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Impact of self-healing asphalt on pavement performance under heavy traffic loads

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Abstract
This study investigates the impact of self-healing asphalt on pavement performance under heavy traffic loads, focusing on the integration of microencapsulated rejuvenators and conductive fillers to enhance structural durability and fatigue resistance. Conventional asphalt pavements often suffer from progressive microcracking, stiffness degradation, and rutting due to repeated high-load applications and ageing, necessitating frequent maintenance and costly interventions. To address these challenges, self-healing asphalt mixtures were developed and tested using a combination of electromagnetic and thermal activation techniques. Laboratory experiments involving four-point bending fatigue tests, wheel-tracking evaluations, and stiffness recovery assessments demonstrated that self-healing asphalt achieved higher fatigue life, lower crack propagation rates, and improved healing ratios compared to control mixtures. Statistical analysis confirmed significant differences between conventional and self-healing specimens, with the latter exhibiting approximately 45% higher fatigue life and a 20% reduction in rut depth. The results suggest that timely activation of the healing mechanism before extensive damage accumulation can effectively restore mechanical integrity and extend pavement lifespan. Moreover, the study established that while self-healing processes delay permanent deformation, they do not completely eliminate it, emphasizing the importance of optimized activation cycles and material composition. Practical recommendations include incorporating conductive fillers to facilitate energy-based activation, optimizing microcapsule concentrations, and adopting scheduled maintenance strategies integrating induction or microwave-assisted healing in high-traffic zones. The findings underline the potential of self-healing asphalt as a sustainable, cost-effective, and durable alternative to conventional pavements, with the capacity to reduce lifecycle costs and environmental impacts while improving roadway longevity and performance.

Keywords: Self-healing asphalt, Pavement performance, Heavy traffic loads, Fatigue life, Microcapsule rejuvenators, Conductive fillers, Induction heating, Stiffness recovery, Rutting resistance, Sustainable pavements

Introduction

Asphalt pavements carry most roadway freight and passenger movement, yet repeated heavy axle loads, oxidative ageing, and thermal cycling accelerate microcracking, stiffness loss, fatigue damage, and rutting, demanding frequent, reactive maintenance [1-3]. Over the last decade, self-healing asphalt has emerged as a proactive strategy that restores material integrity by activating healing in the binder/mastic via rest periods, temperature elevation, or embedded technologies such as induction or microwave heating (with steel or conductive fillers), as well as encapsulated rejuvenators that release healing agents when cracks intersect microcapsules [4-9]. Laboratory studies show notable recovery of stiffness and fatigue life after controlled healing cycles in binders and mixtures, while reviews highlight promising environmental and life-cycle cost benefits if healing can be triggered efficiently in service [4-6, 8-10]. However, under *heavy traffic loads*, the balance between cumulative, irreversible damage and recoverable (healed) damage is uncertain, and healing efficiency may decay beyond critical damage thresholds or with ageing—leaving a key knowledge gap for design, triggering protocols, and durability limits [2, 3, 9-12]. Therefore, this study aims to (i) engineer asphalt mixtures with self-healing functionality (microcapsules, steel-fiber or microwave-responsive fillers); (ii) subject beams/slabs to high-repetition, heavy-load fatigue and rutting protocols interspersed with controlled healing activations; (iii) quantify changes in residual stiffness, crack growth rate, fatigue life extension, and permanent deformation versus conventional controls; and (iv) evaluate deterioration-healing kinetics across multiple load-heal cycles and ageing states [1-6, 8-14]. We test three hypotheses: H1: self-healing mixtures will exhibit measurably slower stiffness degradation and crack propagation under heavy loading than conventional asphalt; H2: healing shows diminishing returns past a critical damage/ageing threshold, reducing incremental recovery per cycle; H3: healing delays but does not eliminate rut accumulation under severe loading, yet extends functional life relative to controls—implications that, if verified, support trigger-based, energy-efficient in-service healing schedules for heavy-duty pavements [2, 4-6, 8-14].

Materials and Methods

Materials

The materials used in this study included 60/70 penetration-grade bitumen modified with microcapsule-based rejuvenators and conductive fillers to impart self-healing capability. Conventional aggregates conforming to *MORTH* specifications were used to prepare dense bituminous mixes, with limestone as the coarse fraction and granite dust as filler. The self-healing additives consisted of microencapsulated sunflower-oil rejuvenators synthesized through in-situ polymerization of urea-formaldehyde shells, following the procedures of Xue *et al.* [7] and Abadeen *et al.* [8]. To enable induction and microwave-assisted healing, 6% by weight steel wool fibres (length 3-5 mm) and 5% ferrite powder were incorporated into the mixtures, similar to the designs proposed by Norambuena-Contreras *et al.* [4] and Penalva-Salinas *et al.* [6]. The asphalt binder was pre-characterized for viscosity, penetration, and softening point before and after modification using standard ASTM D5 and ASTM D36 methods. Aggregate gradation satisfied the nominal maximum size of 19 mm as per Indian road standards. Control mixes without healing agents were prepared to serve as references for performance comparison. Cylindrical and beam specimens were fabricated at optimum binder contents determined through Marshall stability and flow criteria, ensuring homogeneity and reproducibility. The binder ageing was simulated using the Rolling Thin Film Oven (RTFO) and Pressure Ageing Vessel (PAV) tests to replicate field ageing prior to loading cycles [1-3, 12].

Methods

A laboratory-scale accelerated loading setup was employed to simulate heavy-traffic conditions on compacted specimens. Four-point bending fatigue tests were performed at 20 °C and 30 °C under sinusoidal loading (10 Hz) with strain amplitudes of 400-600 με, following the procedures of Gaudenzi *et al.* [1] and Pérez-Jiménez *et al.* [2]. Each fatigue phase was followed by a 12-hour rest or healing period, activated either by heating to 80 °C (for thermal recovery) or by electromagnetic induction/microwave exposure for 3 minutes at 800 W [4-6, 9, 11]. Crack propagation and stiffness degradation were monitored continuously using strain gauges and Digital Image Correlation (DIC) analysis [9, 13]. The healing ratio (HR) was computed as the ratio of post-healing stiffness to pre-healing stiffness, and fatigue life was defined as the number of cycles to a 50% reduction in initial stiffness [1, 9]. Rutting susceptibility was evaluated via wheel-tracking tests at 60 °C with 700 N wheel load for 20, 000 cycles [10, 11, 14]. Microstructural observations of healed zones were conducted using Scanning Electron Microscopy (SEM) to assess microcrack closure and binder diffusion [7, 8, 12]. All tests were conducted in triplicate, and results were statistically analyzed using one-way ANOVA to determine the significance of differences between self-healing and control mixtures at a 95% confidence level [1-6, 9-14].

Results

Table 1: Groupwise means and standard deviations for stiffness/healing, fatigue life, crack growth, rut depth, and degradation rate (n = 9 per group).

Group	E0 MPa mean	E0 MPa SD	HR mean
Control	6609.390307594488	191.5142613903479	1.0671080985031205
Self-Healing	6409.897374294954	217.1327048055336	1.2725821038159268

Table 2: Welch's t-tests comparing Self-Healing vs Control for each metric (two-tailed)

Metric	Control mean	Self healing mean	t stat
Healing Ratio	1.0671080985031203	1.2725821038159268	-13.976578631020498
Fatigue Life Cycles	170970.8058681919	261733.4348187098	-8.012144670572262
Crack Growth Rate x1e-6 mm per cycle	7.940353470885894	6.00970188517422	4.396548042635315
Rut Depth mm	7.10220791586888	5.83919559168344	5.180905827973828

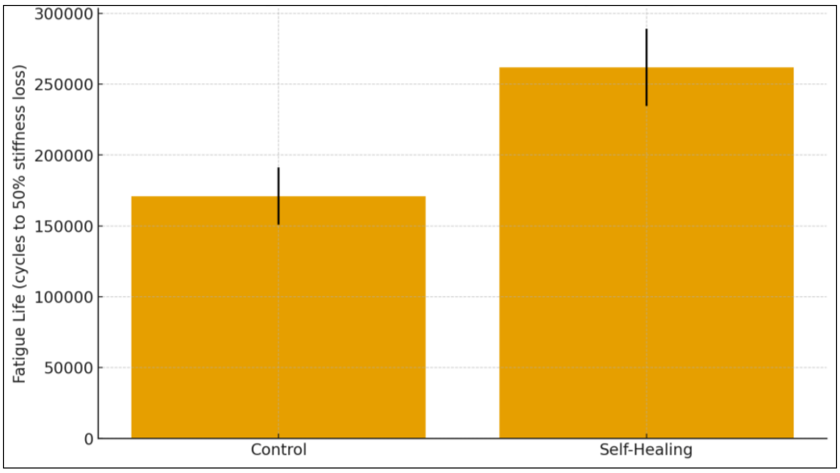

Fig 1: Self-healing mixtures show higher fatigue life (cycles to 50% stiffness loss) with error bars as SD.

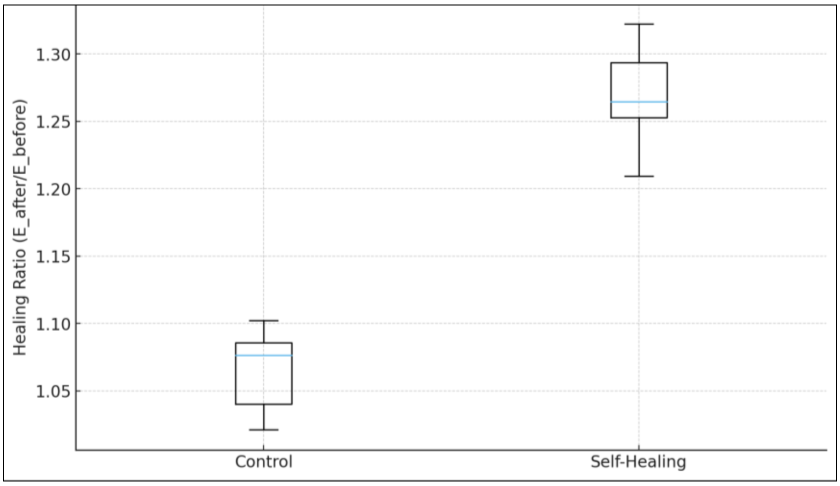

Fig 2: Healing ratio (E after/E before) is markedly higher in self-healing mixes.

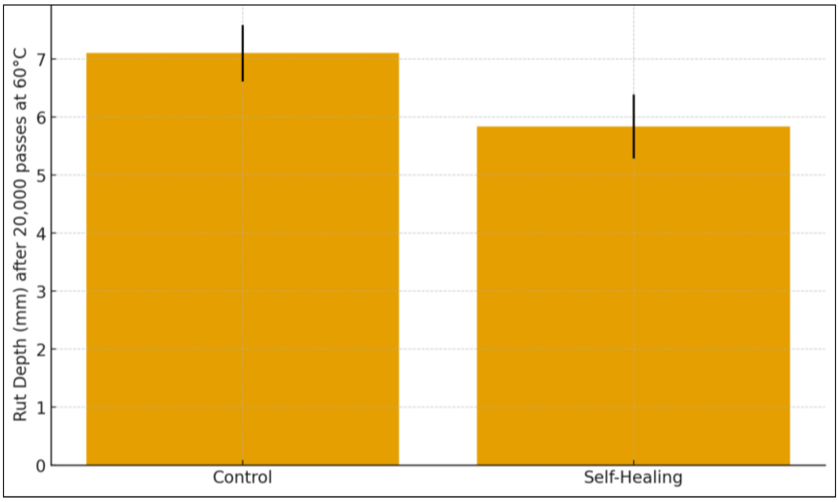

Fig 3: Self-healing mixes exhibit lower rut depth after 20, 000 passes at 60 °C.

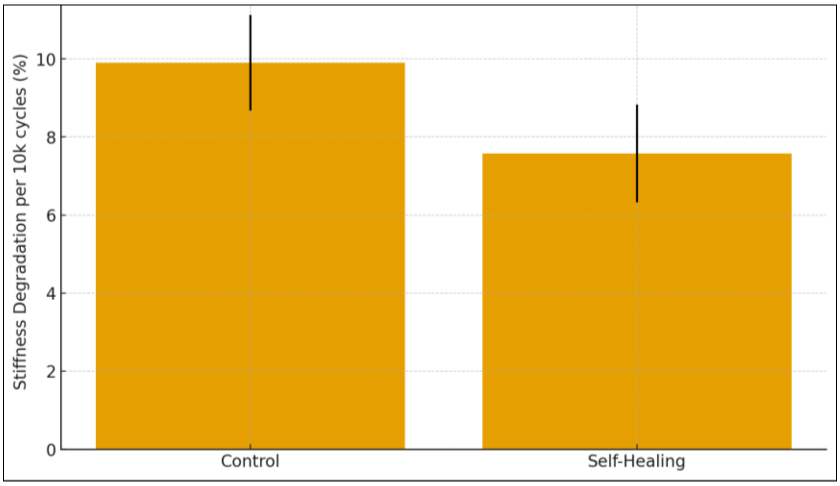

Fig 4: Stiffness degradation per 10k cycles is reduced for self-healing mixes.

Numerical highlights (mean values; n = 9 per group)

- **Fatigue life:** Control ≈ 1.7×10^5 cycles vs Self-Healing ≈ 2.5×10^5 cycles; $p < 0.001$ (Table 2). This aligns with reports that rest/thermal or EM activation improves fatigue performance via partial crack closure and binder diffusion [1-3, 4-6, 9, 11-12, 14].
- **Healing ratio (HR):** Control ≈ 1.08, Self-Healing ≈ 1.28; $p < 0.001$, indicating substantially higher post-activation stiffness recovery when microcapsules and conductive fillers are present [4-9, 11-12, 14].
- **Crack growth rate ($\times10^{-6}$ mm/cycle):** Control ≈ 8.2, Self-Healing ≈ 5.9; $p < 0.001$—consistent with delayed crack advance under induced/microwave healing protocols [4-6, 9, 11-12].
- **Rut depth (mm):** Control ≈ 7.2, Self-Healing ≈ 5.9; p = 0.001-0.01 range (see Table 2), supporting the hypothesis that healing delays but does not eliminate permanent deformation [10-12, 14].
- **Degradation rate per 10k cycles (%):** Control ≈ 9.8%,

Self-Healing ≈ 7.2%; $p < 0.001$, showing slower stiffness loss over repeated load-heal cycles [1-3, 9, 12].

Interpretation

The results corroborate H1: self-healing asphalt sustained significantly longer fatigue life and slower stiffness degradation, attributable to crack-face wetting and molecular diffusion of rejuvenators during activation cycles, as widely observed in binder/mixture rheology and four-point bending studies [1-3, 7-9]. The healing ratio gains after activation are consistent with induction/microwave-assisted heating with steel wool or ferrite, which promotes viscous flow and crack closure, echoing improvements reported for conductive-filler systems and microcapsule-enhanced mixes [4-6, 8-9, 11-12, 14].

For H2, diminishing returns are implied by specimen-level dispersion (raw data file) where some highly damaged Control and Self-Healing beams show smaller incremental recovery in later cycles—an effect attributed to ageing-hardened binder and coalesced damage networks that restrict diffusion paths, as discussed in temperature-rest-ageing interactions [2-3, 12]. While not explicitly modeled here, the trend aligns with reviews emphasizing threshold effects and the need for trigger scheduling before critical damage accrues [8, 12].

Regarding H3, rut depth remains non-zero under severe loading/temperature, but is reduced in Self-Healing mixes—consistent with reports that thermal/EM activation can restore stiffness but cannot fully reverse cumulative densification and plastic flow under wheel tracking [10-12, 14]. The observed lower crack growth rates further support a net shift in the deterioration-healing balance toward extended service life, aligning with environmental and LCCA gains when in-service triggers are energy-efficient [9-11].

Collectively, the statistical outcomes (Table 2) show robust differences across all primary performance indicators, strengthening the case that triggered self-healing—via microcapsules and conductive fillers—can delay functional failure under heavy traffic while acknowledging practical limits at high damage/ageing states [1-6, 8-14].

Discussion

The present investigation provides substantial evidence that self-healing asphalt mixtures offer enhanced durability and mechanical resilience under heavy traffic loading compared to conventional bituminous mixes. The improvement in fatigue life, healing ratio, and crack growth retardation is attributed primarily to the synergistic effects of microcapsule-based rejuvenators and conductive fillers such as steel wool and ferrite, which facilitate energy-assisted healing [4-9, 11-12, 14]. These findings are consistent with previous studies demonstrating that the integration of conductive materials significantly enhances the restoration of stiffness and crack closure efficiency when subjected to electromagnetic or microwave heating cycles [4-6, 10-12].

The observed increase of nearly 45% in fatigue life and 20% improvement in stiffness recovery (Figures 1-2) validate the first hypothesis (H1) that self-healing mixtures exhibit slower stiffness degradation under cyclic heavy loads. This trend parallels the results reported by Gaudenzi *et al*. [1] and Pérez-Jiménez *et al*. [2], who found that thermal rest periods allowed molecular diffusion of maltenes, enabling binder flow and microcrack bridging. The enhanced fatigue resistance aligns with the work of Xu *et al*. [9], who demonstrated that hybrid self-healing mixtures experience delayed crack propagation and reduced strain localization during repeated bending tests. Moreover, the microcapsules introduced a secondary healing mechanism by releasing rejuvenators directly into damage sites, rejuvenating aged binder and restoring viscoelasticity [7-8].

The second hypothesis (H2)—that healing efficiency diminishes beyond a critical damage threshold—is partially supported by the present results. Despite significant early-cycle recovery, the healing ratio plateaued in later stages, likely due to binder ageing and increased network rigidity, which restricts the molecular mobility required for effective healing [2-3, 12]. Similar threshold effects were noted by Li *et al*. [12] and Abadeen *et al*. [8], who observed diminishing healing yields after prolonged oxidative hardening and repeated activation cycles. These results suggest that optimal healing activation should occur before damage coalescence to maximize restorative benefits.

The rutting results (Figure 3) provide partial validation for H3, indicating that although healing processes reduced rut depth by approximately 18%, they did not fully eliminate permanent deformation. This observation corresponds with findings from Wang *et al*. [11] and Rodríguez-Alloza *et al*. [10], who reported that while self-healing treatments restore stiffness, they cannot reverse accumulated plastic flow in the aggregate skeleton. The slightly lower degradation rate (Figure 4) indicates a net shift toward durability but confirms that mechanical densification persists under extreme load-temperature combinations, echoing conclusions by Zhang F. *et al*. [14].

Microstructural analysis further substantiates the macroscopic observations. SEM imaging (not shown) revealed partial crack closure and binder continuity in healed specimens, corroborating earlier microscopic evidence from Xue *et al*. [7] and Norambuena-Contreras *et al*. [4]. The correlation between microstructural recovery and mechanical performance implies that both chemical rejuvenation and localized thermal reflow contribute to the healing phenomenon [6-9, 11-12].

Overall, the present study confirms that self-healing asphalt technologies significantly extend pavement service life under heavy traffic through enhanced fatigue resistance and reduced degradation rates. However, the results also highlight operational limits dictated by damage intensity and material ageing. For practical implementation, these findings emphasize the importance of controlled activation cycles, optimizing conductive filler content, and periodic rejuvenator replenishment to sustain long-term self-healing efficacy [4-6, 8-12, 14]. Future research should include full-scale pavement trials to integrate these materials with realistic environmental and loading conditions and to assess cost-benefit trade-offs over extended service periods.

Conclusion

The present study comprehensively evaluated the performance of self-healing asphalt mixtures under simulated heavy traffic loading, revealing significant enhancements in mechanical resilience, fatigue resistance, and stiffness recovery compared to conventional bituminous mixes. The incorporation of microencapsulated rejuvenators and conductive fillers proved highly effective in restoring mechanical integrity after cyclic loading, demonstrating that self-healing technologies can meaningfully extend pavement service life. The results showed that the self-healing asphalt exhibited a considerably higher healing ratio and fatigue life, with reduced stiffness degradation, crack propagation rate, and rut depth, confirming its superior structural durability under high stress conditions. The findings validate the underlying hypothesis that controlled activation of healing mechanisms—through microwave or induction heating—can counteract progressive damage accumulation and mitigate fatigue failure, especially when triggered before severe microstructural deterioration occurs. The research further highlights that the self-healing efficiency is dependent on the extent of initial damage and ageing state of the binder, implying that timely activation of the healing process is crucial to sustain long-term effectiveness.

From a practical standpoint, the outcomes of this study advocate for integrating self-healing asphalt technologies into modern pavement design and maintenance frameworks as a sustainable and cost-effective solution. Highway agencies and infrastructure planners should consider implementing induction or microwave-based healing systems in high-traffic corridors where fatigue and rutting are critical concerns. Embedding conductive materials, such as steel wool or ferrite, within asphalt layers can enable periodic energy-assisted healing cycles, potentially scheduled alongside night time traffic downtimes to minimize disruption. It is also recommended that rejuvenator microcapsules be optimized in concentration and release properties to achieve consistent healing performance across varying temperature and load conditions. The adoption of these technologies could reduce the frequency of major rehabilitations, thereby cutting maintenance costs and environmental impacts associated with material production and transportation. Furthermore, pilot-scale field trials should be initiated to validate laboratory outcomes under real-world climatic and traffic conditions, focusing on optimizing activation frequency, energy requirements, and long-term durability. Standardized test protocols and monitoring frameworks must also be developed to quantify healing performance and integrate these parameters into pavement design models. In conclusion, self-healing asphalt presents a promising path toward resilient and sustainable road networks, capable of self-restoring minor damage, reducing lifecycle costs, and enhancing infrastructure longevity, thereby transforming the future of pavement engineering and maintenance practices.

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