



Review on Mechanistic–Empirical Design of Perpetual Pavements Using Recycled and Modified Asphalt Materials

Gaurav kumar, Jitendra Chauhan, Umesh Rathod

Department of Civil Engineering , Jawaharlal Institute of Technology Borawan Khargone

ABSTRACT

The increasing demand for durable, sustainable, and cost-effective roadway infrastructure has led to significant advancements in pavement engineering, particularly in the development of perpetual pavements. This review paper presents a comprehensive analysis of the Mechanistic–Empirical (M–E) design approach for perpetual pavements incorporating recycled and modified asphalt materials. The M–E design methodology integrates mechanistic analysis of pavement responses (stress, strain, and deflection) with empirical performance models to predict long-term distress such as fatigue cracking, rutting, and thermal cracking. The study critically evaluates the performance of recycled materials including Reclaimed Asphalt Pavement (RAP), Recycled Asphalt Shingles (RAS), and Warm Mix Asphalt (WMA), along with modified binders such as polymer-modified asphalt, crumb rubber-modified bitumen, and nano-modified binders. The review highlights how these materials influence stiffness characteristics, fatigue resistance, healing potential, and resistance to permanent deformation in multi-layered perpetual pavement structures. Furthermore, the paper discusses key design parameters such as strain criteria at the bottom of the asphalt layer and compressive strain at the top of the subgrade, which are essential for achieving a structural life exceeding 50 years with minimal structural rehabilitation. Advanced simulation tools and pavement performance models used in M–E design frameworks are also examined. The findings indicate that the integration of recycled and modified asphalt materials within the M–E design framework enhances sustainability by reducing environmental impact, lowering lifecycle costs, and conserving natural resources, while maintaining or improving structural performance. However, proper mix design optimization, binder characterization, and performance-based evaluation are crucial to ensure long-term durability. This review provides insights into current practices, challenges, and future research directions for sustainable perpetual pavement design.

Keywords- Mechanistic–Empirical Pavement Design, Perpetual Pavements, Recycled Asphalt Materials, Modified Asphalt Binders, Long-Life Pavement Performance

I. INTRODUCTION

Tremendous amounts of “reclaimed asphalt” are available from maintenance works on asphalt road pavements. Reclaimed asphalt (RA) comprises asphalt reclaimed by milling of asphalt road layers, by crushing of slabs ripped up from asphalt pavements, lumps from slabs, and asphalt from reject and surplus production [1]. With the principles of durable development in mind, and urged by economic and ecological factors, the recycling of old asphalt has gained ground over the past few years. This is mainly due to the relatively high cost of bitumen (a by-product of oil refining) and the advances in technologies making high-quality recycling of old asphalt into new bituminous mixtures possible. In situ recycling of asphalt pavements made its appearance in the year 1975. The technology was used on several works over the next ten years or so, without being able to force a major



breakthrough. The principal reason why this technique did not continue as a success was the development of another form of asphalt recycling in the eighties: in-plant recycling, which has a wider field of application than in situ recycling. In view of sustainable development the use of these recycling technologies must increase because reuse of reclaimed asphalt accounts only for about 7 % of the total road rehabilitation work [2].

The primary reasons to build Expressways are to cater for high volume of traffic and achieve fast connectivity to economic hubs. This results in longer driving hours for drivers on high speed with limited stoppages. Due to this Expressways require highest safety measures and comfort conditions for drivers. One of the basic requirements for roads is to have minimum maintenance so that the traffic disruptions are limited. To achieve this the basic requirements are as follows: a. Adequately designed pavement from structural strength considerations, and b. Enhanced safety requirements, compatible with high traffic speeds and volumes; c. Adequate driving comfort for long distance high speed travel; d. Provision of the needed safety and comfort levels on a sustained basis without any dislocation, disturbance or inconvenience to the traffic. Safety and comfort of user's aspects are related more to the surface characteristics. While the structural aspects are generally covered in IRC design standards coupled with MORTH policy. Traffic Safety depends on a number of factors including pavement surface characteristics, the vehicles and the drivers, safe vehicle pavement interaction at high speeds. Adequacy of geometric design for the traffic speeds and volumes, special attention is needed to the aspect of skid resistance and hydro-planning. Driving Comfort considerations call for increasingly more even surface with increase in speed. These properties of the pavement are related to its surface texture and surface drainage characteristics. More stringent norms for surface stability and hardness needs to be adopted for Expressways compared to other highways. The choice of construction material, construction methodology and quality control techniques must be compatible to achieve the surface evenness levels needed level for Expressways. The three main characteristics expected of an Expressway pavement surface from the users' point of view are: i. Good riding quality (low roughness value); ii. Skid-resistance i.e. good pavement - tyre friction including under wet weather situation; iii. Absence or limitation of rutting on wheel tracks. A pavement having a life of fifty years or longer is generally termed as a long-life pavement or Perpetual pavement. IRC 37 2018 suggests that In India the Average Annual Pavement Temperature is close to 35°C and considering the endurance limit of the material, if the tensile strain caused by the traffic in the bituminous layer is less than 70 microstrain the bituminous layer will never crack. Similarly, if the vertical subgrade strain is less than 200 microstrain, there will be practically very little rutting in the subgrade. The design codes suggests that pavements with design traffic of 300msa or more may be designed as long-life pavements. Thus, long-life pavement design involves selecting a suitable pavement layer combination which can keep the horizontal tensile strain and vertical compressive strain limited to the afore-mentioned limiting strain values corresponding to endurance condition. Different layers of the long life pavement have to be designed and constructed in such a way that only the surface course would need replacement from time to time.

II. RESEARCH MOTIVATION

The increasing global emphasis on sustainability in infrastructure development has necessitated the implementation of green and resource-efficient construction materials. One such material that has gained



considerable popularity in the road construction industry is Reclaimed Asphalt Pavement (RAP). RAP consists of milled or reclaimed asphalt materials obtained from deteriorated pavements and later processed for reuse in new asphalt mixtures, reducing dependence on non-renewable resources such as virgin aggregates and asphalt binders.[1] The addition of RAP into asphalt mixtures is in accordance with the broader objectives of sustainable construction by reducing the depletion of natural resources and lowering production costs. Several studies have shown that RAP not only enhances cost efficiency but also enhances the environmental sustainability of road infrastructure projects while maintaining acceptable performance levels in terms of durability and structural integrity[2,3]. In spite of the advantages connected with RAP utilization, there are notable challenges that must be addressed to enhance its performance in asphalt mixtures. Aged RAP binders tend to undergo significant oxidation, leading to increased stiffness, reduced flexibility, and heightened susceptibility to cracking under traffic loads and temperature fluctuations[4]. Also, RAP-containing mixtures often has compaction difficulties due to the tough nature of the aged binder, which can reduce the density and mechanical performance of the final pavement structure. These restrictions underscore the requirement for advanced modification techniques, such as rejuvenation techniques and binder modification, to restore the rheological properties of aged RAP binders and improve mixture workability[5]. To increase a comprehensive understanding of RAP properties and its implications in pavement engineering, researchers have investigated its performance in different structural applications. Exclusive studies have focused on assessing the impact of RAP on performance indicators such as rutting resistance, fatigue behaviour, and cracking susceptibility. Additionally, innovative applications of RAP, such as its combination with epoxy-based repair materials for bridge decks, have been explored to increase structural longevity and load-bearing capacity[6]. Furthermore, advanced computational models, with neural network-based approaches, have been employed to enable the rapid detection and evaluation of surface cracks in RAP-based pavements, further contributing to quality control and predictive maintenance methods[7].

III. RUBBER-MODIFIED ASPHALT TECHNOLOGY

Various proprietary and generic technologies have evolved for the use of CRM in asphalt rubber (AR) binder and rubber modified asphalt concrete (RUMAC). From the late 1980s, the emphasis for this wet and dry process technology has been on its potential as a solution to the solid waste management problems of scrap tires. The material, process, technology, and product schematic for CRM use in AR and RUMAC is shown in Figure 2 (5). There is some dry process interaction to modify the binder, as indicated by the dotted arrow lines, particularly for finer CRM or elevated mixing temperatures. The Ontario demonstration projects have mainly involved dry process generic RUMAC. While the focus on CRM use in asphalt is currently RUMAC and AR, there is a wide range of other asphalt applications for recycled rubber from scrap tires, including hot-poured rubberized asphalt joint sealing compound, hot applied rubberized asphalt waterproofing membrane, hot applied rubberized mastic waterproofing membrane; protection board, paving "bricks," and recreational asphalt surfaces (running tracks, for instance) (6). Rubberized (CRM) asphalt joint sealant and waterproofing membrane are established and preferred materials technology in Ontario.

in developed countries, the waste materials generated by the industries pose a serious environmental problem by manufacturers or individuals that lack any residual value is termed as waste [1,2]. The feasibility engorging waste material used in the highways construction industry is playing a leading role worldwide as a green investment movement [3,4]. In recent years researchers have been carried out to explore the possibility of using alternative waste material such as steel slag, plastic and scrap tires to construct Hot-Mix Asphalt (HMA) pavements to minimize the deterioration of road pavements [3]. In 2018, the total amount of waste generated, including those generated by households and economic activities in 28 European Union countries, exceed 2.5 billion tons. Research has shown that waste material such as rubber tires is suitable for incorporation in asphalt mixture since rubber tire can improve the performance of asphalt pavement and reduce the need to use new raw materials for the construction of road pavements[8-10]. Furthermore, the crushed concrete in several types of research confirmed that the recycled concrete aggregates (RCA) are applicable for reuse on the roads, concrete pavement when it is replaced with a proper percentage of new aggregate [11-14]. The use of recycled materials as an eco-friendly substitute has performance, economic and environmental benefits [15,6]. Figure 1 shows the waste hierarchy applied to pavement materials. The most preferred choice is reducing the production of waste materials, whereas landfilling is the least preferable choice[15].

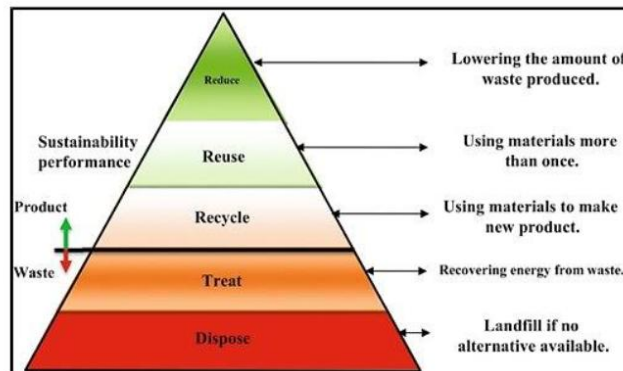


Figure 1. The waste hierarchy for pavement materials [15]

Recent studies have proven the economic advantage of adding tires to asphalt binders since recycled tires markedly reduce the need for using new materials [6]. The use of waste materials for asphalt stabilisation is regarded as a smart strategy for sustainable development. Many researchers have explored the methods for improving the use of waste materials such as crumb rubber, crushed concrete, steel slag, glass fibre and plastic waste in bitumen modifier for hot asphalt mixture properties and performance of factors affecting pavement damage.

IV. ADVANTAGES AND LIMITATIONS OF RECYCLING

Hot-in-plant recycling

As explained before, the percentage of RA that can be allowed in RHM depends on the equipment of the coating plant, but naturally also on the quality and homogeneity of the old asphalt itself. That is why the percentage of reuse of RA has been limited in most countries. Improved understanding of the environmental hazards of the



high concentrations of polycyclic aromatic hydrocarbons (PAHs) in tar has changed the public attitude towards tar-containing products. The problems raised by PAHs, both for the environment (e.g. emissions) and for the health of workers, are critical when heating tar-contaminated asphalt. For that reason, hot recycling of tar-containing materials is now prohibited in Belgium. It should be clarified what concentrations of tar in old asphalt are hazardous to worker health and the environment in hot-mix recycling. This would enable policy-makers to set a maximum tar content that can be allowed in hot asphalt regeneration.

Hot-in-situ recycling

The technique of in situ recycling is difficult to master where road surfacing change too often in composition along a given route. In addition, it requires bulky and very expensive machines, which are only cost-effective on major works. Finally, it must not be forgotten that hot-in-situ recycling only affects the wearing course – heating is effective only to a depth of about 5 cm – and is, therefore, inadequate to remove rutting caused by flow in the underlying layers or by poor structural design (insufficient thickness of courses). The concern about PAHs also applies to this technology.

Cold-mix recycling into a bound base material or base course

As mentioned before, the cold-mix recycling leads to low-grade applications. Nevertheless binder's combination may envisage its application in wearing course of low traffic roads [8]. The technique of stabilization with a bitumen emulsion or with an emulsion and cement, which is used in a number of countries, is worth mentioning [9, 10, and 11]. Cold-mix in situ presents several advantages such as preservation of the environment, the health of the operators and actual cost savings. However mix design and design aspects such as compactive effort, wetting conditions among others must be better specified [9]. Cold-mix recycling into a bound base material may be a solution for tar-contaminated RA. Binding with cement or an emulsion reduces the leaching of environmentally hazardous substances such as PAHs. With emulsion stabilization, possible contact with water and, consequently, leaching may be expected to be even less than with cement stabilization, owing to the hydrophobic properties of the emulsion. This remains to be verified by experiment.

Research objectives

Here are **5 research objectives**:

1. To review the principles and framework of Mechanistic–Empirical (M–E) design for perpetual pavements.
2. To evaluate the performance of recycled asphalt materials (RAP, RAS) in perpetual pavement structures.
3. To analyze the influence of modified binders on fatigue, rutting, and thermal cracking resistance.
4. To assess strain-based design criteria for achieving long-life pavement performance.
5. To identify research gaps and recommend sustainable strategies for M–E based perpetual pavement design.

V. LITERATURE REVIEW

Agustin Iturriaga et al. [1] The incorporation and reuse of Reclaimed Asphalt Pavement (RAP) is increasingly vital within the framework of a circular economy. In the coming years, RAP sources will predominantly consist of modified asphalt pavements. This Modified RAP (RAP M) can significantly influence the performance of new asphalt mixtures, particularly when incorporated at high dosages. Furthermore, combining RAP M with Warm Asphalt Mixtures (WAM) techniques, which are seeing increased global adoption, could substantially



enhance environmental sustainability. The primary objective of this study was to evaluate the performance improvements of WAM containing 20 % and 40 % RAP M. The mixtures were characterized based on rutting, fatigue behaviour, dynamic modulus, and moisture susceptibility, and compared against control mixture. Results indicated that RAP M substantially improved resistance to rutting and moisture damage compared to both the control (virgin hot asphalt mixture) and recycled mixtures produced with conventional RAP. The reduction in rutting was particularly notable in the 40 % RAP M mixture, performing comparably to high-performance virgin mixtures made with modified binders. Additionally, the 20 % RAP M dosage showed a significant improvement in the wheel tracking slope. Regarding moisture sensitivity, RAP M had a positive impact, no detachment of the binder film from the aggregates was noted meanwhile permanent deformation was significantly reduced. Also, fatigue response improvements were noted for recycled mixture with RAP M with increasing in fatigue life.

Teng Wang et al. [2] In the global context of actively seeking decarbonization pathways to address climate change, this study proposes the recycled asphalt binder using waste materials and reduces carbon emissions through waste valorization in the pavement's life cycle. First, waste engine oil residue (WEOR) and crumb rubber (CR) modified reclaimed asphalt binder (WERB) was prepared. Then, WERB's workability, rheological properties, and microscopic properties were evaluated. Finally, the environmental impacts of WERB pavement were quantitatively assessed using life cycle assessment. Results show that the synergistic effect of WEOR and CR significantly improved the rheological properties and low-temperature relaxation of aged asphalt. Furthermore, WERB pavement reduced global warming potential by 79.6 % and non-biotic resource consumption by 90.8 % compared to other pavements, demonstrating significant environmental benefits and carbon reduction potential. This study confirms the feasibility of WERB as a sustainable pavement material and provides the theoretical basis and data support for low-carbon transportation construction.

Sajed Baradaran et al. [3] The growing global concerns over environmental sustainability, particularly with respect to waste plastic accumulation and its impact on global warming, highlight the urgent need for innovative, eco-friendly solutions in civil engineering. Simultaneously, the demand for durable and sustainable infrastructure, especially asphalt pavements, has risen due to increased traffic and population growth. This study addresses these challenges by exploring the potential of warm mix asphalt (WMA) technology combined with recycled plastic waste, specifically from PET bottles, to develop a more sustainable pavement material. Recycled PET was used as an eco-friendly modifier for asphalt binder, alongside Sasobit® as a warm mix additive. Various asphalt mixtures containing 0 %, 1 %, and 2 % recycled PET were prepared and subjected to comprehensive mechanical tests, including dynamic creep (DC), indirect tensile strength (ITS), indirect tensile stiffness modulus (ITSM), and semi-circular bending (SCB) tests. These tests evaluated the mixtures' resistance to rutting, moisture susceptibility, and low-temperature cracking. The results demonstrated that incorporating 2 % recycled PET significantly enhanced the rutting resistance, moisture resistance, and low-temperature cracking performance of WMA pavements. Two-way ANOVA analysis further validated the effects of recycled PET and Sasobit® additives on the asphalt's mechanical properties. Additionally, the environmental and cost impacts of using these materials were assessed, highlighting their sustainability. The PET and Sasobit®



combination, though initially costly, enhances durability, reduces maintenance, and lowers energy consumption, emissions, and hazardous waste, offering cost-effectiveness and improved sustainability. This study provides a promising, cost-efficient, and eco-friendly approach for developing durable asphalt pavements, offering a valuable solution for the future of road construction.

Mingyu Zhao et al. [4] A preparation method for recycled semi-flexible pavement (RSFP) materials was proposed to improve recycled pavement performance and diversify reclaimed asphalt pavement (RAP) recycling approaches. This study investigated the high-temperature performance, low-temperature performance, water stability, secondary aging resistance, fatigue performance, and engineering applications of RSFP materials. Experimental results show that RSFP materials possess better high-temperature stability and secondary aging resistance than conventional recycled pavement materials. RSFP material performance is directly affected by the asphalt skeleton's air voids and the cementitious grouting material's filling rate. A denser and thicker internal cement skeleton enhances high-temperature stability, while a thinner and less continuous structure improves resistance to low-temperature cracking. A lower filling rate results in a more fragmented cement skeleton, which reduces the fatigue life of RSFP materials. Notably, RSFP materials achieve optimal fatigue life at an air void content of 25 %. The application of RSFP materials was validated through two years of monitoring on an experimental road, confirming their suitability for heavy traffic conditions. These findings promote sustainable road construction practices and offer an effective solution for utilizing RAP in high-traffic infrastructure.

Derun Zhang et al. [5] Indiscriminate disposal of styrene butadiene styrene (SBS)-modified reclaimed asphalt pavement (RAP) leads to significant environmental issues and waste of valuable materials. To address this issue, this study explores and validates the feasibility of recycling the high-dosage SBS-modified RAP mixtures at high dosages into the surface layer of the high-grade asphalt pavement based on a warm mix asphalt-synchronous rejuvenation (WMA-SR) technology with a synchronous rejuvenation composite (SRC) synthesized. The optimum ratios of aromatic oil and triallyl isocyanurate (TAIC) in the SRC were first identified as 4.20 % and 4.82 %, respectively, using the FTIR peak area ratio restoration. Sasobit and Evotherm 3 G, two WMA additives, were afterwards combined with different types of rejuvenators to fabricate WMA-recycled asphalt mixtures at RAP dosages of 20 %, 40 %, and 60 %. Subsequently, a series of performance property tests were then conducted on the WMA-recycled asphalt mixtures, and a balanced mix design approach (BMD) was employed to identify the Sasobit as the suitable WMA additive and 40 % as the maximum SBS-modified RAP mixture dosage. Finally, the feasibility of the BMD on the RAP mixture design was proven through the long-term fatigue resistance tests. Evaluation results indicate that both the SRC and WMA additives are indispensable for the promotion of high-dosage SBS-modified RAP mixtures into high-grade asphalt pavement recycling.

Abdul Muhaimin Memon et al. [6] The incorporation of reclaimed asphalt pavement (RAP) into new pavements aids in conserving petroleum asphalt and mineral resources. However, higher RAP proportion can lead to performance issues, which makes the use of rejuvenators necessary. This study investigated the effectiveness of oily sludge (OS) as a rejuvenator for high RAP content through a series of binder



characterizations and evaluation of asphalt mixture engineering properties. Rheological parameters of binders at different temperatures, OS dosage and aging conditions were measured using dynamic shear rheometer. Fourier-transform infrared spectroscopy (FTIR) and atomic force microscopy (AFM) were employed to study detailed insights into the chemical composition and surface morphology of the binders. The rheological results indicated that adding OS reduced the fatigue factor up to 72.9 % compared to recycled asphalt binder and maintained the rutting resistance (PG 64) similar to conventional binder. The morphological analysis showed that incorporating OS decreased the surface roughness of recycled asphalt binder. The addition of RAP up to 90 % increased the Marshall stability by 22 % and reduced the flow values around 1 % of oily sludge recycled (OSR) mixtures. The volumetric properties of OSR mixtures up to 90 % RAP complied with the required PWD specification.

Qiang Song et al. [7] This paper addresses the issues of agglomeration and variability in reclaimed asphalt pavement (RAP) materials generated from road infrastructure. These problems can lead to both environmental and economic impacts. An innovative method that combines physical and chemical separation techniques (PCST) is proposed to improve the recycling rate of RAP aggregates and enhance the performance of reclaimed asphalt mixtures (RAM). In this method, RAP is first classified by particle size using a vibrating screen. The aggregates and asphalt are then separated and recycled through a combination of physical and chemical processes. The recovered materials are used to produce new RAM. The results show that the maximum separation efficiency reaches 83.12 % for coarse aggregates and 88.52 % for fine aggregates. The combined separation method significantly reduces RAP agglomeration and variability, improving the adhesion between aggregates and asphalt. RAM produced with the separated aggregates demonstrates a 13.35 % improvement in low-temperature stability, a 1.28 % increase in residual stability, and a 5.39 % enhancement in freeze-thaw splitting strength compared to the refined separation method (RCS). These findings provide a new approach for the efficient recycling of RAP materials and support the development of more sustainable and cost-effective road construction practices.

Salisa Chaiyaput et al. [8] This study aims to utilize asphalt waste dust, a pollutant by-product of the asphalt production process, to improve the quality of recycled pavement materials for use as base course materials, under the standards of the Department of Rural Roads and the Department of Highways, Thailand. The mixture consisted of 70 % by weight (wt%) reclaimed asphalt pavement (RAP), 30 wt% crushed rock (CR), 3.5 wt% cement (C), and 20 wt% asphalt waste dust (AD), in comparison to the general pavement recycling (RAP-CR-C). Compaction test, permeability test, California Bearing Ratio (CBR) test, and scanning electron microscope (SEM) analysis were performed under all testing conditions. The highest performance was achieved for the recycled pavement materials, containing 3.5 wt% cement and 20 wt% asphalt waste dust (RAP-CR-C-AD20). The coefficient of permeability was 2.32×10^{-7} cm/s under pressurized constant head, 2.40×10^{-7} cm/s under an 8 mm falling head, and 2.59×10^{-7} cm/s under a 14 mm falling head. The CBR values were 493 % at 0.1 in (2.54 mm) penetration and 491 % at 0.2 in (5.08 mm) penetration. The RAP-CR-C-AD20 exhibited a low coefficient of permeability but a high CBR, compared to those of RAP-CR-C, and above the minimum base course requirement (CBR > 80 %). This study highlights the potential of using asphalt waste dust in pavement



recycling as an innovative solution that not only reduces waste but also contributes to sustainable road construction practices.

Yuxuan Sun et al. [9] Moisture damage is a major factor threatening the durability of asphalt pavements. However, while many studies have addressed this issue in conventional or low-reclaimed asphalt pavement (RAP) mixtures, the long-term performance of high-RAP mixtures under repeated recycling remains insufficiently understood. This study examined a dense-graded mixture containing 60 % RAP subjected to five successive recycling cycles with a commercial bio-oil rejuvenator, using surface free energy (SFE) analysis, indirect tensile strength ratio (ITSR) testing, dynamic modulus testing under the moisture-induced stress tester (MIST), computed tomography (CT) scanning, and principal component analysis (PCA). The results showed that recycling progressively weakened interfacial adhesion, with the work of adhesion (W_{add}) and compatibility ratio (CR) decreasing by 28.31 % and 40.38 %, respectively, while the work of adhesion with water (W_{adw}) increased by 20.1 %. These changes were reflected at the mixture scale, where ITSR remained above 80 % through the third cycle but declined to 75 % in the fifth cycle, accompanied by an apparent loss of stiffness under dynamic conditioning. CT analysis further indicated that the first cycle slightly improved compactness, whereas subsequent recycling promoted coarsening and more connected air-void networks. PCA confirmed a mechanism shift, with adhesion-related factors sustaining resistance in early cycles, while moisture intrusion became the main driver of deterioration thereafter. Overall, high-RAP mixtures maintained adequate moisture resistance for up to two recycling cycles, whereas durability degraded sharply beyond this limit due to cumulative binder aging, interfacial weakening, and pore-network coarsening.

Jiaqiu Xu et al. [10] Recycling solid wastes as fillers in asphalt mixtures offers a promising approach for developing low-carbon pavements. In alignment with this initiative, this study explored the feasibility of using five solid wastes with huge reserves in China, including steel slag, desulfurization gypsum, blast furnace slag, waste cement, and iron tailings, as fillers for paving bitumen. This study employed a combined approach of molecular dynamics (MD) simulations and experimental testing to clarify the performance advantages of solid waste-based fillers over mineral fillers in asphalt mastics and to elucidate the underlying atomic-scale mechanisms. To assess the environmental impact of using solid waste fillers instead of conventional mineral fillers in asphalt pavement, a life cycle assessment (LCA) was conducted. The results indicate that most solid waste-derived fillers provide superior performance in asphalt mastics compared to conventional mineral fillers, with improvements of 40 % or more in high-temperature rutting resistance and fatigue properties for most waste fillers, as well as enhanced interaction capacity and adhesion property. MD simulations reveal atomic-scale mechanisms underpinning performance enhancements: rock-forming minerals in solid waste fillers strengthen interfacial interactions with bitumen molecules, as evidenced by increased adhesion work and reduced diffusion coefficients. LCA results further demonstrate that the solid waste substitution technology systematically enhances critical environmental metrics across the lifecycle of pavement materials, with improvements in ecosystem quality exceeding 6 % and resource availability exceeding 9 %. The outcomes of this study establish a sustainable technical framework for green roads and provide a win-win strategy for solid waste management and mineral resource conservation.



Guangji Xu et al. [11] The hot in-plant recycling technology for asphalt pavement, as a solid waste recycling method, can significantly reduce environmental pollution and lower construction costs. However, the variability of Reclaimed Asphalt Pavement (RAP) materials greatly affects the quality of hot in-plant recycled pavement. Effectively controlling the variability of RAP materials has become key to ensuring the long-term durability of recycled pavements. To address this issue, this study proposes an intelligent framework for controlling RAP variability, introducing a method for RAP classification and storage based on the original performance of the pavement, as well as a method for calculating the maximum RAP incorporation rate based on RAP variability. First, road sections are classified and milled according to their original performance to control RAP variability. Then, the maximum RAP content in the hot in-plant recycled asphalt mixture is controlled according to the RAP variability. This proposed framework has been applied to highway maintenance projects in Jiangsu Province, China. After the implementation of the classification and storage method, the coefficient of variation in the passing rate of each sieve in the recycled asphalt mixtures was reduced, and the coefficient of variation in the oil-stone ratio decreased by 1.6 %, demonstrating a significant reduction in variability. Additionally, the carbon emissions of recycled asphalt pavement containing 32 % RAP were evaluated, showing an 8.59 % reduction in carbon emissions compared to the actual pavement constructed with 20 % RAP content.

Yulou Fan et al. [12] The combination of epoxy asphalt and reclaimed asphalt pavement (RAP) provides a promising solution for realizing high-percentage RAP recycling. However, the epoxy-recycled mixture needs to be toughened to enhance its cracking resistance and its fracture behavior after toughening is not clear. This study aims to investigate the fracture characteristics of epoxy-recycled mixtures toughened by styrene-butadiene-styrene/crumb rubber and core shell rubber (SBS/CR-CSR). Four mixtures with RAP contents of 30%, 45%, 60%, and 80% were designed, and their mechanical and fracture properties were evaluated through dynamic modulus tests and semi-circular bending (SCB) tests. Mesoscopic fracture behaviors were revealed through fracture surface analysis using image processing techniques. Results show that the SBS/CR-CSR toughening approach significantly improves the cracking resistance of recycled mixtures and delays crack propagation by enhancing post-peak energy absorption. The flexibility indexes (FI) of toughened epoxy-recycled mixtures with 30%, 45%, and 60% RAP are 14.28, 5.51, 4.49 times of the control group. Finally, the fracture surface recognition analysis provides a mesoscopic explanation for the brittle and ductile fracture mechanisms at various temperatures and RAP contents. These findings provide guidance for fracture mechanism interpretation and material design of epoxy-recycled mixtures, promoting the application of durable and sustainable asphalt pavements.

Yitong Min et al. [13] The sustainable recycling of thermosetting pavement materials is a critical challenge in modern infrastructure. This study addresses this issue by investigating the potential for recycling reclaimed epoxy asphalt pavement (REAP) derived from engineering. Through a series of comparative crushing and abrasion tests, the compressive strength and wear resistance of REAP were evaluated against limestone and basalt as control groups. Surface energy and water immersion tests were conducted to analyze the adhesion behavior of REAP with matrix asphalt and asphalt mastic at three different powder-to-asphalt ratios. Additionally, mixture tests assessed the performance trends associated with incorporating REAP. The findings



reveal that REAP exhibits compressive strength between that of limestone and basalt, while its wear resistance is slightly inferior to limestone. Notably, REAP exhibits no significant adhesion deficiencies with the matrix asphalt, achieving the highest adhesion work of 72.48 mJ/m² with asphalt mastic at a filler-to-asphalt ratio of 1.0. However, the water immersion tests indicate that the adhesion between REAP and asphalt mastic is significantly better than that with matrix asphalt, suggesting that the REAP possesses rich textural characteristics. These results highlight the unique surface textural characteristics of REAP produced through mechanical crushing. A mass conversion method was proposed for designing mixture gradation, effectively minimizing fluctuations caused by density differences between REAP and natural aggregate. Mixture performance tests show that the incorporation of REAP has a significant impact on crack resistance and water damage performance, particularly when combined with natural aggregates.

Maijian Liu et al. [14] High RAP (Reclaimed Asphalt Pavement) content often causes performance deficiencies in recycled asphalt pavements. Epoxy modification is a promising solution, but its long-term durability and lifecycle benefits have yet to be fully demonstrated. Therefore, this study aims to evaluate the durability and lifecycle benefits of epoxy-modified recycled asphalt mixtures (ERAM), using epoxy asphalt mixtures (EAM) and general recycled asphalt mixtures (GRAM) as controls. ERAM's durability was assessed via laboratory mechanical tests, service life predictions, and field observations. A comprehensive lifecycle cost and carbon emissions analysis was conducted across multiple pavement schemes, considering complete lifecycle stages and data variability. Results show that ERAM with 60 % RAP substitution achieves a fatigue endurance limit of 191 $\mu\epsilon$, substantially exceeding the field tensile strain of 53 $\mu\epsilon$. Based on mechanical-empirical models, ERAM is predicted to have a service life of 27–29 years, about 170 % that of GRAM. With enhanced durability and higher RAP content, ERAM reduces annual lifecycle costs and carbon emissions by 10 % and 30 % compared to EAM and GRAM, respectively. These findings demonstrate ERAM's potential as a durable and sustainable pavement alternative.

Yuheng Chen et al. [15] Epoxy-based materials are beginning to be used in asphalt pavement recycling technology to enhance the performance of recycled asphalt mixtures. However, in the context of low carbon and sustainable development, whether epoxy recycling technology has economic and environmental benefits has become a widespread concern. This study developed new recycling technologies with 100% recycled asphalt pavement (RAP) utilization using relatively inexpensive epoxy asphalt and waterborne epoxy resin as binders. The road performance of the different mixtures was investigated using AASHTO tests. The economic and environmental benefits were analyzed using the 'cradle-to-gate' LCA and LCC methods. The results indicated that epoxy asphalt-recycled warm-mix asphalt (RWMA) and waterborne epoxy-recycled cold-mix asphalt (RCMA) exhibited excellent pavement performance. Their moisture sensitivity and low-temperature performance were comparable to traditional reclaimed hot-mix asphalt (RHMA). The dynamic stability at the high temperature of RWMA and two RCMA was improved by 1015.1%, 709.7%, and 765.9% over RHMA. LCA analysis shows that RWMA, and the two types of RCMA contribute to approximately 44.8%, 55.4%, and 52.3% reduction in energy saving, and 39%, 39.7%, and 38.4% of greenhouse gas emissions, compared with regular RHMA. RCMA are cost-effective, and the costs of RHMA and RWMA are 5.5% and 60.4%



higher, respectively. Comprehensively considering performance, cost, and environmental impact, epoxy-based binders demonstrate potential for pavement recycling applications.

VI. CONCLUSION

In conclusion, the Mechanistic–Empirical (M–E) design approach provides a scientifically robust and performance-based framework for developing perpetual pavements with extended service life and minimal structural deterioration. The integration of recycled materials such as Reclaimed Asphalt Pavement (RAP) and Recycled Asphalt Shingles (RAS), along with modified binders including polymer- and rubber-modified asphalt, demonstrates significant potential in enhancing fatigue resistance, rutting performance, and structural stiffness while promoting sustainability. The review highlights that when properly characterized and incorporated within M–E design criteria—particularly tensile strain control at the bottom of the asphalt layer and compressive strain limitation at the subgrade—recycled and modified materials can achieve long-term durability exceeding 50 years. However, challenges remain in terms of material variability, aging characteristics, binder compatibility, and accurate performance prediction models. Therefore, future research should focus on advanced material characterization, performance-based mix design optimization, and improved calibration of mechanistic–empirical models to ensure reliable, cost-effective, and environmentally sustainable perpetual pavement systems.

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