Application of Steel Fibre to Improve the Self-Healing Mechanism of Bituminous Mixtures: A Review

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Abstract. The self-healing mechanism of bituminous mixtures was demonstrated through several studies and was recognised for developing sustainable road pavement. This paper presents a comprehensive summary of various studies related to steel fibre as a self-healing mechanism of bituminous materials. Based on the extensive literature, it was found that steel fibre was likely to be used in the asphalt industry due to several benefits. First, the idea of using steel fibre in pavement engineering materials gives great attention to their utilisation in asphalt. It helps increase the self-healing mechanism and contribute to reducing the problem related to potholes, ravelling, slipping during raining while driving and many more. Second, this study identifies the gap of research for future research in pavement engineering. Finally, some proposals were made for the possible construction of self-healing asphalt.

1. Introduction

The road had become an integral part of the land transport system and our everyday lives as road users. In Malaysia, there are two main types of roads: flexible pavement and rigid pavement. Both pavements, however, were not indestructible due to a variety of reasons, including repeated loading, bad weather, or possibly poor construction. To keep the road serviceable, just like any other asset, preserving the pavement's consistency over its lifetime is necessary to reduce maintenance costs. Furthermore, due to the heavy load on concrete, cracking occurs. If water seeps in through the cracks, the foundation may fail, deteriorate, and degrade. Thus, cracking occurs on the pavement, where repairing the damage caused by cracking is usually expensive. As a result, new technologies that can improve the cracking obstruction of asphalt, also known as self-healing asphalt, must be implemented.

Self-repair in the context of pavement engineering, asphalt was characterised as a material's ability to withstand the effects of water, ageing, and temperature variation in the sense of a given amount of traffic loading without significant degradation for an extended period [1]. Furthermore, self-healing materials capable of healing themselves instantly and subsequently retaining different electrical, mechanical, or optical properties have been studied extensively for a variety of materials, including polymers, cement blends, asphalts, metals, composites, and many more [2].

While the issue of asphalt pavement crack healing has been studied since the 1960s [3], the number of publications in this area has increased dramatically in the last decade [4]. As a result, a new generation
of asphalt materials with improved self-healing properties was created, increasing their longevity and reducing the need for maintenance, as well as the traffic congestion that resulted from it [5].

One of the most successful and non-invasive approaches was adding electrically conductive particles such as steel fibre (SF) to the asphalt mixture that can be heated by a combination of external electromagnetic induction and the Joule effect [6]. As the SF is heated, the embedding bitumen spreads, and its viscosity decreases, allowing it to move through cracks and close them before ambient temperatures are restored [7]. As a result, understanding the use of SF materials in the asphalt industry, where they are still used today, was critical.

However, based on the researchers' initial analysis of relevant literature, it was discovered that the technologies used in the asphalt industry to apply SF materials were rarely studied directly. As a result, the current paper offers a scientific review of various studies related to SF materials' self-healing capabilities and their application in long-term construction and maintenance.

2. Self-Healing Mechanism of Asphalt

Self-healing technologies can repair themselves and naturally regain distinctive mechanical, optical, and electrical properties after activation. Self-healing concepts have been used in fields ranging from chemistry to engineering [8]. In this subsection, the understanding of the self-healing mechanism was explored in terms of molecular interdiffusion, capillary flow, and thixotropy.

2.1. Molecular interdiffusion

The molecular self-diffusion through the crack interface was another curing structure [9]. The interaction of atoms and molecules based on physical laws is called digital simulation of molecular dynamics (MD)[10]. Wool et al. [11, 12] proposed a theory derived from MD widely used in asphalt materials [13]. The MD model is shown in Figure 1(a) and (b), which shows a molecular diffusion model through a cracker interface. Asphalt particles dispersed via the artificial cracker interface, while crack healing was examined according to numerical simulation. On the other hand, the ability of asphalt binders to heal was measured using the diffusion coefficient discovered [14].

Self-healing relies heavily on molecular diffusion. This parameter was applied because an increase in the coefficient of diffusion enhances asphalt's self-healing ability. Due to a rise in the coefficient of diffusion accelerates the self-healing performance of asphalt, this measure was employed to calculate its self-healing ability. The rate of molecular diffusion has a significant impact on asphalt's ability to self-heal.

![Figure 1](image-url)

**Figure 1.** Molecular diffusion's influence on self-healing asphalt. (a) two amorphous interface cells are layered together in a layered system; (b) the matrix is coated during rapid recovery at high temperatures [9, 14].
2.2. Capillary flow
Intermolecular diffusion does not occur when a wide distance separates the latest asphalt cracks. Healing would proceed, while noticeable cracks will vanish if the asphalt material is allowed to rest for some time where adequate energy was applied. This creates the capillary flow-based healing theory better to describe the healing of cracks on asphaltic concrete. Contact points and holes were discovered where the crack surface was in contact. A difference in pressure at the point of contact that will be found in the binder is identical to a Newtonian fluid. This will serve as the driving force for the asphalt binder's capillary flow as well.

Capillary movement in asphalt cracks causes crack closing under some temperature conditions [15]. The capillary effect can be observed by changing the interpreted Lucas-Washburn equation (Figure 2) [16]. Capillary phenomena would initiate between both cracks if the asphalt pavement temperature was high enough to cause it to behave like Newton's fluid. Any crack in the capillary flow system will let the asphalt pass through and rebound until the temperature rises above the temperature threshold [17]. Consequently, the most effective technique to restore the asphalt was to raise the temperature above the Newton transition temperature at a given time. As a result, the most effective way to extract the asphalt mixture was to raise the temperature past the Newton transition temperature at a given moment [18].

![Diagram of forces acting in an asphalt mixture crack during healing](image)

**Figure 2.** Scheme of the forces acting in an asphalt mixture crack during healing [16].

2.3. Thixotropy
Thixotropy is a fluid process in which molecular reconfiguration in the bituminous state causes reversible structural changes [19]. When a bituminous substance is exposed to external tension, thixotropy and self-healing coexist [4, 20]. The nature of interactions at the molecular or macromolecular
scale causes the emergence of contacts at the molecular or asphalt thixotropy scale. At high temperatures, thixotropy was used to describe asphalt cement's non-Newtonian behaviour [21], [22]. As loading time increases, the viscosity of the asphalt steadily reduces, and when the load is completed, the viscosity gradually rises.

The destruction and reorganisation of the microstructure resulted in a decrease and increase in viscosity. This occurrence was identical to asphalt fatigue and self-healing, which occurs as microstructures decompose and restructure. Microscopically, this state can be seen as a decline and rise in variables, for instance, viscosity and modulus. Thixotropy affects fatigue and healing by causing structural changes in the asphalt binder when subjected to oscillatory loads during the oscillation cycle and lengthy transients [23]. A uniaxial "push-pull " test with three loading phases on a cylindrical specimen was used by Soltani and Anderson [24] to investigate the healing and fatigue. In addition, the effects of self-heating, self-cooling, and nonlinear non-fatigue techniques were discussed. Thixotropy outputs significantly impacted the modulus acquired by rest or load reduction and lost in the fatigue test.

3. Application of Steel Fibre Materials in Asphalt Industry

Fundamentally, the key role of fibre as a reinforcing material increases the tensile strength of the resulting composite, which would improve the amount of strain energy absorbed during the fatigue and fracture phases of the mixture [25]. In addition, steel fibre (SF) and iron particles were among the most commonly used additives to speed up the healing of asphalt concrete [26]. This study focused more on the application of steel fibre. This is due to the capability of steel fibre in improving the mechanical performance of the fibre and healing them. They are used to heal the asphalt mixture via electro-thermal procedures. When the samples are placed in the electromagnetic field zone, currents begin to flow in the steel fibre, which warms the surrounding binder matrix since steel fibre are conductive. The binder then melts and repairs the micro cracks, thus preventing crack propagation [27–29].

3.1. Effects of steel fibre on the properties of bituminous mixtures

Several research studies looked into the impact of applying SF on the quality of the flexible pavement in terms of the materials themselves. In the design of modern pavements, the use of SF was beneficial from both an economic and environmental standpoint. The SF was used in [30] to improve the pavement's strength and lifespan while lowering the overall cost of road construction. This was due to a combination of environmental factors and traffic loads that resulted in the valuable deterioration of asphalt concrete pavements and a decline in pavement longevity and strength. However, asphalt concrete, subjected to a rest period, recovers its stiffness and strength.

In addition, adding steel fibre significantly improves particle loss resistance [28, 31]. According to Gonzalez et al. [28], steel wool and steel grit improve porous asphalt mixtures' moisture susceptibility and indirect tensile strength value. Consequently, they stiffen the combination and make it more resistant to fatigue cracking. Furthermore, steel fibre does not affect the mixture's workability, implying that they may be compressed with the same effort. Three different types of steel fibre were employed in the study by Liu et al. [29]. Steel fibre with a small diameter and a longer length performed better than steel fibre with a large diameter and a shorter length because the fibre-to-fibre contact was better in the former, resulting in higher conductivity.

Serin et al. [31] researched various contents ranging from 0% to 2.5 %. At 0.75 % fibre content, the highest level of stability was observed. However, the stability values were also lower at higher fibre content than in control samples with no fibre content, which agrees with Tabakovici et al. [32], who indicated that very long steel fibre and high contents could contribute to cluster formation. Additionally, clusters can also result due to bad mixing [33]. These clusters may subsequently develop into high temperature zones, weakening the specimen's structure.

However, SWF also can pose some risks in asphalt mixtures, which are frequently linked to the engineering efficiency of SWF-containing mixtures. For example, poor construction results in early pavement discomfort and shorter service life, rising maintenance costs, energy consumption, and
emissions. A study conducted by [11] also found that these fibres would split into smaller pieces during mixing and compaction regardless of their initial length, so the final length of SWFs can be considered independent of their initial length. Here, the electrical resistivity of asphalt concrete is independent of the length of SFs, while the fibre diameter had negligible effects on the thermal conductivity of asphalt concrete.

3.2. Steel fibre used in asphalt industry: Enhanced technology for healing

There are three different techniques for improving the healing properties of asphalt concrete pavements that use steel fibre: induction-heating, microwave heating and a combined healing system.

3.2.1. Induction Heating

The process of heating an electrically conductive metal element by electromagnetic induction is known as induction heating [34]. The electromagnetic induction process has been altered to make use of composites' self-healing characteristics. The crack was filled by molecular diffusion under the operation of electromagnetic induction caused by the thermal impact of superconductors and rest periods. The behaviour of the induction heating system design was demonstrated in Figure 3(a) as micro-cracks in the asphalt were observed. In contrast, the expansion of the fatigue life caused by natural and induction heating is shown in Figure 3(b). The fatigue life during the healing process was 149,860 hours, with a fatigue enrichment ratio of 56.7%, for the rest times alone. Using a fatigue life extension ratio of 190% and four occurrences of 50,000 cycles of damage loading followed by four instances of induced heating and rest intervals, the fatigue duration was extended to 277,720 cycles, which was 2.9 times longer than the real fatigue life. The temperature, as well as the fibre content, influenced the self-healing effect.

Furthermore, [30] described the conductive constituent as the mechanical, rheological, induced heating, and healing action of asphalt concrete containing SWFs. The addition of 0.2 total mix weight (wt) per cent SWF met all heating and healing criteria in this study's experimental findings (e.g., uniaxial power, indirect pressure, and semi-circular bending tests). Thus, the comparatively low content of SWF had substantially less harmful effects on the mechanical and rheological properties of asphalt concrete as compared to higher percentages of SWF.

It is also proved by [35], who used energy induction to heat the cement inside it to determine how it will regenerate. In fracture-healing experiments, three samples were used at various heating temperatures. After nine cycles at 60°C, different samples show 35.8% and 56.8% peak load recovery, respectively. At the same temperature, 63.2% and 73.6% of the initial fracture strength were attained. Without modifying the physical properties of the asphalt materials, the best curing effect was obtained when the heating temperature was set to 100°C. Thus, it is possible to heal the crack and achieve high fracture strength by adding steel fibre.

In addition, Liu et al. [36] investigated the ability of steel wool reinforced porous asphalt to heal (the steel wool content: 1.27 % weight). Induction heating improved the healing of porous asphalt beams, according to the findings. Furthermore, repeated rest periods of induction heating considerably increased the fatigue life of porous asphalt [36, 37]. Moreover, Dai et al. [35] examined the induction heating of a dense asphalt mixture containing 5.66% steel fibre by volume. The optimum induction heating temperature of the asphalt mixture was determined to be 100°C. Still, temperatures between 60°C to 80°C were also suitable because more than 50% of strength was recovered after six fracture-healing cycles. Finally, García et al. [16] investigated the induction heating behaviour of dense asphalt mixture with various steel fibre contents (2%, 4%, 6%), with heating temperature ranging from 30°C to 130°C. At a temperature of 100°C, 60% mechanical resistance may be repaired, according to the findings. Furthermore, the healing recovery of dense asphalt can occur at temperatures above 50°C, corresponding to the asphalt's near Newtonian behaviour temperature.

3.2.2. Microwave Heating
Microwave heating is also a common method for assisting self-healing. Microwave-absorbing materials made of steel fibre are commonly used in asphalt mixtures for this technology. According to Apostolidis et al. [39, 40], adding steel fibre to asphalt mortar can improve its microwave-absorbing capabilities. It is proved by Schlangen [41] that the addition of steel wool to asphalt concrete mixtures enhanced their microwave-absorbing performance. Gallego et al. [42] confirmed that adding steel wool to asphalt concrete improves energy efficiency and that microwave heating promotes self-healing because the asphalt mixture reached 30°C-160°C after 120 seconds of heating when using 0.2% weight steel wool (10mm length and 0.04-0.06mm thickness).

Steel fibre and graphite additives were used to improve the mixture’s tolerance to electromagnetic induction [43]. According to the findings, the energy consumption of microwave devices was much less than that required by electromagnetic induction to produce comparable performance. Furthermore, in a microwave-heated mixture, 0.2% medium SF had the same effect as 1.5% to 5% steel fibre in an electric induction mixture, resulting in significant cost savings.

Jendia et al. [12] investigated the impact of adding SF to asphalt concrete. SF was applied to 20 samples at a rate of (3.5% and 7%) by weight of asphalt. The volumetric, stability and flow characteristics of asphalt were assessed, and the impact on asphalt conductivity and the degree of impact on asphalt self-healing properties. It had been determined that the 4.33% level of SWF enhanced the asphalt's conductivity.

The heating efficiency of microwave asphalt mixtures containing SF was calculated in an article by [44]. The additive's effect on the proportion of air voids in different ratios was also investigated. The asphalt mixtures were prepared using three varieties of low-carbon SF with five different diameters. It was discovered that as the amount of SF is increased, the amount of air spaces increased accordingly. Although adding SF to asphalt concrete improved induction heating properties, several studies have shown that high-content SF (approximately 6%-8% of binder volume or 2%-3% of asphalt concrete weight) causes an increase in mixture air voids, which has negative effects on the mixture's mechanical properties [11, 26].

Furthermore, the results of microwave and induction heating were compared by [45]. The asphalt specimens reached a surface temperature of 71.7 °C after microwave heating and 50.85 °C following induction heating. The temperature of the microwave heater was difficult to control. It may be greater than the asphalt flash point temperature, causing the binder chemical composition to be lost. It is also crucial to pay attention to the heating time [46]. The appropriate microwave heating period was attained at the optimum curing speeds without producing early bitumen disruption.

Overall, microwave induction has proven to be a suitable approach for in-situ heating since the optimum steel wool content for microwave induction is lower than for electromagnetic induction. Moreover, the proportion of electricity used by microwave heating devices is significantly less than that required by electromagnetic induction to achieve a similar effect. Therefore, a more effective energy-based healing technology is likely to be developed in the future to construct long-lasting asphalt pavements.
3.2.3. Combined healing system

Additionally, steel fibre has been used for the combined healing system by Xu et al. [47]. A combination of encapsulated rejuvenator and induction heating was used for the combined healing system due to [47], indicating that both systems are very complementary in healing mechanism. The process involved is where the induction heating will heal the asphalt damage, i.e. cracking, and rejuvenation to rejuvenate the aged binder. Both microcapsules encapsulating rejuvenator and steel fibre were inserted into the porous asphalt concrete mix. The idea of a combination healing system that incorporates the benefits of both induction heating and an encapsulated rejuvenator is predicted to improve asphalt concrete healing.

The comprehensive healing effect of the combined healing system is based not only on encapsulated rejuvenator and induction heating but also on synergistic effect, which promotes each process, namely accelerated rejuvenator diffusion (with induction heating) and increased induction healing (with asphalt binder rejuvenation). As a result of the three healing systems, the combined healing system has the better result of extending the life of asphalt concrete. Figure 4 shows that the combination of these two technologies illustrates the crack healing mechanism.

Figure 3. Heating through electromagnetic induction (a) Using induction heating, cracks were closed. [38] and (b) Multiple occurrences of induction healing result in fatigue life extension [37].
Figure 4. Crack healing mechanism of the combined healing system [47].

4. Conclusion and future research

The areas of research on the applications of steel fibre in the asphalt mixture were delineated in this paper using a systematic literature review method. Asphalt pavements' service life is subjected to varying loads and environmental factors, leading to pavement deterioration. Self-healing potential is a fundamental property of asphalt materials that significantly impact the service life of asphalt pavement. Although revolutionary pavement construction methods have evolved, bituminous pavements' basic materials, such as aggregate, bitumen, and filler, have not been replaced in the last five to six decades. Since they were all non-renewable commodities, special care was required to ensure enough was left for future generations.

This technology aims to save material supplies, so there was no longer a need for the typical overdesign of materials. Instead, the main aim of the self-healing pavement technique was to create a smart bituminous pavement that could evaluate, anticipate, and recover on its own in time without human intervention and return to its original state, which is why the healing rate was boosted by additional electrically conductive particles known as SF.

A summary of SF material as self-healing material was done in this report. Based on the published literature, the following conclusions can be drawn:

- Self-healing should be included in the design of asphalt pavements because it significantly impacts their service life.
- In general, incorporating fibre into the bitumen increases its viscosity and softening point and reduces its penetration grade. Therefore, the optimum fibre content in the bitumen should be considered to achieve good workability and optimal properties.
- Previous research into incorporating SF into modern pavement systems has been extensive.
- By using SF material in constructing the current pavement system, potential maintenance costs can be significantly reduced.
- The most popular application of SF was high-temperature mixing with aged asphalt mixtures. In addition, the heating technologies can significantly enhance the self-healing capability of asphalt materials.

In the future, it was planned that a more efficient energy-based healing system or a novel material-based healing system would be built to design a more sustainable and robust asphalt pavement. Furthermore,
to improve the road surface's efficiency, further optimise the parameters, propose a rational prediction model, and design the electromagnetic induction heating system.

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