

ABSTRACT

The use of reclaimed asphalt pavement (RAP) has become one of the most promising approaches in attaining sustainability in the road construction. RAP allows valuable aggregates and binders from old pavements to be reused, reducing the demand for virgin resources. However, its widespread use is limited by the presence of an aged and stiff binder that surrounds the RAP aggregates. This aged binder significantly reduces flexibility and makes recycled asphalt mixtures more susceptible to cracking. To overcome this challenge, rejuvenators are added to soften the aged binder and restore its desirable properties. Despite their increasing popularity, several key questions remain unanswered: how should rejuvenators be selected, what dosage is truly effective, how does the source of a rejuvenator matter, and most importantly, how durable are the rejuvenated mixtures in the long term?

This study was designed to provide insight into these questions through a systematic evaluation of four different rejuvenators at two RAP levels (40% and 80%). Among the selected rejuvenators, two were derived from waste sources, waste engine oil (petroleum-based) and waste vegetable oil (organic-based), and two were commercial products, one bio-oil based and the other a compound type. RAP binder was artificially produced by subjecting a viscosity-graded (VG-30) binder to rolling thin film oven (RTFO) aging followed by 20 hours of pressure aging vessel (PAV).

Initially, the standard American Association of State Highway and Transportation Officials (AASHTO) R30 aging protocol was evaluated by subjecting virgin asphalt mixes to different durations of laboratory aging periods: 0, 5, 10, 20, 30, 45, 60, 80, 100 and 120 h at 85°C. The results confirmed that R30 adequately simulated long-term changes in mix properties, as increases in stiffness, rutting resistance, and decreases in flexibility and moisture resistance were consistently captured. One of the question addressed in this study was whether the source

of waste engine oil, which is often a mixture collected from multiple vehicles, influences its performance as a rejuvenator. A direct comparison between single-source oil and blended oils showed that source variability had little impact on mixture performance. This finding has practical importance, as it suggests that commonly available blended oils from service shops can still be considered viable rejuvenators without compromising performance.

When comparing waste-derived rejuvenators to commercial products, clear differences are observed. Waste engine oil and waste vegetable oil demonstrated better resistance to aging than commercial products, even though their physical properties appeared similar. All rejuvenators comprise of aliphatic and aromatic hydrocarbons, similar to the maltenes portion of asphalt. This suggests that chemical composition, particularly the balance of aliphatic and aromatic hydrocarbons that resemble the maltenes fraction of asphalt, is more important than viscosity alone. In terms of dosage, results indicated that the optimum rejuvenator content consistently fell within $\pm 3.75\%$ of the performance grade index (PGI). Moreover, weight change after RTFO testing showed a strong correlation with Global Total Rank Value (GTRV), indicating that this simple laboratory measure can be used as a practical criterion for selecting rejuvenators with the best performance.

The durability assessment offered further insights. In general, rejuvenated mixtures displayed better cracking resistance and slower rates of stiffness increase than virgin mixes throughout the aging process. This was especially clear from the Indirect Tensile Asphalt Cracking Test (IDEAL-CT) and resilient modulus tests. However, durability is not uniform across all properties. Rutting resistance of rejuvenated mixes was more sensitive to early stages of aging, while moisture resistance became more vulnerable at later stages. Fatigue resistance and resilient modulus performance were consistently better in rejuvenated mixes compared to virgin mixes, indicating that rejuvenators provide long-term structural benefits. Interestingly, some unique trends were also observed, such as the reverse behaviour of cracking tolerance

index (CT_{index}) and resilient modulus values in high RAP mixtures treated with waste vegetable oil. These anomalies highlight complex interactions between rejuvenator chemistry and binder aging that require further investigation.

Overall, the findings of this study lead to several critical conclusions. First, the source of waste engine oil does not significantly affect its role as a rejuvenator. Second, waste-derived rejuvenators outperform commercial rejuvenators in terms of aging resistance, highlighting their potential as both cost-effective and sustainable alternatives. Third, optimum dosage can be reliably estimated using the PGI range and verified by RTFO weight change, offering a simple and practical guideline for engineers. Finally, while rejuvenated mixes show superior fatigue resistance and reduced stiffness progression, special attention must be given to rutting in the early life and to moisture resistance at later stages to ensure balanced durability.

This study contributes to a deeper understanding of how rejuvenators interact with aged binders in RAP and provides a framework for selecting and dosing rejuvenators effectively. By showing that waste-derived rejuvenators can not only restore short-term performance but also provide better long-term durability than commercial products, the results support their broader implementation in the field. At the same time, the work highlights the need for ongoing research into durability, especially for high RAP mixtures and for rejuvenators derived from organic wastes. Together, these findings move the industry closer to confidently adopting high RAP contents in asphalt pavements, thereby saving natural resources, reducing environmental impacts, and promoting truly sustainable infrastructure.