Epoxidized Soybean Oil Rejuvenator for High-RAP Asphalt Pavements: Field Evaluation at the NCAT Test Track

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Abstract. This study evaluated the laboratory and field performance of a high-RAP asphalt mixture incorporating an epoxidized soybean oil-based rejuvenator. A 12.5-mm dense-graded asphalt mixture with 50% reclaimed asphalt pavement (RAP) was designed using a Balanced Mix Design (BMD) framework to determine the optimum rejuvenator dosage based on the Indirect Tensile Asphalt Cracking Test (IDEAL-CT) for cracking and the Hamburg Wheel-Tracking Test (HWTT) for rutting performance. Laboratory testing indicated that the rejuvenator substantially improved cracking resistance while maintaining rutting performance within acceptable limits. The optimized mixture containing 4.1% rejuvenator was produced in an asphalt plant and placed on the NCAT Test Track (Section S1) for monitoring under heavy truck traffic and warm climate conditions. After one year of truck trafficking (approximately 4 million ESALs), no visible surface cracking was observed, and rut depth remained below 3.5 mm. Ride quality, measured by the International Roughness Index (IRI), stayed stable at 1.0–1.2 m/km, while surface texture, expressed as Mean Profile Depth (MPD), gradually decreased from 1.0 mm to 0.7 mm due to normal aggregate polishing under heavy truck traffic. These early findings demonstrate the potential of the bio-based rejuvenator to maintain satisfactory field performance in high-RAP asphalt mixtures.

Keywords: Bio-based Rejuvenator; Soybean Oil; Reclaimed Asphalt Pavement (RAP); Field Performance.

1 Introduction

Recycling asphalt pavements has become an essential practice for advancing sustainable and cost-effective infrastructure. This process reduces the reliance on non-renewable resources, including virgin asphalt binder and aggregates, conserves natural resources, and lowers production and construction costs [1]. However, the use of high percentages of Reclaimed Asphalt Pavement (RAP) is still limited. The aged binder in RAP is often stiff and brittle, which can negatively affect cracking resistance and the overall durability of recycled asphalt mixtures. These challenges have prompted the search for effective rejuvenators that can improve the properties of aged RAP binder while ensuring balanced performance in the mixture.

Among commercially available rejuvenation technologies, bio-based rejuvenators have gained increasing attention due to their renewable feedstock and environmental compatibility. Derived from natural sources such as vegetable oils, these materials soften the aged RAP binder and improve mixture flexibility [2]. The rejuvenation effectiveness depends on factors such as rejuvenator type, chemical composition, and dosage. While many laboratory studies have demonstrated that bio-based rejuvenators enhance binder and mixture properties, field validation under heavy truck traffic and real environmental conditions remains limited. Understanding long-term field performance is critical to ensure the durability and practicality of these rejuvenators.

This study evaluates the laboratory and field performance of a high-RAP asphalt mixture incorporating an epoxidized soybean oil-based rejuvenator. A 12.5-mm nominal maximum aggregate size (NMAS) mixture containing 50% RAP was designed using a Balanced Mix Design (BMD) framework to determine the optimum rejuvenator dosage. The mixture was then produced in an asphalt plant and placed on the NCAT Test Track (Section S1) for long-term performance monitoring. The study aims to demonstrate how bio-based rejuvenators can enable greater RAP utilization without compromising cracking, rutting, or overall pavement quality.

2 Materials and Test Methods

A dense-graded hot mix asphalt mixture with a 12.5-mm NMAS was designed in the laboratory using 50% RAP and a PG 67-22 virgin binder. The mixture design followed a BMD framework to determine the optimal dosage of the epoxidized soybean oil-based rejuvenator, ensuring an appropriate balance between cracking resistance and rutting performance.

Two laboratory performance tests were used for mixture evaluation: (1) the Indirect Tensile Asphalt Cracking Test (IDEAL-CT) to assess cracking resistance at intermediate temperature, and (2) the Hamburg Wheel-Tracking Test (HWTT) to evaluate rutting performance. The optimum rejuvenator dosage was selected based on achieving sufficient cracking resistance without compromising rutting performance.

After determining the optimal dosage of rejuvenator using IDEAL-CT and HWTT results, the mixture was prepared and placed at the NCAT Test Track (Section S1) for field evaluation under truck traffic loads and real environmental conditions. Field performance was monitored periodically by measuring rutting using the Pathway PathRunner inertial profiler, ride quality through the International Roughness Index (IRI), surface texture based on the Mean Profile Depth (MPD), and surface cracking through systematic visual inspections and distress mapping.

2.1 Indirect Tensile Asphalt Cracking Test (IDEAL-CT)

Cracking resistance at intermediate temperature was evaluated using the IDEAL-CT in accordance with ASTM D8225. Specimens measuring 150 mm in diameter and 62 ± 1 mm in height were compacted to 7.0 ± 0.5% air voids and conditioned at 25 ± 1°C for 2 hours prior to testing. For each mixture, five replicates were tested, and the average Cracking Tolerance Index (CT_{Index}) was determined from the load-displacement curve. A higher CT_{Index} corresponds to greater resistance to intermediate-temperature cracking.

2.2 Hamburg Wheel-Tracking Test (HWTT)

Rutting resistance was evaluated using the HWTT in accordance with AASHTO T 324. Test was conducted at a temperature of 50°C on specimens that were compacted with a Superpave Gyratory Compactor (SGC) to a height of 62 ± 1 mm, with air void content maintained at 7.0 ± 0.5%. Four specimens were arranged in pairs and tested simultaneously under the two steel wheels of the device. The relationship between rut depth and wheel passes was used to assess the mixture's performance against rutting.

3 Results and Discussion

3.1 Mix Design

During the laboratory mix design phase, multiple dosages of rejuvenator were tested to ensure sufficient resistance to cracking based on CT_{Index} from the IDEAL-CT, as cracking is the main concern in high-RAP mixtures. After determining the dosage that met the cracking criterion, the rutting performance was evaluated at that same rejuvenator content to confirm balanced performance.

Fig. 1 illustrates the effect of rejuvenator dosage on cracking resistance (i.e., CT_{Index}) of the mixture. The CT_{Index} increased consistently with higher rejuvenator dosages, indicating that the epoxidized soybean oil-based rejuvenator effectively improved binder flexibility and mixture cracking performance. The control mixture (without rejuvenator) yielded a CT_{Index} of 32.2, failing to meet the minimum threshold of 50 required for Alabama surface mixes [3]. At rejuvenator dosages of 2.5%, 3.5%, and 4.1%, the CT_{Index} values increased to 49.2, 54.2, and 57.7, respectively.

While the dosage of 3.5% achieved an average CT_{Index} slightly above the minimum criterion, the observed variability among replicates suggested the need for a slightly higher dosage to ensure consistent performance. Therefore, a 4.1% rejuvenator was selected as the optimum dosage for plant production.

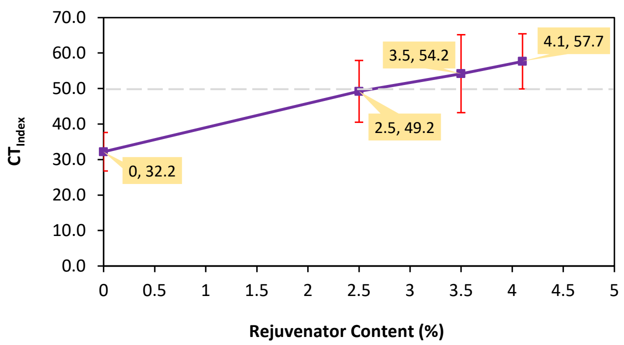

Fig. 1. Effect of rejuvenator dosage on CT_{Index}.

The mixture containing 4.1% rejuvenator was then tested using the HWTT to confirm that its rutting performance remained satisfactory. As shown in **Fig. 2**, the mixture had a rut depth of 4.6 mm after 10,000 passes, well below the 10-mm limit specified by the Alabama Department of Transportation (ALDOT) for wearing surface mixtures with PG 67-22 binder tested at 50°C in accordance with AASHTO T 324 [4]. This confirmed that the rejuvenator improved cracking resistance without compromising rutting performance.

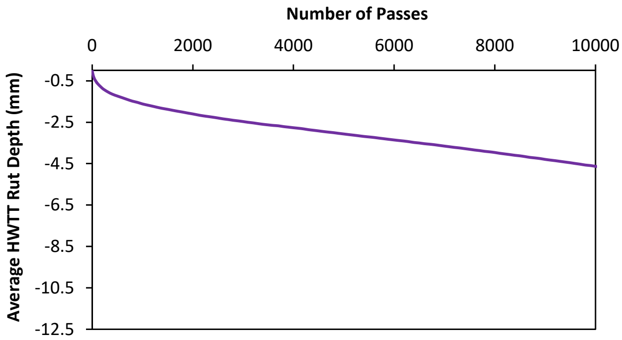

Fig. 2. Average HWTT rut depth curve for the mixture containing 4.1% rejuvenator.

3.2 Construction

After conducting the laboratory mix design and determining the optimal dosage of the rejuvenator, the mixture was produced at a continuous asphalt plant. To improve the mixture's resistance to moisture damage, an anti-stripping agent was added at a dosage of 0.5% by weight of the total binder during production. The mixture was then laid down in a single thick layer on the NCAT Test Track (Section S1) for field performance monitoring (**Fig. 3**).

(a) Cross Section (b) Placement of Surface Layer

Fig. 3. Construction of Section S1 on the NCAT Test Track in September 2024.

Table 1 compares the target and quality control (QC) gradation and volumetric properties of the plant-produced mixture. The close agreement between target and QC values indicates that the plant successfully replicated the laboratory mix design.

Table 1. Target versus quality control (QC) gradation and volumetric properties.

Sieve Size	**Target**	**QC**
25 mm (1")	100	100
19 mm (3/4")	100	100
12.5 mm (1/2")	99	99
9.5 mm (3/8")	89	90
4.75 mm (#4)	62	63
2.36 mm (#8)	50	49
1.18 mm (#16)	40	39
0.60 mm (#30)	28	28
0.30 mm (#50)	16	16
0.15 mm (#100)	10	10
0.075 mm (#200)	6.3	5.8
Volumetric Properties		
Binder Content (P_b) (%)	6.1	6.1
Effective Binder Content (P_{be}) (%)	5.4	5.5
Dust-to-Effective Binder Ratio	1.2	1.1
RAP Binder Replacement (*RBR*) (%)	47.0	46.0
Maximum Theoretical Specific Gravity (G_{mm})	2.436	2.438
Bulk Specific Gravity (G_{mb})	2.390	2.399
Air Voids (V_a) (%)	1.9	1.6
Voids in Mineral Aggregates (*VMA*) (%)	14.4	14.3
Voids Filled with Asphalt (*VFA*) (%)	87.0	89.0
Rejuvenator Dosage by Weight of Total Asphalt Binder (%)	4.1	4.1

3.3 Field Performance

Fig. 4 shows the field performance of Section S1 after one year of trafficking with about 4 million equivalent single axle loads (ESALs) and exposure to a warm climate in Alabama, USA. No visible surface cracking has been observed, consistent with the favorable cracking resistance indicated by IDEAL-CT results. These results demonstrate that the soybean oil-based rejuvenator effectively mitigated cracking in a 50% RAP mixture under actual traffic and environmental conditions. Continued monitoring of the section through the remainder of the trafficking cycle will be important to fully assess the long-term performance of the mixture.

As shown in **Fig. 4a**, rutting remained low and stable during the first 2.9 million ESALs. A modest seasonal increase to roughly 3.3 mm occurred during the summer of 2025 due to elevated pavement temperatures, similar to trends observed in other sections on the NCAT Test Track during the same period. Despite this increase, the rut depth remains well below the typical 12.5-mm failure threshold, confirming good mixture stability.

Fig. 4b indicates that the *IRI* stayed within a narrow range of 1.0–1.2 m/km, reflecting a smooth surface with no noticeable distress affecting ride quality. Similarly, **Fig. 4c** shows that the *MPD* decreased gradually from about 1.0 mm to

0.7 mm, which is consistent with normal surface aggregate polishing under heavy truck traffic.

Collectively, these results confirm that the rejuvenated high-RAP mixture maintained a desirable balance between cracking and rutting performance while preserving surface characteristics and ride quality during the first year of trafficking.

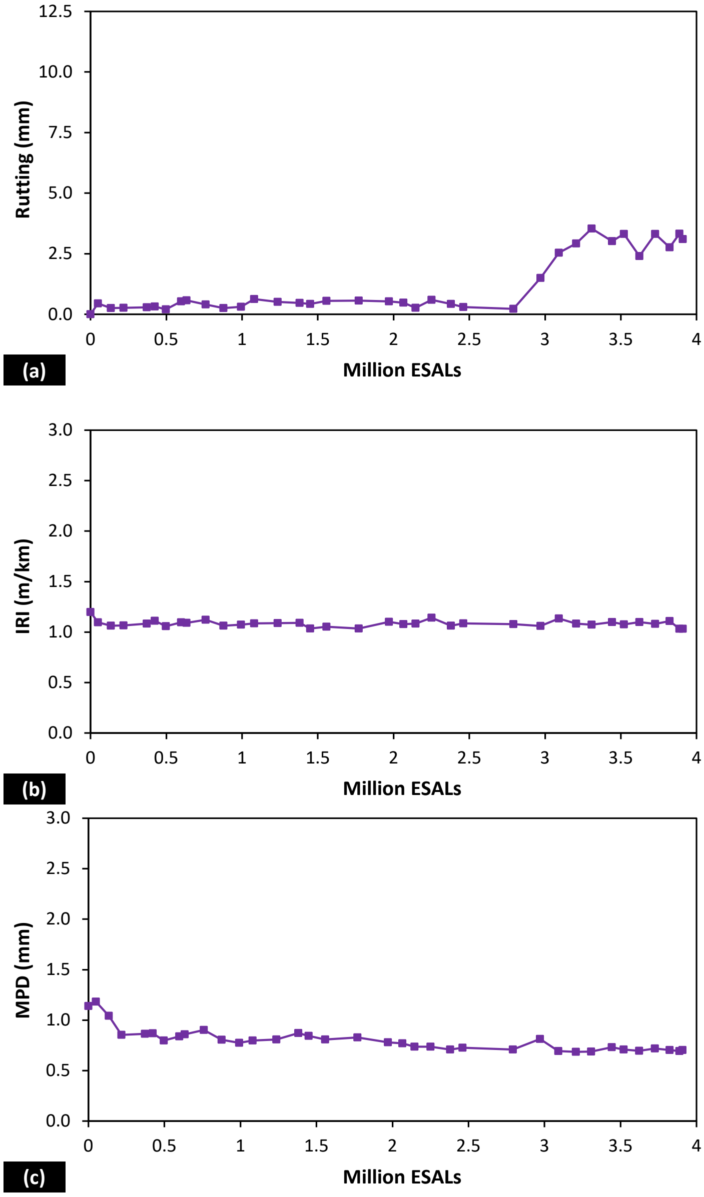

Fig. 4. Field performance: (a) Rutting; (b) *IRI*; and (c) *MPD*.

4 Summary and Conclusions

A 50% RAP asphalt mixture incorporating an epoxidized soybean oil-based rejuvenator was evaluated through a combination of laboratory testing, plant production, and field performance monitoring at the NCAT Test Track (Section S1). The study followed a BMD framework to identify the optimum rejuvenator dosage that provided improved cracking resistance without compromising rutting performance.

Laboratory results from the IDEAL-CT and HWTT during the mix design phase demonstrated that the rejuvenator effectively improved mixture cracking resistance while maintaining rutting resistance well within acceptable limits. The optimum dosage of 4.1% rejuvenator produced a mixture with balanced mechanical properties, confirming the suitability of the BMD approach for optimizing high-RAP mixtures containing bio-based additives.

Field performance monitoring after approximately one year of trafficking (with about 4 million ESALs) showed:

- No visible surface cracking, consistent with laboratory cracking performance;
- Rut depth less than 3.5 mm, indicating good mixture stability;
- Consistent ride quality with *IRI* values between 1.0–1.2 m/km; and
- Gradual texture reduction (*MPD* from 1.0 mm to 0.7 mm), reflecting normal aggregate polishing under heavy truck traffic.

These results demonstrate that the epoxidized soybean oil rejuvenator provided durable early performance in a high-RAP mixture under heavy truck traffic and warm climate exposure. The findings confirm the feasibility of using bio-based rejuvenators to enable higher RAP utilization while maintaining good pavement performance. Continued trafficking and monitoring at the NCAT Test Track will provide valuable insight into the long-term durability and sustainability benefits of this rejuvenation strategy.

5 References

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