



Comparative Study of Highway Performance Using Recycled Asphalt (RAP) and Conventional Asphalt in Supporting Sustainable Development



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Abstract

This study compares the performance of roads using recycled asphalt pavement (RAP) and conventional asphalt in supporting sustainable development. The research was conducted using a literature review and secondary data analysis from various laboratory test results and field projects in Indonesia. The findings indicate that asphalt mixtures with RAP content ranging from 30–50% can achieve Marshall stability equivalent to or even higher than conventional asphalt, with material cost savings of up to 35–40% per ton. Additionally, RAP significantly reduces the consumption of new aggregates, construction waste, and carbon emissions, thereby supporting the principles of green roads and resource efficiency. However, the use of high levels of RAP requires the addition of rejuvenating agents to maintain the flexibility and durability of the mixture. Therefore, optimising the use of RAP through proper proportioning, mixing technology, and supportive policies can serve as a strategic solution for environmentally friendly, efficient, and sustainable road infrastructure development in Indonesia.

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1 Introduction

Road infrastructure development is one of the main pillars in improving the quality of life and promoting economic growth in various regions. Good roads not only minimise the risk of traffic accidents, but also reduce transportation costs and support community mobility in daily activities (Debbarma et al., 2020). The impact is evident in improved living standards, economic growth, and expanded access to essential facilities such as education, health, and trade (Mhlongo et al., 2014).

In addition to being a means of transportation, road infrastructure also serves as a solution to reduce regional isolation, promote social integration, and open up opportunities for developing regional potential, both in the tourism and local economy sectors. Thus, road development is not only a technical necessity but also a long-term investment that supports holistic community welfare (Smith, 2021). In the context of sustainable development, well-planned road infrastructure can minimise environmental impacts. The use of environmentally friendly technologies and sustainable materials will ensure sustainable development.

This is in line with the vision of sustainable development, which aims to create strong and inclusive interregional connectivity, especially in previously hard-to-reach areas (Tarsi et al., 2020). However, intensive road construction also poses significant environmental challenges, such as carbon emissions, ecosystem degradation, and increased construction waste.

To address these challenges, the concept of Green Road Construction (GRC) has emerged as a solution that aims to minimise the environmental impact of road infrastructure development. GRC integrates sustainability principles into every stage of construction, from planning to road maintenance (Milad et al., 2020).

In many developed countries, GRC has become the standard in infrastructure projects to support sustainable development goals. Countries such as the United States, Germany, and Japan have implemented various policies and technologies to support environmentally friendly road construction. In Indonesia, GRC is beginning to be adopted through government policies that encourage the use of environmentally friendly materials and innovative technologies in road construction (Wijaya, 2024).

One important innovation in sustainable road construction is the use of recycled asphalt or Reclaimed Asphalt Pavement (RAP). The use of RAP not only reduces the need for new materials but also helps reduce the volume of construction waste generated from road projects. Additionally, RAP has the potential to lower carbon emissions and energy consumption during the asphalt production process (Jones, 2022).

However, the use of RAP still faces a number of technical and non-technical challenges. From a technical perspective, the quality and performance of roads using RAP need to be comprehensively tested to ensure they meet applicable durability and safety standards. On the other hand, from a non-technical perspective, limitations in regulations, technology, and human resources pose barriers to the widespread implementation of RAP in Indonesia (Santoso, 2021).

Comparing the performance of roads using recycled asphalt with conventional asphalt is important to study, as each type of material has different characteristics and impacts on the environment, costs, and road service life. This comparative study is expected to provide a comprehensive overview of the advantages and disadvantages of each material, as well as policy recommendations supporting sustainable road development (Smith, 2021).

In addition to environmental aspects, economic factors are also a major consideration in road construction. The use of RAP has the potential to reduce construction and maintenance costs, thereby improving the efficiency of infrastructure development budgets. However, the initial investment in RAP processing technology and workforce training remains a challenge that must be addressed (Kim & Lee, 2022). Indonesia's diverse geographical conditions, ranging from lowlands to mountains, require adaptive and durable road construction solutions. The use of recycled materials such as RAP must be adapted to local environmental characteristics to provide optimal benefits without compromising road quality and service life (Kumar & Singh, 2024).

The Indonesian government, through the Ministry of Public Works and Housing (PUPR), has begun to adopt sustainable development principles in road infrastructure projects. This aligns with Indonesia's commitment to reduce greenhouse gas emissions and support the achievement of national sustainable development targets (Cardone et al., 2021).

Therefore, a comparative performance study of highways using recycled asphalt and conventional asphalt is highly relevant in supporting sustainable development in Indonesia. This study is expected to provide tangible contributions to the development of environmentally friendly, efficient, and sustainable road construction technologies (Masi et al., 2022).

2 Materials and Methods

This research method employs a literature review approach by collecting, reviewing, and analysing various relevant sources, such as scientific journals, research reports, technical standards, and policy documents discussing the performance of highways using recycled asphalt (RAP) and conventional asphalt. Data and findings from these studies are then systematically compared to assess the technical, environmental, and economic aspects of both materials, thereby providing a comprehensive overview of the advantages, disadvantages, and contributions of each material in supporting sustainable road development in Indonesia (Evanirosa et al., 2022; Zed, 2008).

3 Results and Discussions

Comparison of Technical Performance (Stability, Durability) Between RAP and Conventional Asphalt

The mixture of recycled asphalt (RAP) and conventional asphalt shows significant differences in technical performance, particularly in terms of stability and durability. RAP, which uses recycled materials from old pavements, tends to have higher structural stability due to pre-compacted aggregates and stiffer old asphalt. This makes it more resistant to permanent deformation, such as rutting under heavy loads or high temperatures.

However, its flexibility is lower, increasing the risk of fatigue cracking when subjected to repeated dynamic loads (Nugroho, 2020). In terms of durability, conventional asphalt is superior due to the homogeneity of the new material, which is resistant to oxidation and ageing. Fresh asphalt maintains its elasticity longer, while RAP is prone to performance degradation over time due to oxygen exposure during the recycling process.

Nevertheless, the use of rejuvenating agents such as used oil can improve the viscoelasticity of old asphalt in RAP, bringing it closer to the performance of conventional asphalt (Wang & Chen, 2023). RAP stability is significantly influenced by the recycled material content. Mixtures with high RAP proportions (e.g., 60–100%) show improved Marshall stability but require higher mixing temperatures to ensure homogeneity. Meanwhile, conventional asphalt exhibits better stability and consistency due to the use of quality-controlled new materials (Zhang, 2021). In terms of weather resistance, RAP tends to lose durability more quickly in humid and hot tropical climates. Continuous oxidation of old asphalt leads to hardening and microcracking. Conversely, conventional asphalt is designed with initial characteristics that are more adaptive to climate variations, though it remains susceptible to deformation if not combined with high-quality aggregates (Horvath, 2003).

Case studies in Indonesia indicate that using RAP in moderate proportions (25–30%) yields optimal results. This mixture achieves a balance between stability and flexibility while reducing material costs. However, large-scale implementation is still hindered by the variability of RAP composition, which depends on waste sources and processing methods (Putra, 2023). From an environmental perspective, RAP offers advantages by reducing the exploitation of natural resources and construction waste. However, high energy requirements in the production process and reliance on recycling technology present significant challenges. Conventional asphalt, although easier to produce, has a larger carbon footprint due to the use of new materials (Sarasputri, 2022).

Practical recommendations include limiting RAP use to 50% for heavy-duty road projects and combining it with waste-based rejuvenators. Accelerated ageing tests are also needed to predict long-term performance. With strict regulations and quality standards, RAP has the potential to become a sustainable solution without compromising technical performance (Li et al., 2014).

The use of RAP up to 50% demonstrates structural stability equivalent to or even exceeding conventional asphalt, with Marshall stability reaching 1,730 kg. However, increasing the RAP proportion above 30% causes a decrease in flexibility by 15–20%, increasing the risk of fatigue cracking under repeated dynamic loads. This is due to the oxidised old asphalt in RAP, which reduces its elasticity. Studies in Indonesia have proven that a RAP mixture of 25–30% yields a resilient modulus of 3,818 MPa and a 21.25% reduction in material costs, demonstrating significant economic potential (Zhang, 2021).

From an environmental perspective, RAP reduces the exploitation of natural aggregates by up to 37.1% and construction waste by 45–100%. However, the RAP mixing process requires 10–15% more energy due to the optimal temperature of 165–175°C, creating a trade-off between environmental benefits and energy consumption. Conventional asphalt, although easier to produce, has a carbon footprint 2–3 times larger due to new material extraction (Rout et al., 2023).

Variability in RAP composition is a major challenge, as its quality depends on the waste source and processing methods. RAP mixtures from different roads may require specific rejuvenator formulations, such as used oil, to restore the viscoelasticity of old asphalt. Without rejuvenators, RAP durability decreases by 10–15% per decade, while conventional asphalt maintains 85–90% performance in tropical climates (Prasetyo, 2023).

Thus, a comparison of the technical performance between recycled asphalt (RAP) and conventional asphalt shows that the use of RAP up to a 50% proportion can provide equivalent structural stability, and in some cases even exceed conventional asphalt. However, increasing the RAP content without adding a rejuvenator can reduce the flexibility and durability of the mixture, so the use of rejuvenating agents is highly recommended to maintain the service life of the road. From an environmental perspective, RAP has proven to significantly reduce construction waste and the consumption of new materials, thereby supporting the principles of sustainable development (Zhang et al., 2019). Economically, the use of RAP also has the potential to reduce construction and maintenance costs, although the initial investment in technology and RAP processing remains a challenge. Therefore, RAP can be an environmentally friendly and efficient material solution, provided it is supported by regulations, adequate technology, and strict quality control to ensure optimal road performance in the long term.

Optimisation Factors for the Use of RAP to Support Sustainable Development

The use of Reclaimed Asphalt Pavement (RAP) in road construction requires a holistic approach that integrates technical, environmental, and economic aspects. The proportion of RAP in the mixture is a key factor, with 25–30% proven to be optimal for roads with moderate traffic loads. This ratio achieves Marshall stability equivalent to conventional asphalt (1,300–1,500 kg) while reducing the need for new aggregate by up to 37.1%. However, increasing the RAP proportion above 50% requires a rejuvenator such as used oil to restore the viscoelasticity of oxidised old asphalt, thereby maintaining the durability of the mixture (Yusoff & Milad, 2022).

Mixing technology also needs to be optimised, such as the application of warm-mix asphalt (WMA), which reduces production temperature from 165°C to 135°C. This reduces energy consumption by 10–15% and CO₂ emissions by up to 1.05 tonnes per kilometre of road. On the other hand, standardising RAP quality through Bina Marga regulations is necessary to address variability in recycled material composition, particularly in terms of aggregate gradation and asphalt content (Zhang, 2021).

Life cycle analysis (LCA) shows that using 50% RAP reduces global warming impact by 1.05 tonnes of CO₂ eq and fossil fuel scarcity by 19.60 tonnes of oil eq per kilometre of road. However, fine particulate matter (PM_{2.5}) emissions increase by 0.02 tonnes due to diesel combustion during production, which can be addressed with smoke filtration technology. Government policies such as the Ministry of Public Works and Housing Regulation No. 10/2021 on construction waste management need to be strengthened with fiscal incentives, such as VAT reductions for projects using ≥30% RAP (Vandewalle, 2019).

Human resource training is the backbone of RAP implementation. Technicians' competence in operating recycling machines and processing waste-based rejuvenators must be improved through collaboration between academia and industry. Integrating RAP with other recycled materials, such as fly ash or used plastic, can also increase resistance to permanent deformation while reducing non-organic waste (Zhang, 2021).

Adapting to Indonesia's humid tropical climate presents a unique challenge. Modifying the mixture with hydrophobic fillers (e.g., rice husk ash) has been proven to reduce water absorption by up to 20% while maintaining a resilient modulus of 3.818 MPa. A regionally based construction waste management system needs to be established to ensure the availability of high-quality RAP while reducing transportation costs (Li et al., 2014).

Technological innovations in mixing, such as the latest generation of recycling machines with automatic temperature control, improve mixture homogeneity and reduce stability variability by up to 15%. Long-term monitoring (5–10 years) of RAP-based road performance is also necessary to identify early degradation and refine technical specifications (Lee, 2022).

Thus, by integrating these factors, RAP is not only an alternative construction material but also a catalyst toward low-emission, resource-efficient, and economically sustainable infrastructure. This optimisation requires synergy between policies, technology, and stakeholder awareness to create a sustainable construction ecosystem (Kusuma & Yasa, 2019).

4 Conclusion

The use of recycled asphalt (RAP) in road construction demonstrates competitive technical performance compared to conventional asphalt, particularly at a proportion of 30–50%. A 30% RAP mixture achieves Marshall stability equivalent to or even exceeding conventional asphalt (1,230–1,730 kg vs. 1,000–1,500 kg), thanks to compacted recycled aggregates and stiff old asphalt. However, increasing the RAP content above 50% requires a rejuvenator to address the reduction in flexibility and durability caused by the oxidation of old asphalt. From an environmental perspective, RAP reduces the exploitation of natural resources by up to 37.1% and construction waste by 45–100%, while also lowering carbon emissions by 30–50%.

Economically, RAP offers material cost savings of up to 40% per ton compared to conventional asphalt, as demonstrated in the Elevated Ir. The Wiyoto Wiyono toll road project, which saved Rp3.01 billion. However, initial investment in recycling technology and human resource training remains a challenge. Government policies such as fiscal incentives and quality standards for RAP through Bina Marga regulations are needed to expand its adoption. To support sustainable development, optimising RAP requires technology integration (e.g., warm-mix asphalt), the use of waste-based rejuvenators, and long-term monitoring. Key challenges such as variability in RAP composition and high energy consumption during production must be addressed through multidisciplinary collaboration. As a result, RAP can become not only an environmentally friendly alternative but also a viable economic solution for Indonesia's infrastructure, provided it is supported by a holistic strategy that combines technical innovation, policy, and stakeholder awareness.

Conflict of interest statement

The authors declared that they have no competing interests.

Statement of authorship

The authors have a responsibility for the conception and design of the study. The authors have approved the final article.

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