Microcapsules-Encapsulated Rejuvenators for Asphalt Self-Healing: Effects on Pavement Performance

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ABSTRACT: Encapsulating rejuvenators in asphalt offers a promising approach to extend pavement lifespan. This study synthesized calcium alginate capsules containing rejuvenator oil, achieving a compressive strength of 18 N and a 75.83% weight loss at 900°C. Capsules were added to asphalt mixes at 0%, 0.5%, and 1% by weight of aggregates. Laboratory tests on unaged, short-term aged (STA), and long-term aged (LTA) samples showed that capsule inclusion did not affect volumetric properties or significantly alter rutting, ITS, or resilient modulus. However, SARA fractionation revealed a 9.4% increase in aromatics content in LTA samples with 1% capsules, indicating enhanced bitumen properties through gradual rejuvenator release.

1 INTRODUCTION

Creating long-lasting asphalt pavements requires timely maintenance and durable bituminous mixtures. Traditionally, bitumen's durability is enhanced by modifiers to improve rheology, adhesion, and aging resistance. Recently, enhancing asphalt's self-healing capability through encapsulated rejuvenators has been explored. Bitumen naturally self-heals by wetting and interdiffusion at damaged sites, but this is slow at service temperatures and less effective as bitumen ages. Encapsulated rejuvenators release healing agents when cracks occur, softening the mastic and restoring strength [1]. Methods like porous sand, sodium alginate gelation, and urea-formaldehyde polymerization have been developed to encapsulate rejuvenators [2, 3]. Calcium-alginate beads show promising results, enhancing self-healing without compromising rutting or moisture resistance. These rejuvenators release under traffic loads, softening bitumen and aiding crack repair, thus significantly restoring aged bitumen. The right rejuvenating agent is crucial for reducing costs and environmental impact [4]. This study focuses on commercial rejuvenator oil in capsules, highlighting the need for innovative methods to improve asphalt self-healing efficiency.

2 OBJECTIVES

The study aims to evaluate the effect of adding microcapsule-encapsulated rejuvenators on asphalt mix performance. Microcapsules will be incorporated at 0.5% and 1% dosages by aggregate weight, and tests for fatigue resistance, rutting resistance, moisture sensitivity, and SARA analysis will be conducted under unaged, short-term aged (STA), and long-term aged (LTA) conditions. The goal is to ensure the capsules do not alter the initial mix properties but activate only when exposed to oxidative aging and repeated loading.

3 MATERIALS USED

3.1 *Bitumen*

This study utilized a viscosity-graded binder (VG-40), and its physical properties were tested following standard guidelines. The results showed a softening point of 51.6°C (ASTM D36-14), ductility greater than 100 cm (ASTM D113-17), a penetration of 42.44 mm (ASTM D5M-20), specific gravity of 1.06 (ASTM D70-21), and a viscosity of 463 cS at 135°C (ASTM D4402-15). These values confirm the binder's suitability for use in asphalt mixtures.

3.2 *Aggregates*

The physical properties of the aggregates used in this study were tested according to standard guidelines. The combined index (flakiness and elongation) was 31.04% (IS 2386 Part 1:1963), the aggregate impact value was 18.03% (IS 2386 Part 4:1963), and the Los Angeles abrasion value was 26.3% (IS 2386 Part 4:1963). These results ensure the aggregates meet the required criteria for use in the asphalt mix.

3.3 *Microcapsule-Encapsulated Rejuvenators*

Rejuvenator capsules were synthesized in the lab using ionic gelation, where sodium alginate was cross-linked with calcium ions (Ca^{2+}). A 2% weight/volume aqueous solution of sodium alginate was stirred for 24 hours and then emulsified with rejuvenator oil.

This mixture was pumped at 2 mL/min through a syringe into a calcium chloride ($CaCl_2$) solution, which acted as a hardener. The hardener solution was stirred continuously at 300 rpm. Once the capsules formed, they were filtered and dried at 40°C. The resulting calcium alginate capsules ranged from 2 to 3 mm in diameter.

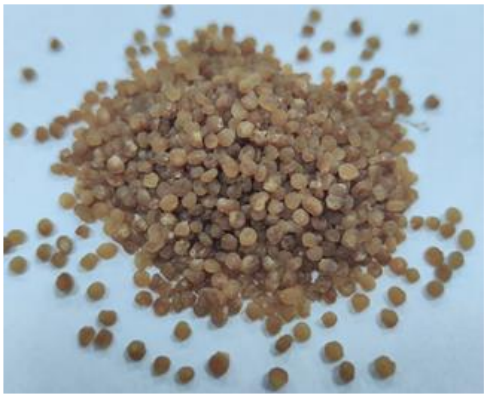

Figure 1. Laboratory Synthesized Calcium Alginate microcapsules.

4 METHODOLOGY

The study used Bituminous Concrete Grade-2 (BC-II) mix gradation (Figure 2) according to MoRT&H specifications [5], with Marshall mix design conducted per the Asphalt Institute MS-2 manual. The optimum binder content (OBC) was determined to achieve 4% target air voids with 75 blows on each side of the Marshall specimen. Aggregates and bitumen were heated separately and mixed at a specified temperature, and rejuvenator microcapsules were added and blended for uniformity before compaction.

Specimens were prepared in three conditions: unaged, short-term aged (STA), and long-term aged (LTA). STA specimens were conditioned at 135°C for 4 hours, while LTA specimens were aged at 85°C for five days. Performance tests, including Marshall stability, moisture sensitivity, indirect tensile strength (ITS), resilient modulus (MR), dynamic creep, and SARA analysis, assessed the impact of the microcapsule-encapsulated rejuvenators on asphalt mixes.

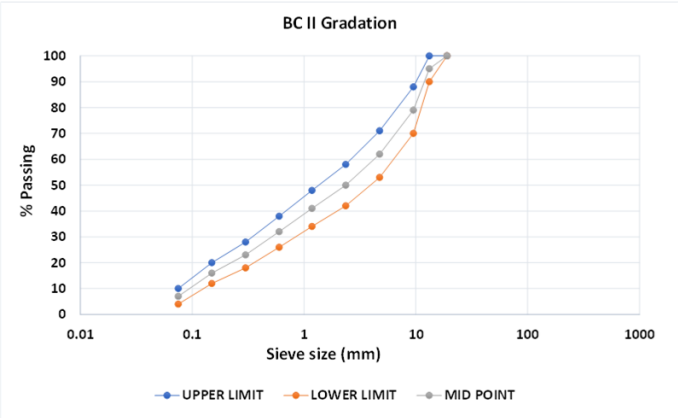

Figure 2. Gradation for BC-II Mix.

5 LABORATORY EXPERIMENTS, RESULTS AND DISCUSSIONS

5.1 *Preparation of Bituminous Mix*

The coarse and fine aggregates were first proportioned according to the gradation shown in Figure 2. The preheated aggregates and bitumen were mixed at the specified mixing temperature. Then, the microcapsules were added to the mix and blended uniformly. The mixture was compacted in Marshall moulds with 75 blows on each face.

5.2 *Mechanical strength and Thermal stability of Microcapsules*

Calcium alginate microcapsules are integrated into asphalt mixtures to assess their impact on performance and self-healing capabilities. Their mechanical strength is evaluated through a uniaxial compression test, where a compressive force is applied until the yield point is reached. The load-displacement curve reveals that the microcapsules initially behave elastically but undergo permanent deformation beyond the yield point, increasing the risk of rejuvenator leakage. The microcapsules demonstrated a maximum force of 18 N before crushing, with previous research indicating that a compressive strength above 10 N ensures their integrity during mixing and compaction [1].

To assess thermal stability, thermogravimetric analysis (TGA) was conducted to measure mass loss at elevated temperatures, confirming that the microcapsules remain stable with less than 5% mass loss up to 200 °C (Figure 3). This indicates that the microcapsules will not melt at the mixing and compaction temperatures of asphalt mixtures, ensuring their effectiveness in enhancing self-healing properties without compromising the mix's integrity.

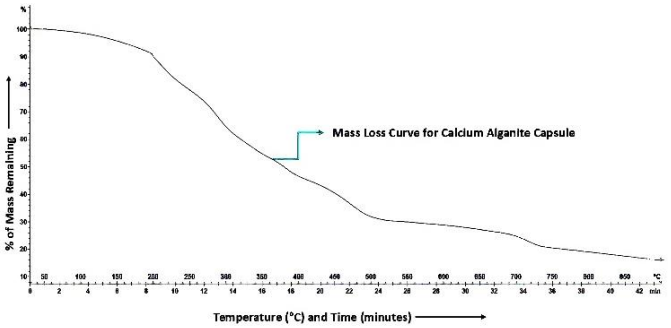

Figure 3. TGA results of calcium-alginate microcapsule.

5.3 *Influence of microcapsules on volumetrics of asphalt mixes*

The asphalt mix design followed the MS-2 procedure, determining the optimum binder content (OBC) to be 5.80% for target air voids of 4%. The measured values for Marshall stability, flow value, bulk density, voids in mineral aggregates (VMA), and voids filled with bitumen (VFB) were 1750 kg, 3.7 mm, 2.41

g/cc, 15.58%, and 74%, respectively. Although adding microcapsules can theoretically increase air voids and reduce the percentage of voids filled with asphalt, laboratory experiments showed that incorporating 0.5% to 1% of microcapsules did not significantly affect the asphalt mix's volumetrics, which are crucial for its performance.

5.4 *Influence of microcapsules on ITS and moisture-sensitivity of asphalt mixes*

The ITS and TSR (AASHTO T-283) tests on unaged, STA, and LTA specimens with 0%, 0.5%, and 1% microcapsule additions showed no significant changes in values. While ITS values slightly decreased with increased microcapsule content, these variations were minimal, and TSR values exhibited minor fluctuations without a clear trend. This suggests that microcapsule additions up to 1% do not significantly affect the mechanical properties or moisture damage resistance of the mix. The variations in ITS and TSR values are illustrated in Figures 4 and 5, respectively.

5.5 *Influence of microcapsules on esilient modulus of asphalt mixes*

The resilient modulus (MR) tests (ASTM D4123-20) on unaged, STA, and LTA specimens with 0%, 0.5%, and 1% microcapsule additions indicated a marginal decrease in MR values with higher microcapsule dosages. Specifically, MR values decreased from 3137 MPa at 0% for unaged specimens to 2871 MPa at 1%. STA and LTA specimens showed similar trends, with MR values decreasing notably at higher capsule contents (Figure 6). This decrease may be linked to microcapsule breakage during loading, affecting stress distribution and the material's ability to recover after deformation. The results suggest that the microcapsules alter the elastic properties of the asphalt-microcapsule mixtures due to mechanical interactions under repeated loading.

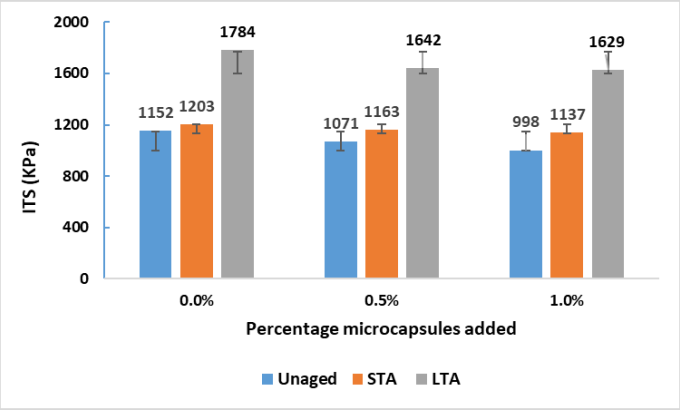

Figure 4. Variation of ITS (in kPa) with a percentage increase in microcapsules addition.

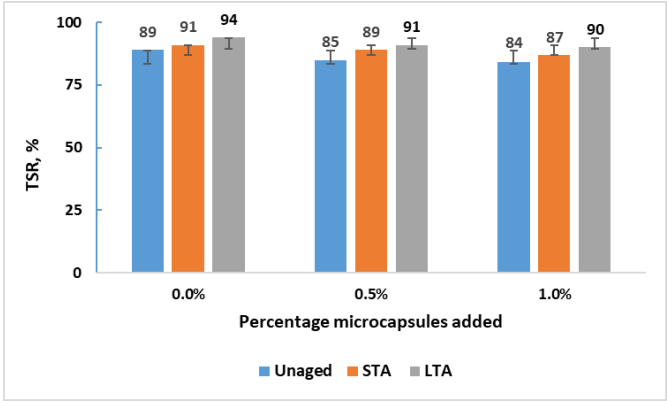

Figure 5. Variation of TSR (in %) with a percentage increase in microcapsules addition.

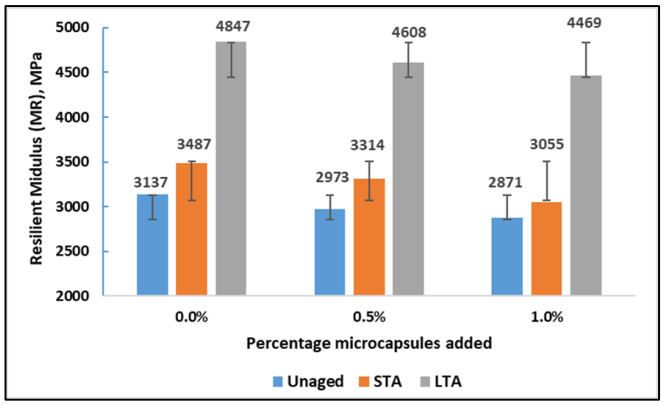

Figure 6. Variation of Resilient Modulus (in MPa) with a percentage increase in microcapsules addition.

5.6 *Influence of microcapsules on rutting behaviour of asphalt mixes*

Dynamic creep test (EN 12697-25) results for unaged, STA, and LTA samples with varying microcapsule additions (0%, 0.5%, and 1%) reveal significant trends in asphalt behavior (Figure 7). Permanent strain accumulation decreases as samples age, attributed to increased asphaltene content and reduced maltene content, leading to a stiffer binder that resists deformation under repeated loading. Although there is a negligible rise in permanent strains with higher microcapsule percentages, this is due to the reorientation of microcapsules during loading, causing slight increases in plastic deformation. The addition of microcapsules influences mechanical behavior across all aging conditions, but rutting performance remains largely unaffected. Increased microcapsule dosage in STA and LTA specimens results in a slight rise in permanent strain, likely due to rejuvenator release under cyclic loading and oxidative aging. SARA fractionation results confirm that some microcapsules break during testing, increasing aromatic content and enhancing elasticity. The mix can accommodate microcapsule additions without substantial performance loss, even with microcapsule strength at only 18 N.

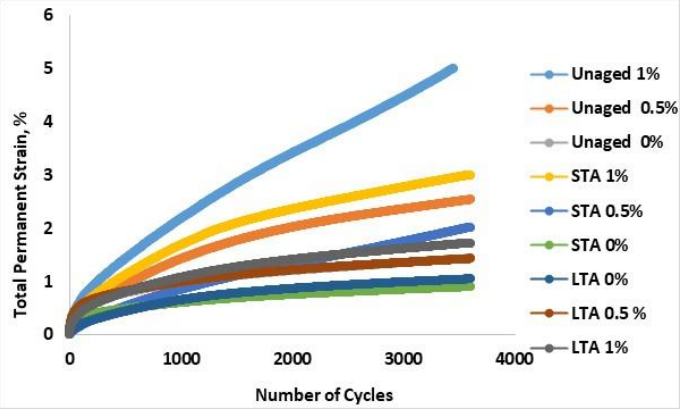

Figure 7. Dynamic creep test results for unaged, STA and LTA asphalt mixes with 0%, 0.5%, and 1% of microcapsules

5.7 *Influence of microcapsules on SARA components*

SARA analysis carried out on the binder extracted after the creep test, which results for unaged, STA, and LTA specimens with 0%, 0.5%, and 1% microcapsule additions indicate several trends (Figure 8). For unaged specimens, increased microcapsule content leads to higher levels of saturates and aromatics while decreasing asphaltenes, a trend also observed in STA specimens but with more modest changes. LTA specimens show a notable increase in saturates and resins, particularly at higher microcapsule content. This enhancement is likely due to rejuvenating oil being released from microcapsules during repeated dynamic loading, which helps rejuvenate bitumen properties, restoring flexibility and resilience.

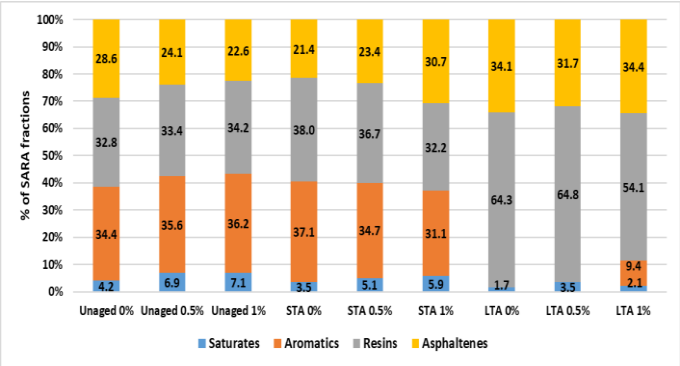

Figure 8. Comparison of SARA fractions for Unaged, STA, and LTA samples with 0%, 0.5%, and 1% microcapsule addition.

The increased maltene components across all aging conditions suggest improved bitumen performance, especially in LTA specimens where resin levels rise significantly. Conversely, higher microcapsule additions decrease asphaltene content, indicating a breakdown of heavier components into lighter fractions. Overall, the results demonstrate the effectiveness of microcapsules in improving bitumen properties through the gradual release of rejuvenating agents during mechanical stress.

6 CONCLUSIONS

This study examined the effects of microcapsule-encapsulated rejuvenators on asphalt mix performance. Calcium alginate capsules containing rejuvenator oil were synthesized and added to asphalt mixes at dosages of 0%, 0.5%, and 1% by weight. Various tests, including ITS, moisture resistance, resilient modulus, dynamic creep, and SARA fractionation, were conducted on unaged, STA, and LTA mixes. Key findings indicate that the capsules have a uniaxial compressive strength of 18 N and can withstand temperatures up to 200°C without any degradation. The microcapsules did not significantly affect volumetric properties or moisture resistance, but increased dosage slightly decreased resilient modulus due to potential capsule breakage under load. SARA analysis showed improved bitumen properties with increased maltene components and decreased asphaltenes, enhancing flexibility and resilience. Dynamic creep tests indicated that while permanent strain accumulation increased with more microcapsules, rutting performance remained largely unaffected. In conclusion, microcapsule-encapsulated rejuvenators can enhance the self-healing properties of asphalt by gradually releasing rejuvenating agents, supporting future research to optimize capsule formulations for improved pavement lifespan.

7 ACKNOWLEDGMENTS

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