. In RAP pre-treatment, fine separation technology can effectively eliminate false particles, reduce the coefficient of variation of the grading, and make RAP have physical properties close to new aggregates, creating conditions for high RAP dosage application.

This paper systematically reviews the characteristics of RAP and the principles of recycling technology, conducts research on the mix design and performance regulation of hot recycling, cold recycling, and semi-rigid base layer recycled mixtures, builds an evaluation method for usage efficiency based on performance prediction models, discusses key process control and intelligent quality monitoring technologies for mixing, spreading, and compaction, and combines engineering applications to verify the feasibility and comprehensive benefits of recycling schemes.

2. Characterization of Waste Asphalt Mixtures and Principles

2.1 Classification and Working Principles

The recycling technology of waste asphalt mixtures can be classified into three types based on process temperature and binder type: on-site hot recycling, cold recycling, and warm mixing recycling. On-site hot recycling involves re-heating and re-mixing RAP with new aggregates, new asphalt, and recycling agents in a mixing plant. The RAP content is usually limited to less than 30%, and the bottleneck lies in the efficiency limit of the heating method used in tropical regions - the heat of new aggregates is insufficient to fully heat a high proportion of RAP, resulting in decreased mixing uniformity, and the aging asphalt requires new asphalt to compensate for the bonding performance, further reducing the RAP proportion. Cold recycling uses emulsified asphalt or foamed asphalt as binders and is mixed and paved at room temperature, achieving a RAP content of over 80%. Its principle relies on the adhesive effect of residual asphalt after emulsification and the strengthening effect of cement hydration products, but the fusion of new and old asphalt at room temperature is insufficient, and the interface adhesion strength is low, with water stability being a weakness. Warm mixing recycling reduces the mixing and compaction temperatures with viscosity-reducing additives, reducing the secondary aging of aged asphalt, and the viscosity reduction mechanism involves two types: surfactant type and organic viscosity reduction type. These three technologies have different advantages and disadvantages in RAP content, energy consumption, road performance, and applicable layers. The selection requires comprehensive consideration of climate zones, traffic loads,

and the characteristics of RAP material sources.

2.2 Mechanisms of Recycled Agents and Binders

During the long-term service of asphalt, it is subjected to combined effects of heat, oxygen, light, and loads, resulting in chemical component imbalance, an increase in asphalt content, and a transformation from a sol gel type to a gel type in the colloid system. Macroscopically, this manifests as a decrease in penetration, an increase in softening point, and a decrease in ductility. When light oil components are added to aged asphalt, they replenish the lost oil during the aging process, reducing the relative concentration of asphalt components and bringing the chemical composition closer to the equilibrium state of fresh asphalt. Functional components further enhance comprehensive performance: resin components enhance high-temperature bonding strength and rutting resistance, avoiding the loss of high-temperature flowability after replenishing light oil components; polar components strengthen the adhesion between asphalt and aggregates, delaying secondary aging. The demulsification of emulsified asphalt is affected by the surface charge of aggregates, temperature, and humidity. Cationic emulsified asphalt has better adhesion to limestone aggregates than acidic aggregates, and after demulsification, the residual asphalt forms a continuous film, with the bonding strength depending on the matching of demulsification rate and mixing time. The expansion rate and half-life of foam asphalt determine the mixing uniformity, and after the foam ruptures, the asphalt adheres to the aggregates in the form of dots or strips, with a bonding strength lower than emulsified asphalt but better construction and workability. Cement in cold recycling reacts through hydration to form C-S-H gel and calcium aluminate, filling voids and enhancing the bonding between aggregates, with particularly significant strengthening effects in the early strength growth stage.

2.3 RAP Pretreatment Process and Fine Separation Technology

The RAP pretreatment process is the prerequisite for ensuring the stable performance of the recycled mixture. The core lies in reducing the impact of issues such as grade variation, excessive impurities, and uneven moisture content through uniform processing. The crushing process adopts a two-stage method of jaw crusher and impact crusher, with the gap of the jaw crusher set at 15-20mm and that of the impact crusher at 8-12mm, reducing the coefficient of variation of the gradation from 18.5% to 6.2%. The screening process uses three-layer vibrating screens for classification, dividing RAP into two grades of 0-8mm and 8-15mm, and stacking them separately to reduce the segregation of coarse and fine materials. The separation of impurities adopts a combination of manual sorting and magnetic separation (≥12000Gs), reducing the impurity mass fraction to below 0.5%. The moisture content is controlled at 3%-5%, and the asphalt content loss is kept within 0.2%. The fine separation technology is the key path to break through the bottleneck of high RAP content, and its core lies in eliminating the "false particles" formed by aged asphalt adhesion - agglomerates that are difficult to disperse during mixing, causing fluctuations in gradation and asphalt-sand ratio. The fine separation process for floor milling materials can achieve a large particle size asphalt-sand ratio of less than 1.5% and a maximum content of false particles in the key sieve holes of no more than 10%. After treatment, the physical properties of the RAP are close to those of new aggregates, effectively promoting the integration of new and old asphalt, and engineering verification shows that the comprehensive performance of recycled mixtures can be improved by using 50% RAP content.

3. Recycled Asphalt Mixture Design and Performance Regulation

3.1 Design of Recycled Asphalt Mixture

The design of hot recycled asphalt mixture aims for a 60% RAP content. A self-developed waste oil composite recycling agent is used. The optimal content is determined based on the recycled old asphalt quality, with five levels set at 6%, 8%, 10%, 12%, and 14% for performance recovery tests. Without the recycling agent, the penetration of aged asphalt is only 33.1 (0.1mm), the elongation is 7.8cm, the softening point is 62.9℃, and the hardening characteristics are significant. When the content is increased to 10%, the penetration recovers to 63.7 (0.1mm), the elongation is 70.9cm, and the softening point is 52.1℃, all three indicators have entered the range of the 70-grade asphalt specification. When the content is 12%, the penetration is 73.4 (0.1mm), the dry-wet splitting strength ratio reaches 100cm at 10℃, the softening point is 50.8℃, and the low-temperature ductility has increased by over 40% compared to the 10% content. When the content is 14%, the penetration is 82.6 (0.1mm), the 10℃ elongation exceeds 100cm, and the softening point is 48.9℃. The indicators exceed the reasonable range, and the excessive introduction of light components may weaken the high-temperature rutting resistance. Considering the higher demand for low-temperature ductility and the reasonable retention of high-temperature performance of high RAP content, the optimal recycling agent content is determined to be 12%. The mineral aggregate gradation is designed as AC-13 type, with a mineral aggregate ratio of 20% 10-15mm crushed stone, 10% 5-10mm crushed stone, 9% manufactured sand, 1% mineral powder, 40% 8-15mm old material, and 20% 0-8mm old material. The synthesized gradation curve falls near the specification median, with a 13.2mm sieve hole through rate of 93.7%, 4.75mm of 51.4%, 2.36mm of 37.9%, and the measured gradation is in good agreement with the designed gradation. Based on the Marshall test, the optimal new asphalt dosage is determined to be 1.87%, corresponding to an asphalt-sand ratio of 5.11%, and the new asphalt dosage is significantly lower than that of the conventional AC-13 mixture, with the contribution rate of old asphalt in RAP exceeding 60%. The stability reaches 15.58kN, the flow value is 35.7 (0.1mm), the void ratio is approximately 4.0%, and the volume characteristics and mechanical indicators are balanced.

3.2 Design of Cold Recycled Asphalt Mixture

The cold recycled asphalt mixture uses emulsified asphalt as the binder, selects slow-cracking and fast-setting emulsified asphalt with an evaporation residual content of no less than 60%, and uses cement and recycling agent in combination. The RAP content is set at 60%, 70%, 80%, 90%, and 100% in five levels, and the optimal moisture content is determined by the compaction method. When the moisture content is 4%, the dry density reaches the peak value of 2.28g/cm^3. The optimal emulsified asphalt dosage is determined based on the dry-wet splitting strength ratio as the indicator. When the dosage is 4.5%, the dry-wet splitting strength ratio reaches the peak value of approximately 87.5%, and 4.3% is taken as the optimal emulsified asphalt content. When the cement dosage is 1.5%, the early strength increases significantly, and the 3-day splitting strength is 37.7% higher than the 2-day splitting strength. The increase in RAP content has a positive impact on high-temperature performance, with the dynamic stability reaching 2425 times/mm at 100% RAP content, an increase of 56.9% compared to 60% RAP content. The viscosity of aged asphalt increases, enhancing the high-temperature shear resistance. The RAP content is negatively correlated with the freeze-thaw splitting strength ratio, with 100% RAP decreasing by 19.1% compared to 60% RAP content. The interface adhesion strength is restricted by the insufficient fusion of aged asphalt coating and normal temperature fusion. Considering both high-temperature and water stability performance, 90% RAP

content is determined as a reasonable scheme, with a ratio of RAP: 10-20mm: 0-5mm = 90: 6: 4, 1.5% cement, optimal moisture content of 4%, and optimal emulsified asphalt of 4.3%.

3.3 Design of Mix Proportions for Semi-Rigid Base Recycled Mixtures

The semi-rigid base uses cement as the binder, and P.O42.5 ordinary silicate cement is selected. The new aggregate is limestone, and the RAP content is set at five levels: 30%, 40%, 50%, 60%, and 70%. As the RAP content increases, the optimal moisture content rises from 5.8% to 6.8%, and the need for water increases due to the aging asphalt in RAP adsorbing moisture; the maximum dry density decreases from 2.32g/cm^3 to 2.22g/cm^3, and the RAP density is slightly lower than that of the new aggregate. The 7-day unconfined compressive strength of the hot recycled mixture shows a significant downward trend with the increase in RAP content, reaching 4.8MPa at 30% content and dropping to 3.5MPa at 70% content. The strength variation coefficient increases from 5.2% to 10.3%. When the RAP content is 30% to 50%, the cement usage can meet the design requirement of no less than 3.5MPa for the semi-rigid base of high-grade highways, and the strength variation coefficient does not exceed 7.5%. The material uniformity is good. When the RAP content exceeds 60%, the cement usage needs to be increased to above 5.5% to meet the strength requirements, and the variation coefficient rises to above 8.9%. The economic and uniformity advantages are not dominant. Based on the performance prediction model, the reasonable RAP content range for the semi-rigid base is 30% to 50%, corresponding to a cement usage of 4.5% to 5.0%.

3.4 Comprehensive Evaluation of Road Performance of Recycled Mixtures

The rutting test dynamic stability of the hot recycled mixture reaches 4866 times/mm, far exceeding the requirement of not less than 2000 times/mm in the specification. The high-temperature rutting resistance is excellent, and the aging asphalt in RAP hardens and the reinforcing effect of the recycling agent and the strengthening of high-temperature adhesion work synergistically. The residual stability after immersion water Marshall test is 99.2%, the freeze-thaw splitting strength ratio is 107.1%, and the TSR exceeds 100% due to the continued cross-linking and solidification of the active components such as epoxy soybean oil in the recycling agent under the water-heating conditions of freeze-thaw cycles, enhancing the cohesion of the binder. However, the long-term stability needs to be verified through multiple freeze-thaw cycles. The bending test at -10℃ shows a flexural strain of 2131.5$\mu\varepsilon$, which meets the requirement of not less than 2000$\mu\varepsilon$ in cold regions. The 12% recycled agent content effectively restores the low-temperature ductility of the aged asphalt. The freeze-thaw splitting strength ratio of the cold recycled mixture at 60% to 90% RAP content meets the requirement of not less than 80% in humid areas, and the 3-day splitting strength of the on-site core sample at 90% content is 0.62MPa, reaching the design strength of 0.6MPa. The 7-day unconfined compressive strength of the semi-rigid base at 30% to 50% RAP content meets the requirement of no less than 3.5MPa. The three types of recycled mixtures show different balanced characteristics in terms of high temperature, water stability, low temperature and mechanical performance, and the applicable layers and climate zones need to be matched differently.

3.5 Evaluation of the Usage Efficiency of Recycled Mixtures Based on Performance Prediction Models

The regression analysis, genetic neural network and grey theory are three types of prediction models with their own advantages and disadvantages in terms of data dependence, computing power requirements and nonlinear processing capabilities. The regression model is based on

measured data and has a simple process, but it relies on a large amount of experimental data； the genetic neural network has the self-optimization ability of the grid structure, but faces an exponential increase in computing power requirements； the grey theory is suitable for limited data conditions, but is difficult to handle nonlinear complex problems. Based on the field detection data, a PCI regression model is constructed, $PCI = 95\{1 - \exp[-(\frac{12}{t})]^{0.8}\}$, After coefficient correction $\alpha = 10.89$ and $\beta = 0.83$, the model prediction values have a small deviation from the measured values, and the predicted curves of the up and down road surfaces PCI are in good agreement with the actual detection data, verifying the accuracy and reliability of the model in target prediction. This model can be used for long-term prediction of the performance of recycled road surfaces and for making maintenance decisions, providing a quantitative tool for evaluating the adaptability of the recycling technology under different traffic loads and climatic conditions.

4. Application of Recycling Technology Engineering and Quality Control

4.1 Key Process Control for Mixing, Compacting and Rolling of Semi-Rigid Base Recycled Mixtures

The mixing sequence for semi-rigid base recycled mixtures is as follows: pre-treated RAP and new aggregates are dry-mixed in the mixing cylinder for 30 seconds, then cement is added for dry-mixing for 20 seconds, followed by wet-mixing with water for 60 to 80 seconds. The total mixing time is 110 to 130 seconds, ensuring uniform color of the mixture, no gray lumps or streaky materials, and the moisture content is controlled within the optimal range ±0.5% of the optimum moisture content through an automatic water addition device. For flexible base recycled mixtures, new aggregates are heated to 160 to 170°C, while RAP is not heated separately. The residual heat from the new aggregates is used to raise the temperature of RAP to 80 to 90°C, which is then added to the mixing cylinder and mixed with new asphalt and emulsified asphalt for 60 to 70 seconds. The total mixing time is 80 to 90 seconds, and the factory temperature is controlled at 120 to 130°C. Compaction is carried out using a tandem operation of asphalt pavers with a width of no less than 9 meters, with a speed control of 2 to 3 meters per minute to ensure continuous uniformity and avoid segregation. The preheating temperature of the leveling plate for flexible base is no less than 100°C. The loose laying coefficient for semi-rigid base is 1.25 to 1.30, and for flexible base it is 1.20 to 1.25. The loose laying thickness is monitored by a level gauge, with a deviation control within ±10mm. Semi-rigid base is compacted using a combination of 12t double steel wheels and 26t rubber wheels, with the initial compaction using double steel wheels for 1 pass, the secondary compaction using rubber wheels for 4 to 5 passes, and the final compaction using double steel wheels for 1 to 2 passes. When the RAP content is 30% to 50%, the compaction degree of the base can reach 97% to 98%. When the RAP content exceeds 60%, an additional 1 pass of secondary compaction is required to meet the compaction requirements.

4.2 Construction Quality Inspection and Acceptance Standards

Raw material inspection covers RAP gradation, asphalt content, cement strength grade and evaporation residue content of emulsified asphalt. RAP gradation is tested every 2000 tons by the sieve method, the asphalt content is controlled at 3% to 6% by the combustion method, the cement strength grade is tested once per batch, and the evaporation residue content of emulsified asphalt is no less than 60%. Mixing process inspection includes the moisture content and temperature of the mixture. The moisture content is tested hourly by the drying method, controlled within the optimal moisture content ±0.5%, and the temperature is tested every 10 trucks, for semi-rigid base at room

temperature and for flexible base at 120 to 130°C. On-site forming inspection includes compaction degree, flatness and thickness. The compaction degree is tested with the sand filling method or nuclear density instrument every 2000 square meters, with a minimum of 97% for semi-rigid base and 96% for flexible base; the flatness is tested with a 3-meter straightedge every 200 meters, with an error of no more than 5mm/3m; the thickness is tested with the core drilling method every 2000 square meters, with a deviation control within the design thickness ±10mm. During the curing period, the 7-day unconfined compressive strength of semi-rigid base is no less than 3.5MPa, tested with 6 specimens per 2000 square meters every 2000 square meters, and the 28-day unconfined compressive strength is no less than 4.0MPa, tested with 6 specimens per 5000 square meters every 5000 square meters; the Marshall stability of flexible base is no less than 7.0kN, tested with 6 specimens per 2000 square meters every 2000 square meters. The curing temperature is controlled at 20±2°C, with a relative humidity of no less than 90%, and inspected twice a day.

4.3 Intelligent Construction and Full Process Quality Monitoring

Unmanned aerial vehicle surveying and laser scanning technology conduct high-precision modeling of pavement defects on the construction section, accurately locate the types and depths of defects, and rely on the AI big data analysis platform, combined with traffic flow and vehicle type data, predict the stress and durability requirements of the recycled layer, and intelligently match the best recycling plan. During the mixing process, near-infrared spectroscopy analysis technology monitors the asphalt in real time, automatically adjusting the dosage of recycled agents, new asphalt, and aggregates, as well as the mixing temperature, time, and feeding speed, to ensure the uniformity of the mixture. Transport vehicles are equipped with intelligent temperature control systems and GPS, which provide real-time feedback on the temperature and location information of the mixture, and interact intelligently with the paver to avoid interruption and cold joints during paving. The paver is equipped with a 3D printing high-precision paving device, which automatically adjusts the paving thickness, width, and slope according to the previous modeling data, and laser guidance ensures the flatness of the pavement, achieving millimeter-level precision control. The paver is also equipped with an intelligent compaction management system, which collects compaction data through vibration sensors and displacement sensors in real time, automatically generating a compaction degree cloud map to guide the paver to adjust the compaction speed, number of passes, and amplitude. Blockchain technology records the data of the entire construction process, achieving full-process quality traceability from raw material entry to compaction formation, providing a data foundation for the long-term performance tracking of recycled pavement.

4.4 Engineering Application Effect and Benefit Analysis

Based on the maintenance and renovation project of the G246 National Highway section from K816+324 to K830+617, this section is a 10-year-operated secondary road with a pavement width of 7.5m. The upper layer of the asphalt concrete with a thickness of 4cm has cracks, rutting, and potholes, with crack-type diseases accounting for 76%. The milling operation length is 8km, and the estimated production of RAP material from milling the 4cm upper layer is approximately 2400m^3. The factory-mixed hot recycling process uses RAP for the production of AC-13 asphalt concrete, with the target RAP dosage of 60%. Field core sampling tests show that the splitting strength of the emulsified asphalt cold recycling mixture after 3 days of curing reaches 0.62MPa, meeting the design strength of 0.6MPa, verifying the correctness of the mix ratio and RAP dosage. The use of emulsified asphalt cold

recycling technology can save material costs by approximately 20%, shorten the construction period by approximately 30%, reduce energy consumption and greenhouse gas emissions at normal temperatures, and significantly reduce the consumption of RAP and the occupation of land resources and environmental pollution caused by waste materials. The large-scale application of high-dosage RAP recycled mixtures can significantly reduce the consumption of new asphalt and new aggregates, providing significant environmental and economic benefits, and providing a reliable technical path and engineering demonstration for the resource utilization of road maintenance.

5. Conclusion

This paper systematically studied the recycling technology and performance of waste asphalt mixtures, and obtained the following main conclusions: The optimal scheme for hot recycling mixtures is with 60% RAP content, 12% recycled agent content, and 1.87% new asphalt content. The dynamic stability reaches 4866 times/mm, the water immersion residual stability is 99.2%, the freeze-thaw splitting strength ratio is 107.1%, the −10℃ flexural strain is 2131.5 με, and the high-temperature and water stability performance are outstanding. For cold recycling mixtures, the ratio with 90% RAP content is RAP: 10-20mm: 0-5mm = 90 : 6 : 4, with 1.5% cement, the optimal moisture content is 4%, the optimal emulsified asphalt is 4.3%, the dynamic stability is 2425 times/mm, the freeze-thaw splitting strength ratio is 82%, and it also takes into account the high-temperature and water stability performance. For semi-rigid base layers, the reasonable RAP content is 30% - 50%, the cement content is 4.5% - 5.0%, and the 7d unconfined compressive strength meets the requirement of not less than 3.5 MPa. The fine separation of RAP can reduce the grading variation coefficient to 6.2%, and the false particle content is controlled within 10%, laying the foundation for high content application. Intelligent construction and full-process quality monitoring technology effectively guaranteed the construction quality of recycled pavement, and the engineering application saved material costs by approximately 20%, shortened the construction period by approximately 30%, and had significant economic and ecological benefits.

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