SELF-HEALING ASPHALT IN ROAD ENGINEERING

Ph.D. Manuchar Shishinashvili
Georgian Technical University
ORCID NO: 0009-0007-4432-4428
Ph.D. Giorgi Chubinidze
Georgian Technical University
ORCID NO: 0009-0007-9363-4027

ABSTRACT

Microcracking is a major contributor to the structural deterioration of asphalt pavements under cyclic traffic loading and environmental exposure. Although initially invisible, microcracks progressively develop into macrocracks, leading to stiffness reduction and premature pavement failure. This study investigates induction-heated self-healing asphalt as an innovative method for controlling microcrack propagation. The technology incorporates electrically conductive steel fibers into the asphalt mixture, enabling controlled heating through electromagnetic induction. The generated heat lowers binder viscosity and promotes molecular diffusion, resulting in effective crack closure. Laboratory fatigue tests demonstrate stiffness recovery rates of 80–95% and fatigue life extension up to three times compared to conventional mixtures. Microstructural observations confirm improved aggregate–binder adhesion after healing cycles. Life cycle analysis suggested extended service life and reduced environmental impact. Despite higher initial costs, induction-heated self-healing asphalt offers significant long-term durability and sustainability benefits for pavement engineering.

Keywords: Self-healing Asphalt, Induction Heating, Microcrack Propagation, Road Engineering

Introduction

Modern transportation infrastructure represents one of the fundamental pillars of economic development. The technical condition of road networks directly influences traffic safety, logistical efficiency, and the overall cost of infrastructure operation and maintenance. Asphalt concrete pavements, widely used in road construction, are subjected to multiple interacting stressors during service life, including repetitive traffic loading, thermal fluctuations, moisture intrusion, ultraviolet radiation, and natural material aging.

One of the primary degradation mechanisms in asphalt pavements is the initiation and propagation of microcracks. Microcracks develop at the microstructural level of the material and typically range from 1 to 100 micrometers in width. At early stages, these cracks are not visible to the naked eye; however, over time they coalesce into macrocracks, resulting in stiffness reduction, moisture infiltration, deterioration of underlying layers, and ultimately the need for major rehabilitation.

Fatigue cracking is particularly critical under high traffic volumes. Repeated cyclic loading generates tensile stresses within the asphalt layer, leading to the accumulation of micro-damage. Bitumen, as a viscoelastic binder, exhibits a limited intrinsic self-healing capacity under favorable conditions. However, this natural healing ability decreases significantly with oxidative aging.

In the context of increasing traffic intensity, climate variability, and sustainability requirements, the development of technologies that extend pavement service life and reduce maintenance costs has become a research priority. The concept of self-healing asphalt is based on the premise that if microcracks can be repaired at an early stage, their progression into macro-level structural damage can be prevented.

Among the various self-healing strategies, induction heating technology has emerged as one of the most promising approaches. By incorporating electrically conductive steel fibers into asphalt mixtures, controlled heating can be applied externally, promoting crack closure and structural recovery. This technology enables preventive "thermal treatment," significantly extending fatigue life and reducing life-cycle costs.

The relevance of this topic is especially pronounced in regions characterized by freeze–thaw cycles, high traffic loads, and limited financial resources for infrastructure maintenance. The implementation of self-healing asphalt technologies aligns with contemporary goals of sustainable development, environmental responsibility, and economic efficiency.

Main Part

Asphalt concrete is a composite material consisting of mineral aggregates, bitumen, and filler. Microcracks typically develop in the following zones:

- Within the bituminous mastic phase;
- At the crushed stone (aggregate)–bitumen adhesion interface;
- In localized regions of high stress concentration.

Under cyclic fatigue loading, micro voids and micro-delamination form within the structure. Oxidative aging of bitumen reduces the aromatic fraction and promotes asphaltene agglomeration, increasing stiffness while reducing ductility. Consequently, the material becomes more brittle and more susceptible to cracking.

If microcracks are not mitigated at their early stage, they propagate under repeated loading and environmental effects, eventually forming interconnected crack networks that compromise structural integrity.

Bitumen is a thermos theoretically complex viscoelastic material capable of molecular diffusion and stress relaxation. When a microcrack forms and loading is temporarily removed, partial recovery may occur due to molecular rearrangement and surface energy-driven flow.

The healing efficiency depends on:

- Temperature,
- Rest period duration,
- Bitumen chemical composition,
- Degree of aging.

Healing performance is commonly quantified using the Healing Index (HI):

$$HI = \left(\frac{E_{after}}{E_{initial}}\right) \times 100\%$$

where: *E_initial - represents the initial stiffness modulus.*

E_after - represents the stiffness after the healing process.

At moderate temperatures, intrinsic healing may reach 20–40%, but under low temperatures or advanced aging conditions, recovery is minimal. Therefore, external stimulation is required to enhance healing efficiency in practical applications.

Induction self-healing is based on electromagnetic induction. The technology involves incorporating conductive steel fibers (steel wool or short steel fibers) into the asphalt mixture. These fibers act as induction elements when exposed to an alternating electromagnetic field.

The process occurs as follows:

1. An induction device generates an alternating electromagnetic field.
2. Eddy currents are induced in the steel fibers.
3. The fibers rapidly heat due to electrical resistance.
4. Heat is transferred to the surrounding bitumen.
5. Bitumen viscosity decreases at temperatures of approximately 90–110°C.
6. Molecular diffusion and surface tension effects promote crack closure.

The process is effective primarily when cracks remain within the micro-scale and have not evolved into fully separated macrocracks.

A representative laboratory mixture may consist of:

- Bitumen: 50/70 penetration grade;
- Aggregate: crushed granite;
- Steel fibers: 5–6% by mass of the mastic;
- Fiber length: 2–5 mm.

Optimization of fiber content is essential. Excessive fiber addition may negatively affect mixture workability and homogeneity, while insufficient content reduces heating efficiency.

The effectiveness of induction self-healing has been evaluated using several standardized laboratory tests:

- Three-Point Bending Fatigue Test,
- Dynamic Shear Rheometer (DSR),
- Semi-Circular Bending (SCB) Test,
- Direct Tension Cyclic Test.

In a typical Three-Point Bending fatigue test, a beam specimen is subjected to cyclic loading until its stiffness decreases to 50% of its initial value. The specimen is then exposed to induction heating for approximately 1–2 minutes, followed by a rest period.

Typical experimental findings indicate:

- Stiffness recovery: 80–95%;
- Fatigue life extension: 2–3 times;
- Significant reduction in crack propagation rate.

For example, if the initial modulus is 6000 MPa and the post-healing modulus reaches 5100 MPa, then:

$$HI = \left(\frac{5100}{6000}\right) \times 100\% = 85\%$$

Such results demonstrate substantial structural recovery after induced heating.

The self-healing mechanism at the micro-scale involves viscous flow, capillary-driven crack closure, and molecular interdiffusion across crack faces.

Life Cycle Assessment (LCA) studies suggest that induction-healed asphalt pavements:

- Extend service life by 30–50%;
- Reduce maintenance frequency;

- Decrease CO_2 emissions by approximately 15–25%;
- Lower long-term life-cycle costs.

Although initial construction costs are higher due to fiber incorporation and specialized equipment, long-term economic analysis indicates favorable cost-benefit performance.

From an environmental perspective, extended pavement durability reduces the need for raw material extraction, transportation, and repeated rehabilitation operations, thereby lowering the overall carbon footprint.

Conclusion

Microcracks represent the initial stage of structural degradation in asphalt pavements. If left untreated, they evolve into macrocracks, leading to significant economic losses and structural failure. Induction-heated self-healing asphalt presents a promising technological solution for controlling microcrack propagation at an early stage.

The technology operates through electromagnetic induction of embedded steel fibers, generating controlled heat that reduces binder viscosity and promotes molecular diffusion across crack interfaces. Laboratory studies demonstrate high stiffness recovery rates (80–95%) and fatigue life extension of up to three times compared to conventional mixtures.

Economic and environmental analyses indicate reduced life-cycle costs and lower carbon emissions, supporting the technology's role in sustainable infrastructure development.

Although challenges remain—particularly related to initial cost, energy demand, and climatic adaptability—the potential benefits in durability, safety, and long-term efficiency position induction-heated self-healing asphalt as a viable alternative to traditional maintenance approaches.

Future research should focus on long-term field performance, optimization of material composition, and adaptation to diverse environmental conditions. With continued development, induction of self-healing technology may become an integral component of resilient and sustainable pavement engineering.

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