

Application of Self-Healing Technology in Bituminous Pavement Construction Using Steel Fibres and Polymer Modifiers

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Abstract - Bituminous pavements are prone to deterioration due to repeated traffic loading, environmental effects, oxidation, and temperature fluctuations, leading to micro-cracks that eventually develop into major pavement failures. Self-healing bitumen technology has emerged as an innovative approach to enhance pavement durability and reduce maintenance costs. This study investigates the effectiveness of incorporating steel wool fibres and SBS polymer modifiers into VG30 bitumen to improve its self-healing characteristics. Steel fibres act as conductive elements that enable induction heating, allowing the bitumen to regain its original properties by closing micro-cracks through thermal activation, while polymer modification enhances elasticity, flexibility, and resistance to permanent deformation. The combined use of steel fibres and polymers was evaluated through softening point, penetration, ductility, viscosity, and Marshall Stability tests. Results indicate that the addition of steel fibres and polymers significantly improves the self-healing capacity, fatigue resistance, and service life of bituminous mixtures, with Marshall Stability increasing from an average of 1227 kg to about 1754 kg upon modification. The technology offers a sustainable and cost-effective solution for extending pavement life, reducing maintenance interventions, and improving road infrastructure performance.

Key Words: Self-Healing Bitumen, Steel Wool Fibre, SBS Polymer, Induction Heating, Bituminous Pavement, Marshall Stability, Crack Healing

1. INTRODUCTION

Self-healing bitumen is an innovative material designed to automatically repair small cracks and micro-damages within the asphalt binder without external intervention. Research in this field is focused on improving the self-healing ability of bitumen through additives such as polymers, rejuvenators, and microcapsules, as well as activation techniques like induction heating.

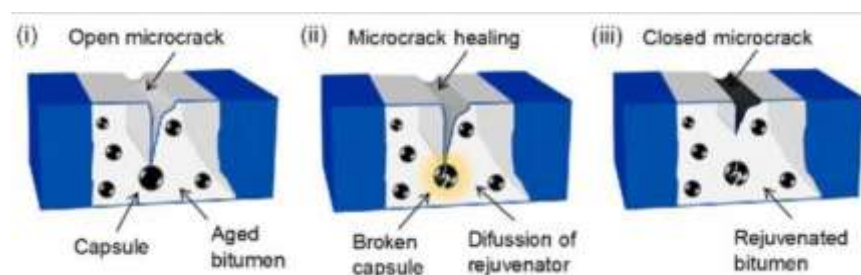


Fig 1: Self-healing of cracks by micro-capsules

Asphalt pavements are prone to various types of deterioration over time, such as cracking, rutting, and ravelling, caused by repetitive traffic loading, temperature variations, and environmental factors. Among these, micro-cracking is one of the earliest signs of distress, which, if left unattended, can propagate and lead to significant structural failure and costly repairs. To address these challenges, the concept of self-healing asphalt has emerged as a promising innovation in pavement engineering, drawing inspiration from biological systems capable of natural healing, with the aim of extending pavement service life while reducing maintenance costs and environmental impact.

One effective method of enhancing self-healing in bituminous mixtures is the incorporation of steel wool fibres. These conductive fibres allow the asphalt mixture to be heated through electromagnetic induction, which softens the bitumen and promotes the healing of cracks. In addition to improving self-healing capability, steel wool fibres enhance the mechanical properties and durability of the pavement. While several studies have quantified macroscopic damage recovery mechanically, not all such recovery can be attributed to true self-repair, since viscoelastic responses can also recover damage during rest periods. This research therefore focuses on bituminous roads incorporating steel fibres, while recognising that the same principle of induction-based self-healing can be extended to any bituminous road surface.

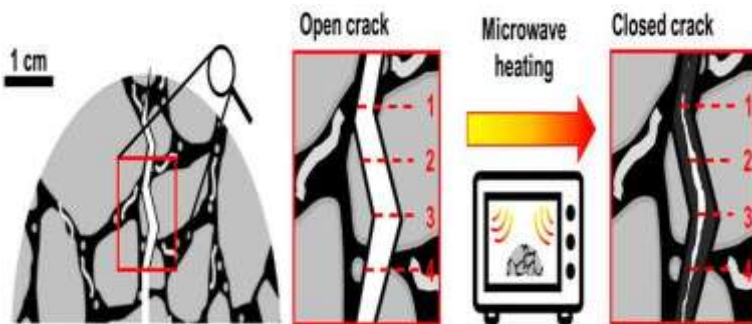


Fig 2: Self-healing of cracks with steel fibres under microwave heating

1.1 Problem Statement

Conventional asphalt pavements are highly susceptible to damage over time due to heavy traffic loads, temperature fluctuations, oxidation, and moisture infiltration. These stresses lead to the formation of micro-cracks that progressively expand into larger cracks and potholes if not treated promptly. The need for frequent maintenance and rehabilitation not only results in high economic costs but also causes traffic disruptions, environmental pollution, and increased consumption of natural resources.

1.2 Aim and Objectives

Aim: To develop and evaluate self-healing bituminous pavement incorporating healing materials for enhanced crack resistance, extended service life, and reduced maintenance frequency.

- To evaluate the parameters of self-healing bitumen by conducting different types of induction-based tests.
- To examine the effects of materials (steel wool fibres, SBS polymer) on healing ability.
- To identify the best conditions (temperature, rest time) for crack repair.

2. LITERATURE REVIEW

2.1 Self-Healing of Open Cracks in Asphalt Mastic (Alvaro Garcia, Elsevier)

Asphalt mastic is a self-healing material; once a crack opens in the pavement it begins to heal and, given sufficient rest time, can close completely. Self-healing in asphalt mastic is directly linked to temperature and rest period and can be classified as a thermally induced phenomenon. The changes in self-healing rate with temperature were related using the Arrhenius equation, and capillary flow through the crack was hypothesised as the primary cause of healing, a hypothesis confirmed visually through CT-scan imaging of healed asphalt beams.

2.2 Self-Healing Technology for Asphalt Pavements (Jin Tang, Quantao Lio, Erik Schlangen, Elsevier)

Induction heating in asphalt pavement design was pioneered by Minsk, who developed the first electrically conductive asphalt pavement using graphite to melt snow and ice by induction heating. Subsequent research demonstrated that electrically conductive fibres and fillers, such as carbon fibres, graphite, steel fibres, steel wool, and conductive polymer Polyaniline (PANI), significantly alter electrical resistivity depending on fibre type, shape, and size, with conductive fibres proving more effective than conductive fillers. Researchers further developed self-healing asphalt mixes by incorporating electrically conductive steel and wool fibres and activating healing through induction heating.

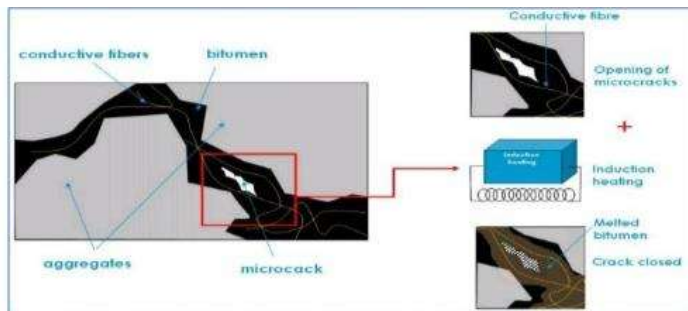


Fig 3: Induction heating mechanism in porous asphalt containing conductive fibres

Binder rejuvenation was also studied as a healing mechanism: as bitumen ages, oxidation converts oils into resins and resins into asphaltenes, resulting in age-hardening. Although this ageing process is irreversible, the viscoelastic state of aged bitumen can be partially recovered through rejuvenating agents such as cationic emulsions. Nanoclay materials have also shown potential to repair micro-cracks, as nanoparticles migrate toward the crack tip under high surface energy and arrest crack propagation, although long-term performance data remains limited.

2.3 Investigation of Optimal Self-Healing Temperatures and Healing Time of Asphalt Binders (Jose Norambuena-Contreras, Materials & Design)

Using a Dynamic Shear Rheometer (DSR) frequency sweep test, the flow behaviour of penetration-grade bitumens (Pen 70 and Pen 90) was studied across a range of temperatures to identify optimal self-healing conditions. Fatigue-healing-fatigue testing confirmed that both binders exhibit a peak self-healing ratio in the range of approximately 40-45°C, beyond which the healing ratio plateaus or slightly declines. Pen 70 (harder grade) is better suited to hot climates and heavy traffic, while Pen 90 (softer grade) performs better in colder regions owing to greater flexibility and reduced cracking tendency.

2.4 Self-Healing of Asphalt Using Steel Fibres (Kishan V. Purohit, Jignesh K. Rathod, IntechOpen)

Marshall specimens incorporating steel fibres were prepared by heating aggregates and bitumen-fibre blends at 150°C and compacting them using 75 blows per face with a Marshall hammer. To verify that fibre-reinforced mixtures could be heated using induction/microwave energy, specimens with and without steel fibres were exposed to microwave radiation for varying durations (20-120 seconds) and their surface temperature rise was monitored using an infrared camera. The results confirmed those mixtures containing steel fibres exhibited a markedly faster and more uniform temperature rise than mixtures without fibres, validating the feasibility of induction-based crack healing.

3. METHODOLOGY

The research methodology adopted for this study is divided into four major stages: library research, field research, material research, and laboratory research, each contributing to building a comprehensive understanding of the topic and validating findings through practical investigation, as summarised in Table 1.

Table 1: Research Methodology Framework

Stage	Activities
Library Research	Analysis of historical records, research papers and case studies
Field Research	Visiting research laboratories; material study of induction-heating, microcapsule-based and rejuvenator-based self-healing systems
Material Research	Selection of Steel Wool Fibre, SBS Polymer and VG30 Bitumen
Laboratory Research	Softening point, penetration, ductility and viscosity tests on bitumen; Marshall Stability and abrasion tests on the mix

3.1 Self-Healing Mechanisms Investigated

- Induction Heating-based: Use of steel fibres, steel wool, or magnetic particles in the mix; asphalt is heated using an electromagnetic induction coil to activate bitumen flow.
- Microcapsule-based: Microcapsules filled with rejuvenator or healing agents are added to the asphalt; when cracks occur, the capsules break and release the healing material.
- Rejuvenator-based: Incorporation of rejuvenators, vegetable oils, or bio-oils that diffuse into aged bitumen to restore its ductility.

3.2 Mix Design and Sample Preparation

Standard asphalt mix design methods (Marshall method) were followed and modified to include self-healing components, ensuring uniform distribution of fibres and polymer, followed by preparation of cylindrical Marshall specimens for testing.

3.3 Materials Used

- Coarse Aggregate (10 mm): 50% — 600 g
- Stone Dust: 25% — 200 g
- Bitumen (VG30): 5% — 60 g
- Steel Wool Fibre: 2% — 1.2 g
- Limestone Dust: 50 g
- Grit (6 mm): 20% — 240 g
- SBS Polymer: 48 g

3.4 Laboratory Tests Conducted

Softening Point Test (Ring & Ball apparatus, IS 1205): A bitumen-filled brass ring with a steel ball positioned on top was heated at a uniform rate of 5°C/min in a water/glycerin bath; the temperature at which the ball, with the softened bitumen, falls through a height of 25 mm was recorded to determine temperature susceptibility.

Penetration Test (IS 1203): Bitumen conditioned at 25°C was subjected to a standard needle under a 100 g load for 5 seconds; the depth of penetration (in 0.1 mm units) was measured to classify the bitumen grade and assess consistency.

Ductility Test (IS 1208): A briquette specimen conditioned at 27°C was pulled apart at a uniform rate of 50 mm/min in a ductility testing machine; the distance at which the bitumen thread broke was recorded to assess elasticity and adhesive properties.

Absolute Viscosity Test (IS 1206): A capillary viscometer filled with fluid bitumen was placed in a constant-temperature bath at 60°C under vacuum, and the time for bitumen to flow between two marked points was used to calculate absolute viscosity.

Marshall Stability Test: Cylindrical specimens (100 mm diameter, 63.5 mm height) were compacted with 75 blows per face, conditioned in a water bath at 60°C for 30-40 minutes, and then loaded at 50 mm/min in a Marshall testing machine until failure; the maximum load sustained (stability) and corresponding deformation (flow value) were recorded for mixes with and without steel fibre and SBS polymer.

4. RESULTS AND DISCUSSION

4.1 Bitumen Test Results

VG30 bitumen was characterised using softening point, penetration, ductility, and viscosity tests. All results, summarised in Table 2, satisfy the limits prescribed by IS 73:2013 (RA 2018), confirming the binder's suitability as a base material for self-healing modification.

Table 2: Bitumen Test Results

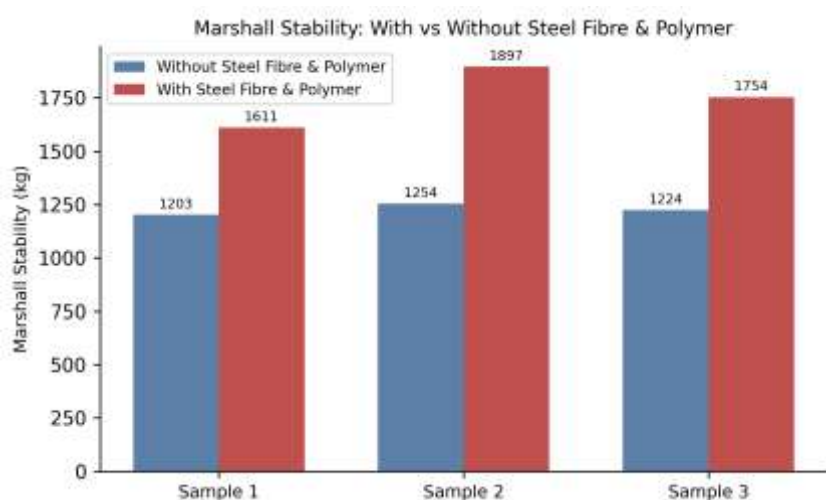
Sr. No.	Name of Test	Test Result	Specified Limit (IS 73:2013) VG30	Method of Test
1	Softening Point (R&B) (°C)	55.2	Min. 47	IS 1205: 2022
2	Penetration at 25°C (0.1 mm, 100 g, 5 s)	53.5	Min. 45	IS 1203: 1978
3	Ductility at 25°C (cm)	97	Min. 40	IS 1208: 1978
4	Kinematic Viscosity at 135°C (cSt)	426.0	Min. 350	IS 1206 (Pt.3): 2021
5	Absolute Viscosity at 60°C (Poises)	3182	2400-3600	IS 1206 (Pt.2): 2022

4.2 Marshall Stability Test Results

Marshall Stability and flow value tests were conducted on three sample sets prepared with and without steel wool fibre and SBS polymer. As shown in Table 3 and Fig. 4, the average Marshall Stability increased from approximately 1227 kg (without modification) to approximately 1754 kg (with steel fibre and polymer) — an improvement of nearly 43%, indicating substantially enhanced load-carrying capacity and resistance to permanent deformation.

Table 3: Marshall Stability Test Results

Sample	Stability without Steel & Polymer (kg)	Stability with Steel & Polymer (kg)	Flow Value (mm)
1	1203.26	1611.15	2.8
2	1254.25	1896.67	3.2
3	1223.65	1753.91	3.8


Fig 4: Comparison of Marshall Stability with and without steel fibre & polymer

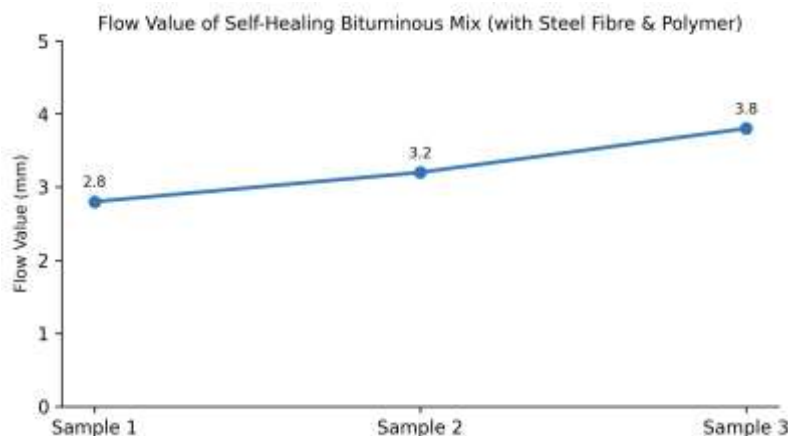


Fig 5: Flow value of self-healing bituminous mix across samples

The flow values (2.8-3.8 mm) remained within typical acceptable limits for dense bituminous mixes, indicating that the addition of steel fibre and SBS polymer improved stability without inducing excessive brittleness.

5. HEALING MECHANISM: THEORETICAL BASIS

5.1 Role of Temperature in Healing

Temperature plays a major role in self-healing. When the pavement becomes warm, bitumen softens and becomes less viscous, allowing it to flow and fill cracks; at low temperatures, bitumen hardens and cannot move, so healing does not occur. The relationship between temperature and healing rate can be explained using the Arrhenius equation, which shows that the healing rate increases with temperature. The minimum energy required to initiate healing — the activation energy — was found in this study to be approximately 75 kJ/mol, confirming that induction heating effectively initiates the self-healing process.

5.2 Capillary Action — The Governing Mechanism

When a crack forms, narrow gaps remain between the two crack faces. At elevated temperature, bitumen behaves like a liquid and flows through these gaps under surface tension — a process known as capillary flow, analogous to the rise of water in a narrow straw. This flow enables bitumen to fill and seal cracks automatically once sufficient heat and rest time are provided.

5.3 Visual Evidence — CT-Scan Observations

CT-scan (X-ray) imaging of cracked asphalt specimens confirmed that healing initiates at the contact points where the two crack faces meet, after which bitumen gradually migrates to fill the gap. Healing was observed to occur faster in deeper layers of the specimen, where confining pressure is higher, supporting the capillary-flow hypothesis.

6. LIFE-CYCLE COST ANALYSIS AND IMPORTANT FINDINGS

A 30-year life-cycle cost analysis was carried out for a conventional bituminous pavement and compared against a 42-year life-cycle for a self-healing pavement, accounting for bitumen, construction machinery, road-freight forwarding, aggregates, fuel, and steel/electricity costs across construction, maintenance/healing, and demolition-rebuild phases. The comparison is summarised in Table 4.

Table 4: Comparative Life-Cycle Cost Analysis

Parameter	Conventional Pavement	Self-Healing Pavement
Initial Construction Cost	~INR 2.01 Crore/km-lane	~INR 2.00 Crore/km-lane
Design Service Life	30 years	42 years
Total Lifecycle Cost	~INR 5.20 Crore/km-lane	~INR 4.69 Crore/km-lane

Although the initial construction cost of the self-healing pavement is comparable to that of the conventional pavement, the extended 42-year service life and substantially reduced maintenance/milling expenditure (achieved through induction-based crack healing rather than repeated overlay and reconstruction) result in an overall lifecycle cost saving of approximately 10% (~INR 0.51 Crore per km-lane), along with reduced material consumption, fewer traffic disruptions, and a smaller environmental footprint over the service period.

7. CONCLUSION

This study demonstrates that the incorporation of steel wool fibres and SBS polymer modifiers in VG30 bitumen significantly enhances the self-healing behaviour of bituminous pavements. Steel fibres facilitate efficient heat transfer during induction heating, enabling closure of micro-cracks before they propagate into larger structural defects, while polymer modification improves flexibility, elasticity, and resistance to fatigue cracking and deformation.

The combined effect of steel fibres and polymer resulted in a Marshall Stability improvement of nearly 43% over the unmodified mix, along with an estimated extension of pavement service life from 30 to 42 years and an overall lifecycle cost saving of approximately 10%. Self-healing bitumen technology therefore presents a promising advancement in sustainable pavement engineering by minimising repair costs, reducing material consumption, and improving road safety. Future research may focus on optimising fibre content, polymer dosage, and induction heating parameters to maximise healing efficiency under varying traffic and environmental conditions.

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