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REVIEW

The self-healing performance of asphalt binder and mixtures: a state-of-the-art review

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Abstract
The intrinsic ability of asphalt pavement to undergo self-healing is not sufficient enough to effectively repair fractures resulting from a range of variables, including traffic load, asphalt aging and weather conditions. Consequently, the field of self-healing technology is focused on advancing crack repair techniques by employing microwave and induction heating and encapsulation amongst other healing procedures. These approaches make use of a range of additives, including waste materials and polymers, to facilitate the healing process. The present paper provides an in-depth review of self-healing technologies used for asphalt pavements, this including their conceptualization, development, application and the methods used to evaluate its performance. The self-healing capacity of materials can be influenced by various parameters including humidity, molecular diffusion, induction conditions, temperature and time. As such, treatments have the potential to enhance self-healing capacity, but with varying degrees of success depending on the specific evaluation indicator and healing situation. By examining international research, this review will also draw attention to the global relevance of the applicability of asphalt self-healing techniques used to enhance the durability and sustainability of transportation infrastructures worldwide. This paper therefore, serves as a valuable resource for researchers, practitioners and policymakers engaged in the pursuit of innovative solutions for resilient and cost-effective pavement systems on an international scale. This review also proposes prospective pathways for further study that will serve as a basis for future development of the industry.

Keywords Asphalt mixtures · Healing mechanisms · Self-healing · Capsules · Induction healing · Microwave healing · Sustainability

Introduction

Transport infrastructures are necessary for modern civilizations due to the constant growth in population and related traffic needs. These infrastructures allow the movement of goods, services and people, which facilitate the connection of social and economic systems with the natural environment [1, 2]. In consequence, concerns over the sustainable management of transportation systems have grown as a result of the direct impact that transportation infrastructures have on the three axes of sustainability, altering the equilibria between economic, environmental and social elements.

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While historically, transportation managers have mainly paid attention to the financial side of sustainability, more and more transportation agencies are implementing sustainable pavement management techniques that incorporate all the sustainability criteria [3, 4]. Since the 1970s, pavement management systems have been used on roads to enhance the upkeep of transportation infrastructures. However, a recent movement has emerged that is centred on sustainable pavement management, with particular attention to the trade-off between expense, environmental effects and the social ramifications of road network investment [5]. Infrastructure managers are required to adopt a sustainable approach to pavement maintenance management under the new framework. This calls for complex solutions that take into account all of these principles and that guarantee technically sound, financially feasible and socially acceptable solutions [6, 7].

The performance of pavements is impacted by various factors, including environmental conditions and traffic load. The projected lifespan of a pavement often exceeds its effective operational lifespan, hence requiring periodic maintenance, this including both minor and major repairs, in order to retain a sufficient level of serviceability. However, it is important to note that said maintenance can have a substantial effect on traffic capacity and lead to increased life-cycle expenses for the pavement [8–10]. Fatigue cracking from repeated traffic loads, represents the main source of distress for asphalt pavements [11–13]. Bituminous materials crack because of complicated mechanisms that are contingent on a wide variety of stress situations and temperatures [14]. A significant amount of energy, or time, is required to restore the original state of the fatigued or cracked pavement, thereby demanding additional waste and transport resources, this resulting in adverse impacts on the environment [15]. An approach to restoring the optimal performance of pavements, which at the same time reduces energy consumption, is required to elongate the life of damaged pavements [16, 17]. An effective measure includes letting the materials of pavement acquire self-healing characteristics. Pavement asphalt mixtures possess self-healing properties, allowing it to repair cracks autonomously and thereby prolong the service life of the pavement [8, 9].

The self-healing properties of asphalt pavements have unique multiscale and hierarchical characteristics that offer an effective approach to enhancing durability, thereby restoring pavement performance and healing cracks without compromise. The definition of the self-healing capacity of a material was given by Fischer as "the ability to substantially return to an initial, proper operating state or condition before exposure to a dynamic environment by making the necessary adjustments to restore to normality and/or the ability to resist the formation of irregularities and/or defects" [18]. Compared to other maintenance methods, self-healing also has the potential to reduce road safety concerns, carbon dioxide emissions and overall maintenance expenses [19–21]. Microcracks, or other signs of damage, are created by discontinuities in the load environment and only sometimes eventually mend allowing the asphalt pavement to function again. It is therefore possible to reverse the formation and healing of cracks under specific circumstances [22, 23]. Initial self-healing investigations date back to the 1970s when research was focussed on grasping the constitutive characteristics of filled elastomers, such as those employed in the Apollo space missions and more recent ballistic missile interdiction systems [24, 25]. In pavement engineering, the self-healing performance of asphalt has been a subject of research since the 1960s [26, 27].

Asphalt by itself has intrinsic self-healing behaviour, allowing it to close cracks, restore strength and stiffness, and improve fatigue performance. However, cracks in asphalt can close on the completion of the entire self-healing process making it crucial for asphalt to possess sufficient self-healing ability [28, 29]. While asphalt possesses self-healing characteristics, these inherent properties alone are insufficient to repair microcracks adequately [30] making it vital to understand both the intrinsic and extrinsic self-healing strategies intended to lengthen lifespan and increase durability of asphalt, in that they differ according to how the healing process starts and completes. Extrinsic self-healing uses external agents or procedures to accomplish the same task as intrinsic self-healing, which in turn, depends on the inherent qualities of the asphalt mixture [22]. Several factors can impact asphalt's self-healing capacity including molecular structure, environmental conditions such as temperature and humidity, asphalt diffusion and movement, duration of self-healing and the viscoelasticity of the asphalt, to name a few [23, 31]. As such, it is important to understand the fundamental mechanisms and elements affecting the self-healing capabilities of asphalt mixtures in order to create efficient plans for pavement design, material selection and building techniques. Because of this challenge, numerous experimental, computational and theoretical techniques are used in this field of study to characterize the healing behaviour of asphalt binders and mixtures under various loading and environmental conditions [32, 33]. Heating and rejuvenation are two conventional techniques used to produce self-healing asphalt pavements. Vascular threads, hollow fibres, or capsules are usually used to integrate regenerators. When the encapsulation breaks, the healing agent seeps out and seals the crack. Typically, induction and microwave energy are used to warm the asphalt and seal the crack. While metallic additions must be added for induction heating to occur, microwave heating can occur without the need for any additives [34–37]. Recently, several additives, e.g. nanomaterials and polymers, have been examined as a means of improving the self-healing capabilities of asphalt [38–42]. Each of these methods has its advantages and disadvantages.

There are several recently published reviews about self-healing asphalt, each study taking its own approach. For instance, Wan et al. [22] provided a brief review on self-healing methods, focusing on the extrinsic properties of asphalt materials. Nalbandian et al. [43] carried out a bibliometric analysis and mapping of articles including a brief description of some articles, while Abejón [44] focused on providing a bibliometric review of self-healing studies over the period 2003 to 2018. Most of the work conducted by Sun et al. [45] focused on computational modelling to simulate self-healing performance at molecular or mechanical levels.

This review seeks to offer insights into the self-healing performance of asphalt, as well as the use of various self-healing methods in asphalt pavements. To the best of the authors' knowledge, there is a paucity of comprehensive review information about the various self-healing methods in asphalt pavements, this paper employing a unique approach to address the contradictory findings present in the existing literature. In addition, this paper discusses more recent publications which have not been discussed in earlier reviews. A systematic literature review strategy was used to review and assemble the significant body of literature published in the last 20 years. There were several research databases used for this including Scopus, Web of Science and Google Scholar. There are various components to this review, the research starting by examining the literature in terms of the self-healing performance of asphalt. Papers were then sorted according to method, this information summarized and examined to allow an assessment of the outcomes and key findings of research. A section about novel approaches to self-healing was also included, this discussing alternative self-healing processes. The research also highlights the gap between existing knowledge and potential areas for future investigation, thereby providing a thorough understanding of the use of self-healing asphalt for researchers, engineers and specialists in the field of materials and pavement construction.

Mechanisms of self-healing

Wool [46] used a reversible crack element to create an ideal self-healing material. Figure 1 illustrates this system, comparing it to the dashpot and spring configurations presented in the Vogit and Maxwell rheological models. In this version, the reversible crack element replaces the spring in those models. The crack forms through the central debonding of two surfaces perpendicular to the direction of the propagation of the crack. The crack is closed simultaneously by the potential between the surfaces with strain deformations [47].

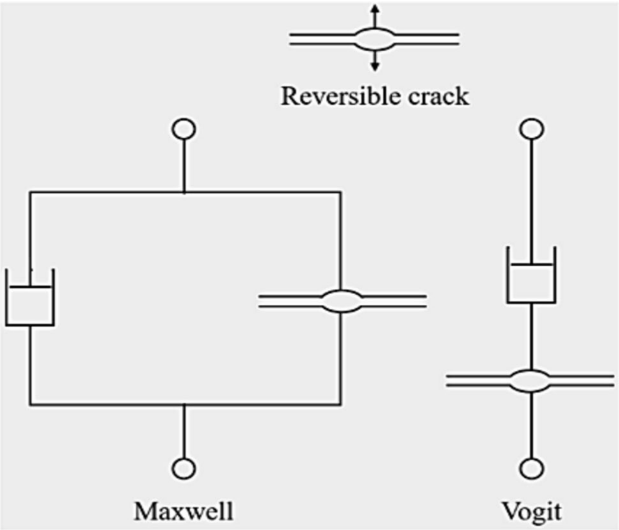


Fig. 1 Integration of the mechanisms of self-healing of viscoelastic material with Maxwell and Vogit models [47]

In 2006, Shen and Carpenter [48] demonstrated the presence of asphalt's self-healing properties through a specially designed, fatigue-healing test in the laboratory. The twofold process of healing was characterized as adhesive healing between the interfaces of aggregates and binder and cohesive healing within the binder [49]. The self-healing capability of asphalt binder is influenced by various components and materials introduced into the asphalt mixture. These components play a crucial role in enabling the asphalt binder to repair itself in the presence of cracks or damage, each component or material influencing the healing properties of the asphalt binder in different ways. Asphalt molecules exhibit stronger diffusion and healing abilities with long, thin structures and low molecular weights. The self-healing performance itself, is negatively impacted by increased aging, greater crack width and moisture. The healing level of an asphalt crack can be improved by lengthening the healing period, however, when healing time exceeds a certain point, the improvement ratio diminishes [50, 51]. Self-healing efficiency is at its highest levels within a specific temperature range. Various theories, such as molecular diffusion, capillary flow, surface energy and phase field, explain the mechanisms of self-healing in asphalt. The basis for surface energy theory is fracture mechanics, where the self-healing process is driven by a decrease in surface energy. The molecular level of self-healing is explained by molecular diffusion theory; however, this does not directly explain the repair of larger cracks. The multi-phase nature of asphalt is a subject of continuous discussion, phase field theory connecting asphalt self-healing to changes in asphalt microstructure seen with tools like atomic force microscopy (AFM). On a larger scale, the capillary flow hypothesis is suggested, based on the assumption that the asphalt binder behaves like a Newtonian fluid [30]. Thus, a combination of these mechanisms is essential for a comprehensive understanding of self-healing in asphalt [30].

Surface energy theory

This theory proposes that asphalt healing and cracking processes involve an increase in the area of fracture interface and a decrease in the surface energy of cracking [52]. In other words, the reduction in the surface energy represents the responsible parameter of the self-healing property. Based on this theory and regarding viscoelastic material, Schapery [53] developed a fracture law whereby shifts in the dissipative energy associated with tensile creep, are subsequently transferred to the surface energy of the newly formed crack, in accordance with the fundamental principles of energy conservation. In addition, the healing process also involves converting energy in a way that counters the energy involved in the cracking process, as proposed by Lytton et al. [54] for viscoelastic materials. Si et al. [55] conducted a study on twelve types of asphalt binders and found that the long-term healing rate was relatively constant while the short-term healing rate varied significantly. Based on this, the long-term rate of healing is dominated by h_2 while the short-term rate of healing is dominated by h_1, as shown in Fig. 2.

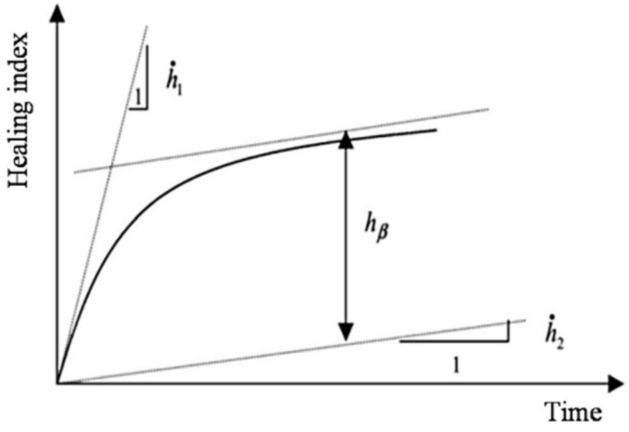
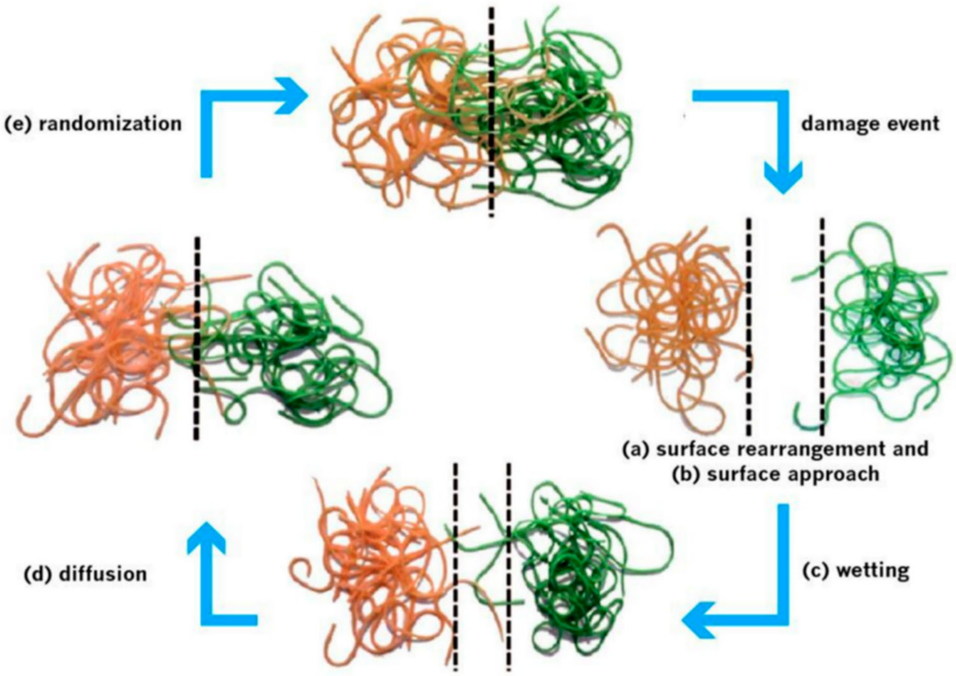


Fig. 2 The rate of healing is determined by a standard healing curve [55]

Molecular diffusion theory

This theory was developed to investigate the mechanisms of self-healing asphalt at the molecular scale, adopting the self-healing mechanism of polymers. Some elements of an asphalt binder might disperse at various speeds because of variations in molecule size and polarity. Molecules that are smaller and more volatile, have a higher potential for rapid evaporation. Within the asphalt binder, molecular diffusion is possible, the material's microstructure affecting the routes those molecules travel on. How molecules travel within the binder depends on the dimensions and configuration of the voids, pores and aggregate surfaces [56]. Wool and Oconnor [57] proposed five healing stages for polymers as shown in Fig. 3.

Fig. 3 Five-stage process of crack healing of polymers [57, 58]



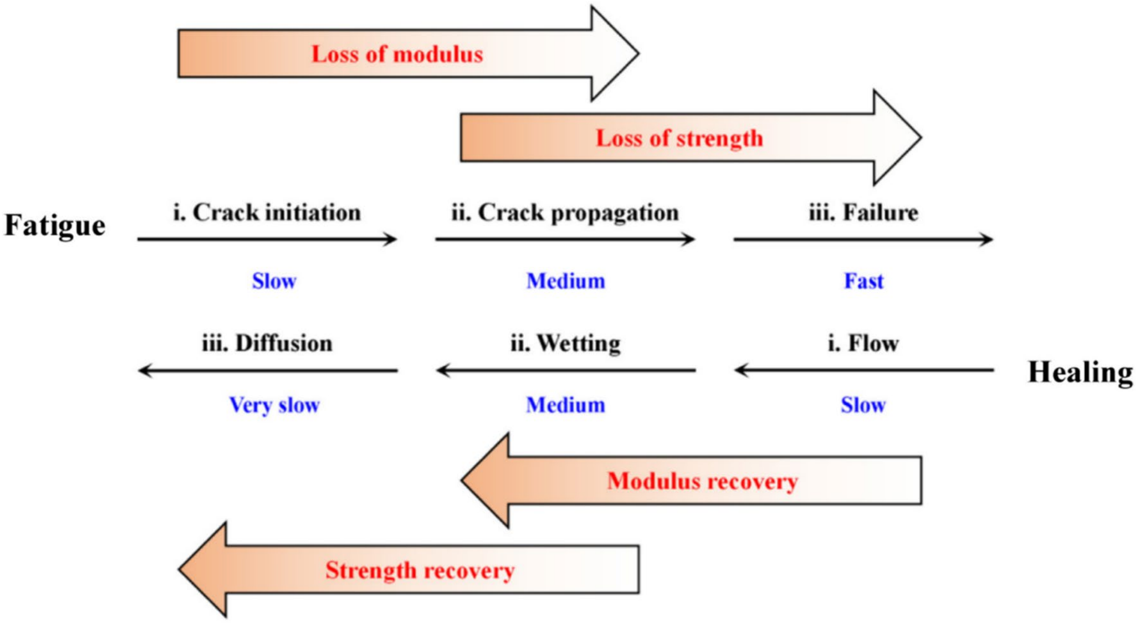


Fig. 4 The asphalt's three-stage crack healing process [59]

Phillips [59] presented a three-stage healing theory for asphalt as shown in Fig. 4. This included: (1) closing of microcracks by asphalt flow and consolidation, (2) closing of microcracks by surface energy driving adhesion and wetting of the crack interface, and (3) recovery of mechanical characteristics by molecular diffusion at the crack interface [59, 60]. The first stage takes a relatively shorter time than the following two stages.

Bhasin et al. [61, 62] simplified the process into intrinsic and wetting healing stages. In the wetting stage, the crack interface is gradually soaked and drawn closer together by intermolecular interactions, ultimately closing the cracks entirely. During the intrinsic stage, the evaluation of mechanical characteristics includes the examination of instant and gradual strain enhancements over a period of time, resulting from fracture closure and inter-diffusion occurring over the surfaces of closed cracks. The temperature during healing is a significant factor alongside healing time. Sun et al. [63] presented an asphalt healing model based on molecular diffusion theory, which included the combined impact of temperature and time. Molecular simulation technology has recently been used to directly explore the self-healing mechanism of asphalt material [52, 64–66]. The conventional approach to self-healing involves the implementation of a vacuum pad that is inserted between two layers of asphalt molecular models. Different conditions are employed to replicate the behaviour of the model and the outcomes, including diffusion capability and density, are used to evaluate the self-healing characteristics of the asphalt.

Phase field theory

By the use of atomic force microscopy (AFM), Loeber et al. [67] discovered the multiphase nature of asphalt, this consisting of a continuous matrix and bee-like structure phases. Subsequently, Stangl et al. [68] associated this phase distinction with the production, propagation and healing of microcracks. Building upon this phase theory, Kringos et al. [69, 70] provided a model using three asphalt binders (depicted in Fig. 5). Under low-stress conditions, no microcracks appeared, but they gradually emerged under medium stress between the two phases, ultimately forming macrocracks under high stress within the bee-like structure phase. The homogeneous liquid phase separated into a continuous matrix phase and the phase with a bee-like structure, as a result of the temperature drop. Due to differing stiffness within the two phases, this process resulted in large internal stress oscillations that were centred near their interfaces. Microcracks first appeared in this region, spreading to produce macrocracks. The bee-like structure melted as the temperature rose during the matrix phase, causing the cracked area to gradually contract and then heal [71, 72].

This theory explores alterations in the asphalt's microstructure during cracking and healing processes, aiming to elucidate crack propagation and self-healing. However,

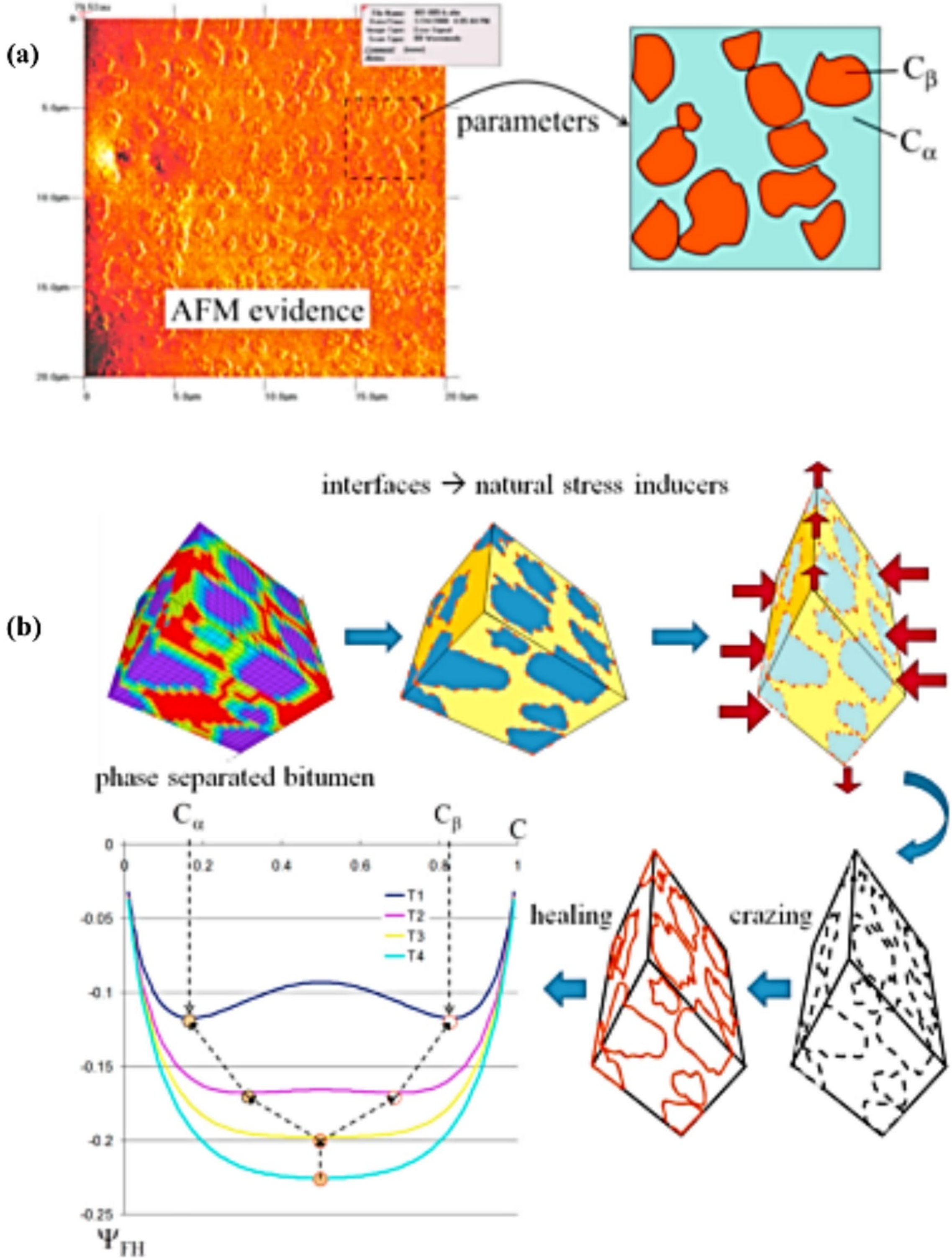


Fig. 5 Developed crack healing model utilizing phase field theory: **a** phase separation; **b** healing model [69]

despite these insights, disputes have arisen regarding the composition and formation mechanism of bee-like structures in asphalt binders, this limiting the use of the theory to explain self-healing behaviour [73].

Capillary flow theory

For this theory, two main conditions should exist. Firstly, contact points should be present between the interfaces of the crack to facilitate capillary flow along the crack. Faster healing rates can be obtained for cracks with lower positioned contact points according to the stress analysis. Secondly, the asphalt binder should be in a Newtonian fluid state, this occurring at relatively high temperatures [74]. Based on this theory, a crack healing model was proposed by García et al. [75, 76]. They simplified the crack to a vertical capillary by the use of six capillaries with dimensions of 0.1 to 1.5 mm diameter and 100 mm length, positioned and fixed in parallel on a thin plate. These were then placed vertically in a glass dish of 100 mm diameter containing 30 g of asphalt. The results showed that the healing rate can be accelerated with an increase in temperature, a high healing rate obtained for a deeply buried crack. Subsequently, Grossegger and Garcia [77] conducted open and sealed capillary flow tests, confirming enhanced self-healing behaviour at elevated temperatures. This was due to additional pressure from the reduction in viscosity and thermal expansion of the asphalt.

Summary of conventional self-healing methods

The are several conventional methods for self-healing asphalt which have been subject to research over the years. These include the use of encapsulation to rejuvenate asphalt or the use of external heating through induction or microwave approaches. Several additives have also been investigated, Table 1 summarizing these works in terms of the type of method used, materials, asphalt type, mixture proportions, preparations of mixtures and evaluation tests.

The principle behind encapsulation is that the propagated microcracks find capsules in their path. The capsules are opened by the fracture energy of the cracks, this releasing the rejuvenating component which is incorporated with the asphalt binder, thereby sealing the cracks and prohibiting their growth. Various rejuvenators for example vegetable, cooking and mineral oils, have been investigated along with additives like polymers, modifiers, fibres and complex engineering products. For asphaltenes to continuously disperse in the asphalt binder, effective rejuvenators should have a significant quantity of maltene. Vegetable oils including soybean, corn and sunflower, have a lower dose of maltene than oils made from petroleum. Capsule morphology includes groups like calcium alginate-based capsules formed by an emulsion blend of rejuvenator and sodium alginate in a hardening solution, as well as microcapsules with a double shell surrounding the rejuvenating agent, typically made from a commercial polymer modified with methanol. Encapsulated fibres are also used in combination with capsules [78–80] Healing capacity is assessed using a healing level index by testing asphalt mixtures before and after the process of healing. Performance properties such as rutting, fatigue and creep, are characterized via dynamic and static tests. Physical properties like viscosity, softening point and penetration of asphalt binders, are analysed in various states, including unaged, aged and rejuvenated binders. Microscopy of the mixtures is carried out by observing diffusion and capillarity phenomena, as well as fracture morphology during and after the healing process [78, 80–82].

Induction heating makes use of the natural ability of asphalt to self-heal and repair damage during testing and to autonomously regain lost strength. To simulate the effect of solar heating, infrared lamps are used since temperature is the primary influential factor. Other heating mechanisms can also be employed. Induction heating targets the binder alone, without heating the entire mix. Thermal energy is produced through the top surfaces of test samples and subsequently transported downwards by infrared radiation, leading to a gradual rise in temperature. This phenomenon is attributed to the increased energy needed to heat the aggregates, this causing a slower rate of temperature growth. During the process of induction heating, the asphalt mixture is subject to an electromagnetic field of high frequency [82, 83]. Michael Faraday presented the fundamentals of electromagnetic induction in the 1930s [84]. As per Faraday's law, an Electro-Motive force (EMF) is induced in a circuit whenever there is a change in the flux connected or linked with it. This electromagnetic field will only last as long as change is happening. According to Joule’s law, heat is produced in a material "when a current is passed through it". Two ways to perform induction heating are: (i) creating eddy currents in a material which then heats up as a result of electrical resistance; and (ii) hysteresis heating, which heats up a portion of the magnetic domain by rotating in line with the direction of the applied magnetic field. Only magnetic materials can benefit from hysteresis heating. Fibres such as steel and wool with various contents and dimensions in terms of lengths and diameters have also been used. In terms of speed and temperature of heating, they are influenced by the type of mixture [82, 83].

Microwave radiation is used as an alternative to heating individually, or in combination with other self-healing methods. Ferrous and metallic materials such as fibres, can be used in mixtures to accelerate the temperature and reflect radiation. Microwave devices require less electricity than induction devices [8, 34]. Electromagnetic waves with wavelengths of one mm to one meter and frequency between 300 MHz and 300 GHz, are known as microwaves, created to increase heating efficiency and homogeneity. Electrical, ionic/atomic and orientational/dipolar polarization, can all happen when an external electric field is applied to a dielectric medium. The main mechanism that links microwave radiation and polymer dielectrics is the

Table 1 Summary of various research in terms of the type of method used, materials, asphalt type, mixture proportions, preparations of mixtures, and evaluation tests

References	Healing method	Materials	Asphalt Type	Asphalt mixture (% of the mass of asphalt mixture)	Preparation method	Tests
[79]	Asphalt rejuvenator encapsulation	Sunflower oil, tap water, calcium chloride, nano Fe_3O_4 powder, Sodium alginate, anhydrous, and Tween 80 anhydrous	Base 60/80 asphalt	Asphalt binder (4.8%)	Incorporated capsules at the end of mixing	Quantification of the rejuvenator release
				Calcium alginate capsules (0.5%)		Fracture-compressive loading-healing test
				Aggregate (basalt)		Fracture-microwave induction-fracture healing test
						Microscope computed tomography (CT)
						High-resolution 3D X-ray
[88]	Encapsulation	Micron-sized microcapsule (Technology company, China)	Waterborne epoxy resin curing agent (WERB), waterborne epoxy resin emulsion (WERA), SBR, and SK-70# base asphalt,	EA (3.9%, 10.5%) microcapsule contents (3%, 4%, 6%) RAP (90%) fresh aggregate	Microcapsules were mixed with asphalt at 500 rpm, at room temperature for 10 min, and manually stirred for 5 min	Developed evaluation indicators
					SCB specimens (JTG/T 5521–2019)	Three-point bending test
						Freeze–thaw splitting test
						LSCM test
						SCB fatigue test
						SCB fracture test
						Rutting test
[78]	Bitumen rejuvenator encapsulation	A calcium-alginate waste mineral oils vegetable oils Polymer Waste	Bitumen B50/70	Bitumen (15%, 26.5 gr) capsule (0.25%, 0.50%, 0.75%, and) 1.0% aggregates (85%, 150 gr)	Bitumen and aggregates were heated for 1.5 and 3 h at 180 °C, then manually mixed, including polymeric capsules at 20 °C then, samples were moulded (30 × 30 × 100 mm)	Fourier-Transform Infrared Spectroscopy (FTIR) test measurement of mastic samples measurement of Crack-healing
						Thermos-gravimetric analysis (TGA)
						Compressive strength
[89]	Bitumen rejuvenator encapsulation	Sunflower oil, sodium alginate ($C_6H_7O_6Na$), calcium chloride solution, water	Stone Mastic Asphalt (SMA) (bitumen 40/60)	Capsules (0.5%) SMA mixture (8.13 kg)	Preconditioning of capsules for 24 h at 25 °C	Skidding resistance of asphalt plastic deformation (rutting) of asphalt

Table 1 (continued)

References	Healing method	Materials	Asphalt Type	Asphalt mixture (% of the mass of asphalt mixture)	Preparation method	Tests
					The aggregates and bitumen were heated for 4 and 12 h at 160 °C	Amount of oil released
					Mixing raw materials for 3 min at160 ºC, and 125 rpm, including capsules at 20 °C then, samples were moulded (30 × 30 × 100 mm)	SEM microscopy
						Computed tomography (CT) scanning
						Quantification of crack self-healing
						Fatigue durability tests
[81]	Encapsulation + microwave radiations	Refined palm oil, sodium alginate ($C_6H_7O_6Na$), calcium chloride ($CaCl_2$)	Asphalt binder PG 64–16	Capsule (0, 0.35, and 0.7%)	Adding capsules at the end 15 s of the mixing at the temperature of compaction long-term without and with the aging of asphalt mixture	Asphalt mixture (crack-healing measurements, semi-circular bending test, thermal sensitivity, and indirect tensile stiffness modulus test), Capsules (SEM, density, size, thermal sensitivity, and compressive strength)
				Low-carbon steel wool fiber (2–8 mm length, 60–140 µm diameter, 0, 1, 1.5, 2, and 4% crushed silica aggregates		
[80]	Microcapsules	Resorcinol, formaldehyde, urea, melamine, sodium dodecyl sulphate (SDS) emulsifier, and Soybean oil	SK-70 asphalt and SBS I-D modified asphalt	SBS modifier (4%)	Heating the SBS I-D modified and neat asphalt to 170℃ and 135℃, respectively	Model of self-healing and Micro mechanism for microcapsule asphalt influence of the microcapsule content, damage degree, healing temperature, and rest time, on the healing index
				Microcapsule (0%, 3%, and 6%)	Adding microcapsules for 30 min at 1000 r/min, then cooling them to room temperature	

Table 1 (continued)

References	Healing method	Materials	Asphalt Type	Asphalt mixture (% of the mass of asphalt mixture)	Preparation method	Tests
[82]	Microcapsules synthesized by in situ polymerization	N-octanol, deionized water, sodium hydroxide, sodium dodecyl benzene sulfonate (SDBS), citric acid (10 wt.%), Formaldehyde (37 wt.%)	Asphalt rejuvenator (70#asphalt)	Microcapsule (0 wt.%, 1 wt.%, 2 wt.%, 3 wt.% and 4 wt.%), sodium hydroxide (10 wt.%), citric acid (10 wt.%),	Heating neat asphalt to 160 °C mechanical stirring of neat asphalt and microcapsules for 15 min and 800RP	Self-healing behaviour
				Formaldehyde (37 wt.%)	Long-term aging asphalt (T 0630–2011)	Self-healing rate
					Short-term aging asphalt (T 0610–2011)	Conventional performance
						Salt resistance
						Thermal stability
						Chemical structure
						Micromorphology
[90]	Asphalt rejuvenator encapsulation	Alginate solution	Asphalt binder (60/80 p)	Original asphalt (4.7%	Term UV-ageing (UVA) 135℃ 4 h + UV 14d (21 W/m^2, 40℃)	DSR test
		Sunflower oil		Capsules (0.5%) alginate solution (2.5 wt.%)	Long-term thermos-oxidative aging (LTA) 135℃ 4 h + 85℃ 5d Long	Temperature sweep Frequency sweep
				Sunflower oil (5%) alginate solution/oil of 10/1	Short-term thermos-oxidative aging (STA) 135℃ 4 h	Fracture-rest-refracture test
						3-point bending test
[91]	Encapsulation	Polymeric capsules (calcium-alginate polymer) sunflower cooking oil	Virgin bitumen 40/60 pen	Capsules to bitumen (26.6%, 22.5%, 19.5%, 12.1%, and 9.0%) cooking oil (6–8%)	Heating aggregates and bitumen for 2 and 10 h at 170 °C and 140 °C, respectively. then manually mixed, including polymeric capsules for 20 s at 20 °C then, samples were moulded (30 × 30 × 100 mm)	Composition of polymeric capsules thermal stability
		Sodium alginate ($C_6H_7O_6Na$) Calcium chloride ($CaCl_2$)		Oil to bitumen (7.2%) gap-graded limestone sand		Quantification of oil release
						Crack-healing measurements
						Compressive strength
						Density
						Thermal characterisation

Table 1 (continued)

References	Healing method	Materials	Asphalt Type	Asphalt mixture (% of the mass of asphalt mixture)	Preparation method	Tests
						Morphological characterisation
[35]	Microwave and induction heating	Steel wool fibres	Bitumen (CA24)	Steel wool fibres (0.157 mm diameter, 30 aspect ratio, and 2 to 8 mm initial length, 2%, 4%, 6%, and 8%) gravel, sand, filler	Heating the materials (6 kg) for 2 h and then 3.5 min at 150 °C, then mixing at 100 rpm	Thermogravimetric analysis (TGA)
					Adding the materials into the bowl in the order of bitumen and fibres, coarse aggregate, fine aggregate, and filler	Self-healing measurements
					Moulding cylindrical samples (height 6 cm, diameter 10 cm)	X-ray computed tomography (CT scan)
					Cutting four semi-circular samples	Microwave and induction heating
						Three-point bending strength
						Particle loss resistance
						Bulk density and air void content
						Morphology of steel wool fibres
[8]	Microwave heating	Steel wool (SW)	AC-13 asphalt	CF (6 mm length, 6–7 µm Diameter, 0.5%, 1% and 1.5%) SF (35–60 mm length 0.75 µm Diameter 1%, 2% and 3%) SW (4 mm length, 0.1 µm Diameter 2%, 4% and 6),	Heating limestone powder, asphalt, and aggregates at 160 °C	Microwave healing conditions
		Carbon fiber (CF), steel fiber (SF)			Add the materials into a blender and mix in the order of aggregates and fibers (for 90 s), asphalt (60 s), and limestone powder (30 s)	Self-healing ability
		Limestone powder				Freeze–thaw splitting
		Fine and basalt coarse aggregates				

Table 1 (continued)

References	Healing method	Materials	Asphalt Type	Asphalt mixture (% of the mass of asphalt mixture)	Preparation method	Tests
[92]	Induction heating	Steel fiber steel slag	Asphalt (60/80)	Optimum asphalt-aggregate ratio (4.7%)	Steel slag as an aggregate of 4.75–9.5 mm	Multi-parameter method
				Steel fiber (0%, 2%, 4%, 6%, 8%, 10%)	Steel fiber as heating material	Single-parameter method
				Limestone aggregate and limestone filler		Optimization for parameter combination
						Cracking resistance
						Moisture stability
						Dynamic stability
[93]	Induction healing, Capsule system, and combined system	Steel fibres and calcium alginate capsules	Bitumen (70/100)	Steel fibres (1.4 mm length, 40 mm diameter, 6%)	Designing mix per Netherlands porous asphalt standard PA 0/11	Healing procedure and evaluation
				Calcium alginate capsules (7%)		Semi-circular bend
						Indirect tensile test
						CT-scan
						Dynamic shear rheometer
						laboratory aging
						Slab production
[94]	Induction heating	Steel grit	Hot mix asphalt (bitumen 40/60 p)	Hot mix asphalt (4.7%)	HMA samples; HMA and aged RAP	Theoretical framework self-healing
			RAP	Limestone steel grit (1- and 2-mm. Asphalt mixture (11.2%)	Replacing natural aggregate with steel grit	Bitumen rheology
				RAP (0%, 20%, 40%, 60%, 80%, 100%)	RAP (ventilated oven for 15 days at 85 °C)	
					Mixing samples for 2 min at 160 °C, obtaining 310×310×50 mm prismatic slabs	
					Cutting into 8 (150×70×50 mm)	
[95]	Induction healing	Virgin steel grits (VM), green slags (GSBP), by-products blasting processes (FBP) dust, grits (GBP), and steel spheres (SBP)	Conventional bitumen (50/70 p)	Ophite stone and limestone (from 0.063 mm to 2 mm)	Adding limestone with ferromagnetic particles (uniform distribution). The samples were compacted by 40 blows	Statistical modelling (Response optimization Multiple regression analysis, Cluster analysis,)

Table 1 (continued)

References	Healing method	Materials	Asphalt Type	Asphalt mixture (% of the mass of asphalt mixture)	Preparation method	Tests
					After de-moulding, samples were pre-notched with a saw and then stored for 24 h in a freezer	
[96]	Additives modified asphalt materials	The bio-oil (i.e. WCOR)	Pure asphalt (PG64-22)	The bio-oil (2%, 3% and 4%) commercial rejuvenator (3%)	Mixing the bio-oil or petroleum-based rejuvenator (300 rpm)	Behaviour characterization within a wide temperature range
					Short-term aging (163 °C for 5 h), long-term aging (160 °C for 30 min), and simulated climate aging (70 °C for 6 d)	Self-healing evolution
						Multiple stress creep recovery (MSCR)
						Frequency sweep
						temperature determination
						Viscoelastic transition
[83]	Additives modified asphalt materials	Crumb rubber, High-Density Polyethylene (HDPE), gilsonite, and	Base asphalt binder (60/80 p)	Asphalt binder (5.0) %	Designing HMA with typical gradation Sup-12.5	Four-Point Beam Fatigue
		Linear styrene–butadiene–styrene (SBS)		SBS (1.5, 3.0, 4.5) %	Designing mixtures per Superpave specifications	Spectrometric index calculations in FTIR
				Sulphur (0, 0.10, 0.15, 0.20, 0.25, 0.30) %,		Binder bonder strength test
				Crumb rubber: neat asphalt (5:95, 10:90, 15:85, 20:80)		
				HDPE (2.0, 4.0, 6.0, 8.0) %		
				Gilsonite (4.0, 8.0, 12.0, 20.0, 24.0) %, aggregates (basalt)		
[86]	Additives modified asphalt with carbon nanotube	Multi-walled carbon nanotubes (MCNT)	SK-70# bitumen	MCNT (3–15 µm tube diameter, 15–30 µm tube length, 0%, 0.5%, 1.0%, 1.5%, and 2.0%)	Base bitumen was heated at 135 °C , then poured into cylinders at 160 °C	Self-healing tests
					Shear mixing (for 15 and 45 min at 3000 and 5000 rpm/min, respectively)	Initial healing temperature

Table 1 (continued)

References	Healing method	Materials	Asphalt Type	Asphalt mixture (% of the mass of asphalt mixture)	Preparation method	Tests
					Developing sheared asphalts for 2 h at 160 °C	Compatibility test
						Modification mechanism
						Rheological properties
[97]	Additives modified asphalt materials	Polyphosphoric acid (PPA)	Asphalt (80/100)	WEO (2%, 4% and 6%)	Heating asphalt at 135 °C . Adding WEO into liquid asphalt (stirring for 10 min stirring with 3000 r/min) Adding PPA into WEO asphalt (stirring for 20 min with 3000 r/min)	Radar chart method
		Waste engine oil (WEO)		PPA (1% and 2%)		Differential scanning calorimetry (DSC)
						Fatigue-healing test
						Establish of G* master curve
						Linear amplitude sweep (LAS)
[98]	Additives modified asphalt materials	Styrene Butadiene Styrene (SBS polymer)	Artificially reclaimed bitumen (H and R)	Artificial reclaimed bitumen (0%, 45%, 100%)	Limestone and bitumens were heated at 165 °C. Then bitumen H and R were blended using a low-shear mixer (60 rpm and 165 °C for 5 min)	Rheological characterisation (Frequency sweep tests, Self-Healing capability)
				SBS (3.8%)	Filler was added and blended gradually for about 10 min using the same mixer	Morphological characterisation
				Limestone filler/bitumen (0, 1) filler/mastic (28%)		
[99]	Additives modified asphalt materials	Steel fibers	SBS-modified asphalt, High-viscosity asphalt to prepare	Bitumen (5.7%)	Casting an STC plate (300 × 300 × 30) mm, kept for 48 h at 25 ℃, then cured in vapour for 48 h	Correlation between fatigue and static healing indexes
			Steel-Super toughness Concrete (STC)-Stone Matrix Asphalt (SMA)	Steel fibers (13 mm length, 0.175 mm diameter, 2.5%)	Shot the surface of the dried plate (0.5 and 0.55 TD/mm)	Shear performance
				Wood fiber (0.4%)	Epoxy resin was spread (for 12 h at 25 ℃, 0.7 kg/m2)	Interlayer failure pattern
				Cement and mineral powder as filler)	STC-SMA for 24 h at 25 ℃ (90 × 90 × 60) mm	Healing performance

Table 1 (continued)

References	Healing method	Materials	Asphalt Type	Asphalt mixture (% of the mass of asphalt mixture)	Preparation method	Tests
				Aggregates (basalt),		Fatigue performance

dipole orientation of the electric field. A number of factors, including the dipole's mass, mobility and strength, affect how well microwave radiation is coupled into a medium. When heating non-conductive materials like asphalt using microwaves, the electric field must be strong enough to polarize charges within the material and to prevent the polarization from reversing at extremely high speeds [47, 85]. The evaluation of the effectiveness of microwave heating as a healing index involves the use of the recovery rate of fatigue life and stiffness modules. Assessments encompass various factors, including the extent of damage, duration of heating and the temperature at which heating occurs. Replacing coarse aggregates with steel slag has also been investigated as it can impact the whole self-healing performance of the mixtures [8, 34].

Additives such as waste oils, fibres, slag, nanomaterials and polymers have also been investigated, incorporated into asphalt mixtures in various percentages. Assessment of these is also conducted through basic properties and performance lifecycle tests. Usually, these materials are added in percentages lower than 10% and have been used individually or in combination [86, 87].

Self-healing testing of asphalt binders and mixtures

As mentioned in Table 1, there are several tests which can be performed on asphalt mixtures or binders to quantify self-healing performance. The more commonly used tests are summarized as follows:

1. Three-point bending test: This test measures stiffness and flexural strength, amongst other factors. Restrained damage is used on the specimens to mimic distressing or cracking. Using techniques like sawing or heat cycling, it is possible to accomplish this by adding predefined fractures or notches. The recovery of mechanical attributes like flexural strength and stiffness, is then compared to the initial testing after the healing period [35, 90].
2. Repeated Load Permanent Deformation Test: In this test, asphalt samples are repeatedly loaded under controlled conditions to replicate traffic loading. Over time, the degree of persistent deformation (rutting) is quantified. The sample is then allowed to rest in order to assess self-healing behaviour, the recovery of deformation monitored throughout this time. To replicate various environmental and traffic circumstances, parameters such as temperature, load magnitude and loading frequency, can be altered [88].
3. Dynamic Shear Rheometer test: The viscoelastic characteristics of asphalt binders are often evaluated

through the use of this test. The complex modulus (G*) and phase angle (δ) recovery, measured after applying a strong strain or deformation to the binder sample, can be used as an indirect indicator of self-healing behaviour. The binder exhibits self-healing activity as the phase angle decreases and the complex modulus recovers [90, 93].

4. Multiple Stress Creep Recovery test: This assesses how resistant asphalt binders are to rutting under various stresses and recovery times. It entails monitoring the binder's creep compliance and recovery behaviour while exposing it to various stress levels at a steady temperature. One way to evaluate a material's self-healing qualities is to look at how it recovers under various stress conditions [96].
5. Indirect Tensile Creep Test: This is used to evaluate how asphalt mixes behave when subject to indirect tensile loading. The asphalt mixture experiences continuous tensile stress or strain, its deformation tracked over time. The recovery of deformation during rest intervals, or following the removal of a load, is an indication of self-healing behaviour [81].
6. Four-Point Bending Beam test: This assesses how asphalt compositions behave in bending scenarios. The number of cycles to failure is used to calculate fatigue life for specimens loaded in a four-point bending mode. Changes in fracture morphology and stiffness can be used to study self-healing properties [78, 83].
7. Semi-Circular Bending (SCB) test: This is another technique for determining fatigue resistance by applying cyclic loading at regulated temperatures and rates to semi-circular specimens of asphalt mixtures. Changes in crack propagation and stiffness can be used to assess the capacity to repair microcracks during rest periods [88].
8. Fatigue-Healing-Fatigue Test: This entails applying controlled damage, like fatigue loading or thermal cracking, to the asphalt binder or mixture and then letting it rest so that it may mend itself. Afterwards, in order to calculate the healing potential, rheological properties including stiffness, viscosity and elastic modulus are recovered [86, 99].
9. Fourier-Transform Infrared Spectroscopy test: This is a method used to examine the chemical makeup of various materials, such as asphalt mixtures and binders. Although FTIR cannot quantify self-healing qualities directly, it can shed light on changes in molecular composition and structure that take place during the healing process. If desired, changes in particular spectral features can be used to measure the extent of healing using quantitative analytic techniques like peak fitting or spectrum subtraction [78].
10. CT imaging: This is a technique that creates three-dimensional, high-resolution images of tiny materials. Researchers can analyse the material's internal structure in detail using this technique when examining asphalt binder and blends. In order to replicate the kinds of wear and tear the material would encounter in actual use, artificial damage is introduced to it. Self-healing asphalt material's ability to reduce damage and prolong service life is assessed by contrasting its performance with conventional asphalt binders and mixtures [79, 89].
11. SEM microscopy: The microstructure of asphalt binders and mixtures can be examined both before and after healing. The distribution of healing agents, the structure of fissures, and the interface between repaired and unhealed areas, can all be understood using this approach [79, 89].

Results and discussion on the use of conventional self-healing methods

5.1. Encapsulation method

The generation and healing mechanism of microcracks at various stages of aging in asphalt, are illustrated in Fig. 6. During the service of the asphalt pavement, thermal-oxidative aging occurs due to high temperatures and oxygen from the environment [82]. The combined action of oxygen and ultraviolet radiation from the sun, causes photo-oxidative and ozone aging [87]. Consequently, asphalt becomes hard and brittle with a significant decrease in self-healing behaviour because of the transformation of its light component (aromatics) to asphaltene. Microcracks then develop as vehicles traverse said aged asphalt pavement. The self-healing process involves two main steps: first, the rejuvenator diffuses into the cracks, and then it reacts with the asphalt to facilitate restoration.

The release of rejuvenators from microcapsules occurs when microcracks traverse them, resulting in the dispersion of the rejuvenator in various directions through capillary action, effectively filling the microcracks. The rate of rejuvenator diffusion is reduced as a result of the progressive agglomeration of larger particles from medium and small molecules in old asphalt [87, 100]. Consequently, the self-healing capacity of microcracks improves. Studies by Chung et al. [101, 102] showed that asphalt containing dosed microcapsules required between 3 to 7 days to fully restore its original strength after damage, while virgin asphalt only achieved about 74% of its original strength within 24 h of breakage. In comparison, asphalt with microcapsules reached approximately 98% of its initial strength under the same conditions. Li et al. [80] studied the mechanism of

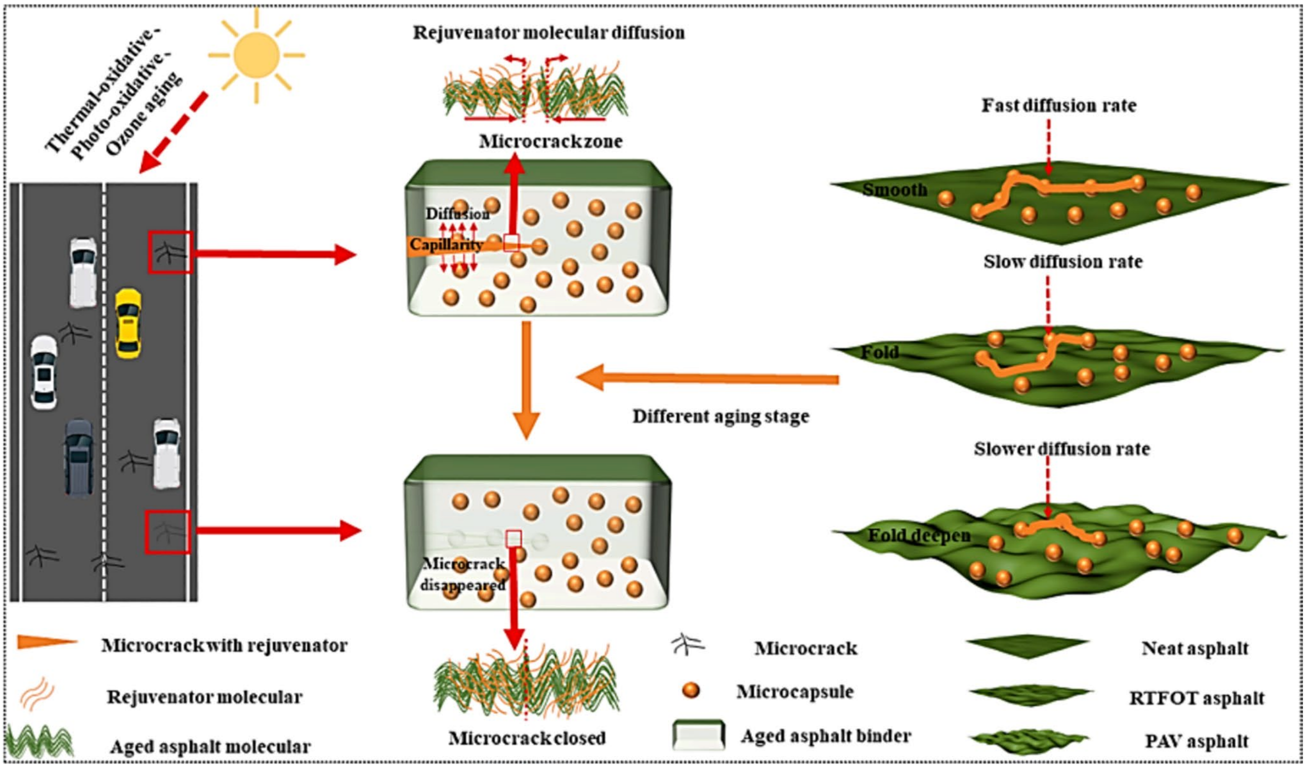


Fig. 6 Mechanism of generation and self-healing of microcapsule/asphalt microcrack at different stages of aging [82]

releasing rejuvenators and repairs to microcracks by fluorescence microscopy. They reported a gradual filling and reduced length of microcracks by core material, through capillary action.

Wang et al. [103] evaluated the use of microcapsules made from graphene which is an inorganic material forming a composite material with a polymer shell. They reported excellent high-temperature resistance and an even distribution of capsules. Following short-term aging, the introduction of microcapsules resulted in a higher recovery rate and a reduction in non-recoverable creep. Furthermore, the incorporation of just 1 wt.% graphene into the microcapsules, significantly enhanced the long-term healing capability of asphalt. Yao and Xu [88] conducted an assessment of microcapsules for the healing of cold recycled modified emulsified asphalt with styrene butadiene rubber latex and waterborne epoxy resin (WSEA). Their findings indicated that the capsules were evenly distributed at a 4% content level. However, at 2% and 6% contents, dispersion and agglomeration were seen, respectively. Enhancements were noted in relation to crack initiation and propagation, encompassing factors such as tightness, peak loads, fracture energy and fatigue life. The WSEA mixture with optimal microcapsule content meets required road performance standards.

Researchers have explored the use of calcium alginate capsules, with Wan et al. [79] studying how effectively they enhance the self-healing ability of asphalt concrete under compressive loading and microwave radiation. There was only a minor difference in strength recovery between asphalt mixtures with and without capsules and before the application of compression loads, indicating the need to activate the healing agent release of capsules through external compression loading. The characterization of capsules after mixing and compaction is shown in Fig. 7. Only a few capsules are present on the surface zone of the asphalt beam mixture due to asphalt cutting (Fig. 7a). Most of the capsules are still intact, revealing the ability of the capsules to survive, with only very small amounts of broken capsules present during compaction and mixing (Fig. 7b). Homogeneous spatial capsule distribution in the asphalt mixture is shown in Fig. 7c, indicative of the conductive healing of randomly generated microcracks. It is difficult to explain such spatial distribution as there is no literature or quantitative index of homogeneity. Due to this uniform distribution of capsules, the short distance between the microcrack and capsules reduced the diffusion and flow distance of the released rejuvenator, enhancing self-healing abilities. The infrared images of asphalt mixtures under microwave irradiation, as illustrated in Fig. 8, show that the surface temperature increases with increased microwave time, which was also found by Wan

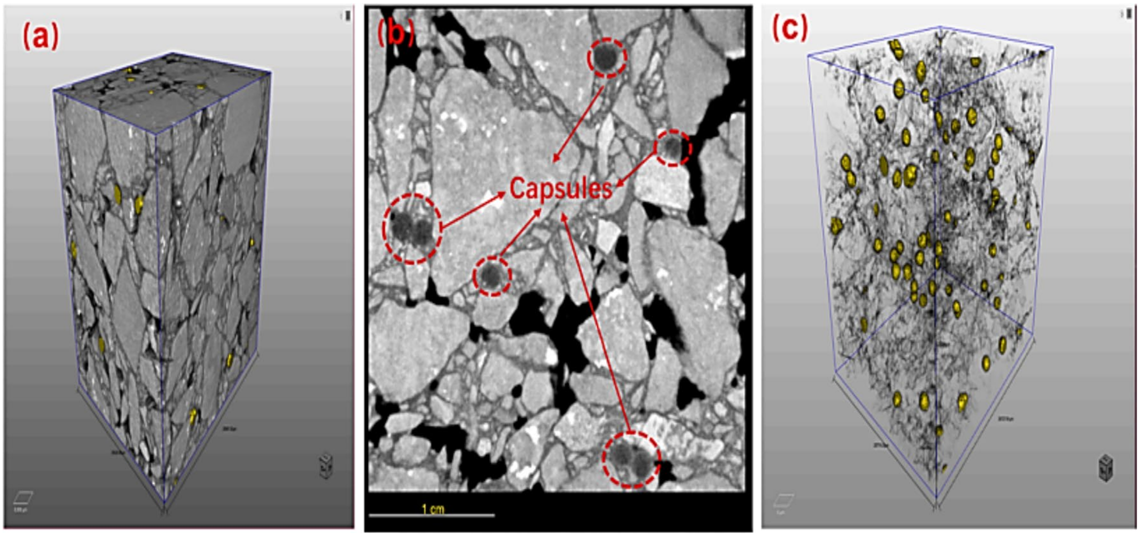


Fig. 7 Images from Computed Tomography (CT) of asphalt concrete samples containing calcium alginate capsules: **a** 3D representation; **b** 2D cross-sectional image; **c** 3D of the capsules spatial distribution [79]

et al. [104]. The temperature decreased slightly at a fixed irradiation time, with an increase in heating cycles.

In their study, Wang et al. [105] studied the application of calcium alginate capsules and observed a consistent distribution of capsules throughout the mixing, compaction and transportation processes. The capsules retained their original shape, their mechanical resistance and thermal stability meeting asphalt production requirements. The amount of agent released was about 6% for cold mix asphalt, this doubling with the thermal effect of hot mix asphalt.

Kargari et al. [81] investigated the application of palm oil in the production of calcium alginate capsules, with various ratios of calcium chloride-to-water and oil-to-water to rejuvenate aged and unaged asphalt. Their research indicated that palm oil capsules effectively enhanced the self-healing behaviour of asphalt. Density and compressive strength increased while the oil released decreased as the oil-to-water ratio increased. However, both strength and oil release decreased with an increase in the amount of calcium chloride. The optimal content was determined as 10% oil to water ratio and a calcium chloride-to-water ratio of 2%. The incorporation of steel wool fibres in microwave healing provides increased thermal stability and reflection of the microwave into asphalt mixtures. This suggests that using steel wool fibres in microwave heating can lead to reduced energy consumption and heating time without significantly compromising the healing rate of mixtures.

Xu et al. [93] proposed a combined healing system comprising capsules and induction healing. The scan images revealed a random distribution of steel fibres and capsules in the samples. The incorporation of capsules increased the lifespan of standard pavement asphalt concrete due to the rejuvenation of aged binders. The induction healing method had a more notable crack-healing effect compared to the encapsulation approach, further extending the lifespan of the pavement concrete (PAC). The benefits of combining both methods were significant, though the comprehensive healing effect also came from the synergistic impacts that support each mechanism, namely improved induction healing (with asphalt binder rejuvenation) and accelerated rejuvenator diffusion (with induction heating). Consequently, the combined methods approach provided the best performance.

The impact of exposing calcium alginate capsules to ultraviolet and thermal-oxidative accelerated aging was studied by Zhang et al. [90]. The authors found a minor impact of capsules on the mechanical characteristics of asphalt concrete, although aging reduced fracture energy and increased the stiffness of all mixes. As shown in Fig. 9, the strength recovery ratio decreased with increased thermal-oxygen aging for all specimens due to the reduced healing ability of the asphalt with aging. When oil was released from the capsules, the recovery rate increased from 41.7 to 59.8% after long-term aging. The introduction of capsules resulted in an impressive 162.1% increase in the energy rate of healing, primarily because of the heightened viscosity of asphalt upon the release of sunflower oil. However, as the aging process advanced, the recovery ability declined since the oil also aged, thereby reducing the overall improvement in asphalt self-healing performance [106].

Ruiz-Riancho et al. [89] evaluated several capsule types to identify the optimal size and strength required to reduce the adverse mechanical and durability impacts of calcium alginate capsules, as well as the quantity of sunflower oil released into the asphalt matrix. Using large, weak capsules

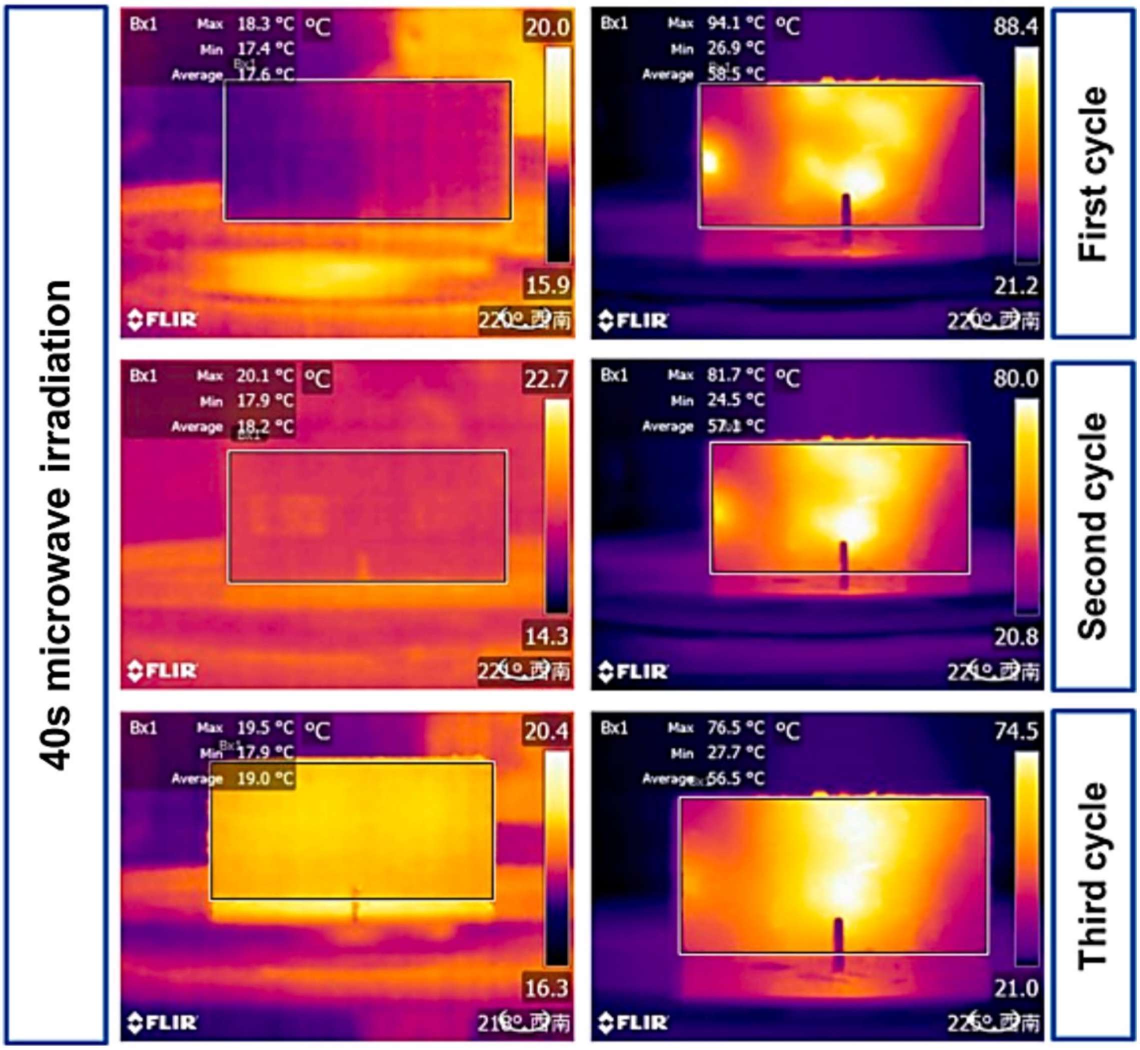


Fig. 8 Surface temperature following three cycles at fixed microwave time [79]

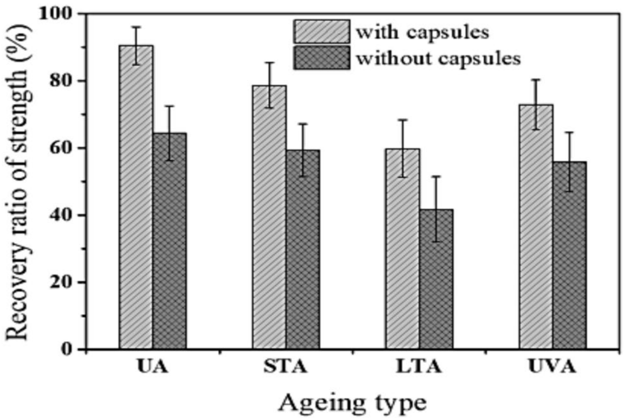


Fig. 9 Strength recovery ratio after 4000 fatigue loads [90]

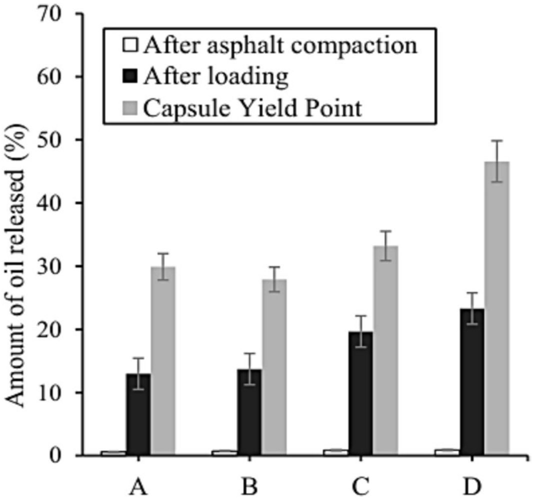


Fig. 10 The release of oil with various O/A ratios [89]

reduced fatigue durability and promoted rutting, while increasing healing rates due to the release of a higher quantity of oil. However, the impact on skidding resistance and rutting was not significant. Reflective cracking was also delayed by the use of capsules, thereby increasing durability by 21%. Figure 10 illustrates the quantity of oil released by different capsules under different conditions, which had various oil-to-sodium (O/A) ratios and a diameter of 1.3 mm. Only 1% of oil is released after mixing and compaction, and while 15–20% less oil is released before the resting period of 30% of the median cycle number for reflective cracking, it is compatible with the capsules at yield points. The maximum release of oil was quantified at 23.3% of contained oil which shows the efficiency of a capsule.

In another study, Yamaç et al. [78] conducted experiments using capsules containing vegetable and mineral oils with varying oil-to-water ratios and sodium alginate content. The results demonstrated the capsules' resilience during compaction and mixing processes, effectively releasing the oil when subject to mechanical loads. They found that a higher water-to-oil ratio led to reduced compressive strength, with the optimal composition determined as 17.5 gr sodium alginate, 500 ml waste oil and 100 ml water. Figure 11 illustrates the influence of capsules on self-healing rates at various temperatures of curing. An increase in the capsule's contents, increased the healing rates of capsules with both oils, while a lower curing temperature provided greater performance. In comparison with vegetable oil, waste mineral oils provide more effective healing. The use of capsules increased healing levels approximately 890% more than without the use of capsules.

The effect of healing temperature on the process of encapsulation was investigated by Al-Mansoori et al. [91]. The impact of temperature on compressive strength is shown in Fig. 12. A lower variability in results was obtained for capsule samples tested at 20 °C in comparison to 130 °C. With an increase in the oil-to-water ratio, the compressive strength of capsules was reduced due to a reduction in the density of calcium alginate because of a higher oil content. The average force measured at 20 °C was double that at 130 °C, evidencing the impact of temperature on the compressive strength of capsules. Similarly, García et al. [107] reported a minimum strength requirement of capsules of about 10 N to resist the mixing and

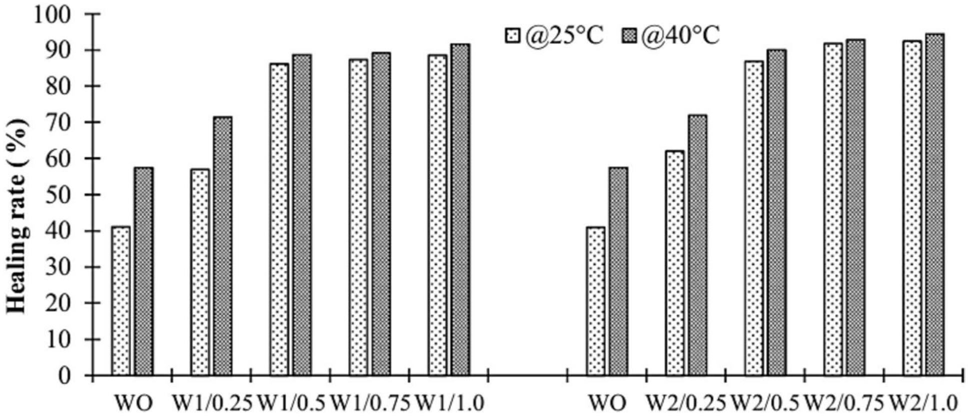


Fig. 11 Healing rate with content and type of used capsules [78]

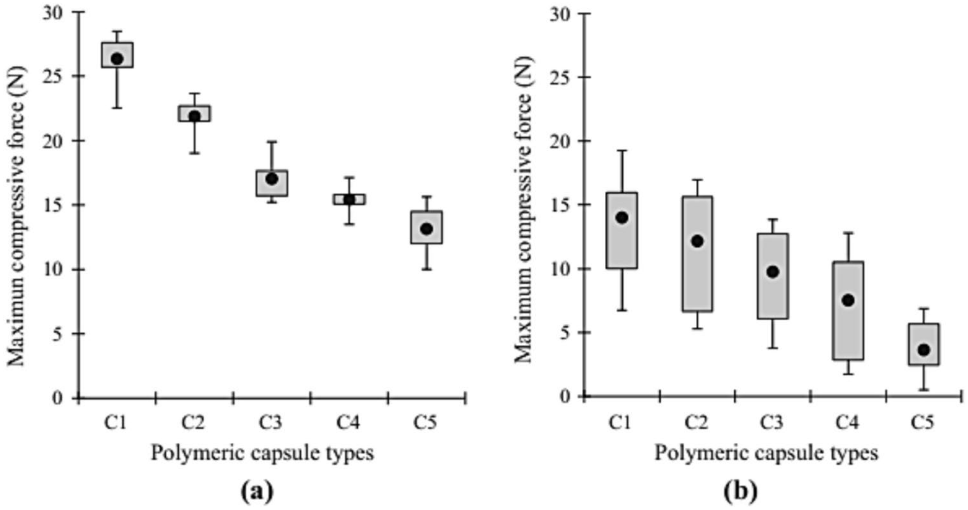


Fig. 12 Compressive force of tested capsules at **a** 20 °C and **b** 130 °C [91]

compaction process. They found that capsules with oil-to-water ratios of 0.5 and 1.0 (C4, and C5 samples) are not recommended for use with self-healing asphalt.

During the encapsulation process, the size of microcapsules must be regulated. In order to prevent crushing or pulverization during the mixing and compaction stages of asphalt pavement, the microcapsule's size must be smaller than 50 µm [108]. However, due to insufficient rejuvenators, microcapsules smaller than 10 µm are not appropriate for self-healing [109]. It is possible to identify three major groupings based on the capsules' shape. Initially, core–shell microcapsules are made up of a double shell that enfolds the rejuvenator and a liquid core that contains the rejuvenating substance. The most representative polynuclear capsules are beads made of calcium alginate [110]. These elements have many cavities creating two primary benefits. Because of their divided structure, the beads do not release all of the rejuvenator when the crack first appears, allowing for better structural reinforcement this maintaining their integrity throughout the asphalt manufacturing process. This allows for both long-term and multiple crack healing [111]. The production of encapsulated fibres has been the focus of current research efforts [44, 112] which has established that given fractures have a greater chance of passing via fibre networks because of their size. These systems can more effectively assure the release of rejuvenator into fissures while also providing the rejuvenator in greater quantities.

5.2. Induction and microwave methods

Induction heating includes blending steel or other magnetically susceptible and electrically conductive materials, into the asphalt mixture. An induction heating unit is then used to heat the mixture. Microcracks begin to self-heal as the temperature of the asphalt reaches a specific level depending on the bitumen type (usually 30–70°C). Induction heating has shown the potential to increase the lifespan of fatigue-damaged Marshall test samples by up to 31%. Nevertheless, it should be noted that the efficacy of this approach is limited to fractures of a particular diameter. In cases when fatigue damage is substantial, the application of induction healing may prove ineffective for broader cracks. Moreover, to achieve enhanced fatigue life, the temperature during induction heating should remain below a predetermined threshold. Interestingly, the healing levels in asphalt samples are uniform regardless of coil distance. However, it is essential to be cautious as excessive heat during induction heating can damage the bitumen and compromise its ability to repair the mixture [33].

Vila-Cortavitarte et al. [95] devised a statistical approach by analysing the properties of incorporated metal particles, along with the duration and intensity of magnetic induction, to forecast the self-healing capacity of asphalt concrete. This approach used response optimization, multiple regression analysis, and cluster algorithms to model laboratory results by testing asphalt mixtures with these inductors. Through their research, the authors were able to obtain the optimal amount of industrial by-products and the duration necessary to achieve the most effective self-healing process. These statistical methods were successful in simulating the experimental performance of mixes.

Gómez-Meijide et al. [94] conducted research on the impact of reclaimed asphalt pavement (RAP) and aging on the capacity of asphalt to repair cracks through electromagnetic induction. Their study revealed two contrasting effects of aging and the addition of RAP, with both negative and positive effects on healing performance. Higher air void content in the resulting mixes facilitated improved healing behaviour. However, the stiffening of bitumen and reduced viscosity made it challenging for the material to flow through cracks and air spaces, leading to inferior results. The data indicated that the negative impact was more pronounced, ultimately diminishing self-healing because of RAP and aging.

Jian et al. [92] conducted a study on self-healing of asphalt which contained steel fibres and slag, focusing on the impact of induction parameters. The results confirmed correlations between the parameters, the best pavement performance observed in an asphalt mixture containing 8% steel fibre. For the single parameter method, the optimum healing rate was achieved with 8% steel fibre content, 5 mm induction distance, 180 s and 16 kW power, resulting in a 69% healing rate. The multiple parameters technique's optimum set included 8.8% steel fibre content, 5 mm induction distance, 107 s and 24 kW power, resulting in a 75% actual healing rate, closely matching the predicted 77%. The study showed that the multi-parameter technique, based on partial least squares, achieved a higher healing rate improvement compared to the single parameter method, indicating the impact of dual effects of induction heating parameters on the asphalt mixtures' self-healing ability.

Although various bitumen types have unique adhesive and rheological characteristics that may impact asphalt mixtures' ability to heal, studies have shown that bitumen type has little to no effect on the ability to heal [113, 114]. The ideal circumstances for induction heating temperature and speed, depends on the kind of asphalt mixture chosen [19]. Primary induction heating mechanisms have been identified and visualized with the help of basic models created to depict thermal heat flow equations for asphalt mixtures heated by induction energy [44]. The application of induction heating has been shown in laboratory tests to greatly prolong the fatigue life of induction-healing porous asphalt, potentially adding at least 30% to the service life of roadways [115]. However, applying too much heat slows down the healing process because the binder melts all the way

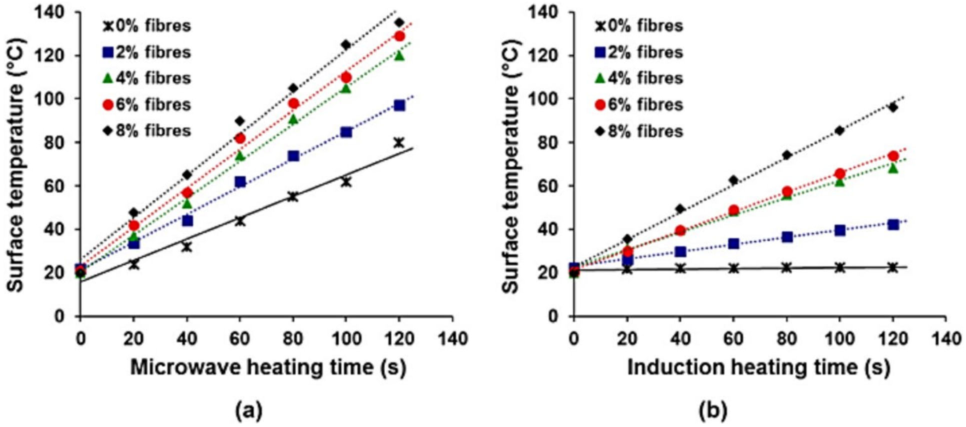


Fig. 13 Surface temperature with heating time concerning **a** microwave heating and **b** induction heating [35]

through and the material's qualities are lost [116]. Every heating cycle causes the healing performance of asphalt mixture to drastically decline, even in cases where this critical heat limit is not surpassed [117].

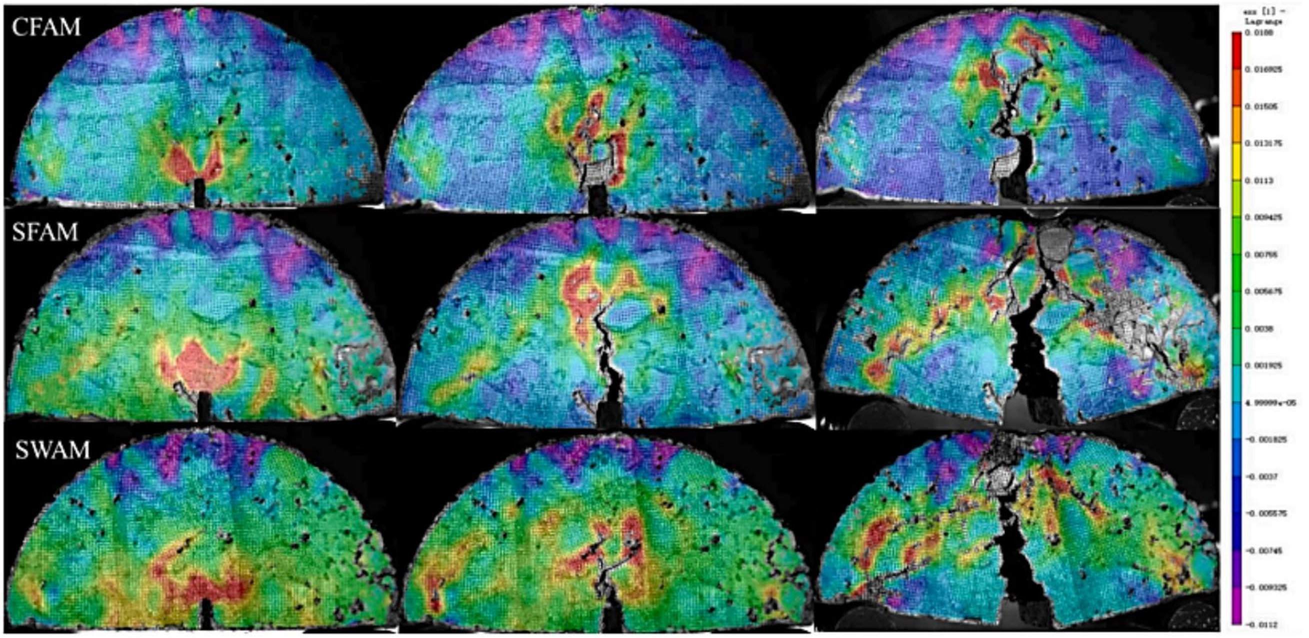
The effect of induction and microwave heating on samples containing steel wool fibres was studied by Norambuena-Contreras et al. [35], their study revealing that microwave technology was more effective than induction heating. As shown in Fig. 13, The temperature of asphalt surfaces increased with prolonged exposure to microwave radiation and higher fibre content. Even asphalt mixtures without steel fibres experienced a rise in temperature during microwave heating, indicating the potential for optimizing microwave heating without using steel fibres. However, the high temperatures of bitumen before releasing heat to the environment and aggregates, due to their weak thermal conductivity compared to steel, pose a challenge. The presence of fibres in the mixture further accelerates the heating process. Conversely, asphalt test samples without fibres did not exhibit a surface temperature increase during induction heating. While most heat is retained in the bitumen and fibres, some is released into the environment and nearby aggregates, specifically when reaching temperatures beyond the flash point of the bitumen.

Flow behaviour and potential optimal self-healing temperature were studied by Tang et al. [118] using DSR viscosity-frequency sweep tests. It was observed that both aged and fresh bitumen binders exhibit a near-Newtonian fluid state during their best self-healing state. Moreover, the binder's ideal self-healing temperature was found to increase with age, indicating a relationship between bitumen type, aging and the preferred self-healing temperature. The Wool and O'Connor model can be used to calculate the time required for complete healing, the accumulated dissipated energy recovery serving as a useful healing index.

Mannan et al. [119] investigated the effect of moisture conditioning, their findings showing that an increase in the amount of water absorbed, reduced the rate of healing, indicating an inverse relationship between healing rate and water content. Determination of the cohesiveness of the binder, which serves as an indicator of its ability to mend instantaneously, can be achieved by applying the work of separation derived from the tack test. The ability of asphalt binders to self-heal was found to be negatively influenced by moisture conditioning, leading to reduced instantaneous and time-dependent healing due to increased activation energy and decreased cohesiveness, respectively. Interestingly, softer binders exhibited faster healing than firmer binders under moisture conditioning circumstances.

The most important factor influencing the degree of healing attained by asphalt mixes exposed to microwave radiation is duration of heating. The optimal amount of time to heat asphalt samples to achieve maximum healing and minimal damage is less than a minute, as prolonged microwave heating deteriorates bitumen and increases the porosity of the asphalt mixture [117]. When heat was used to melt snow and ice, asphalt compositions that were supposed to self-heal by induction or microwave heating, had diminished performance. Effective thermal healing is impeded on crack surfaces by the moisture resulting from snow and ice melt. Increasing costs and environmental effects of asphalt induction or microwave heating are among the primary drawbacks that need to be addressed. The need for metallic particles has been addressed, numerous waste metals such as steel slag, metal fibers, and other steel shavings, have been investigated.

A study by Yang et al. [8] investigated the influence of different fibres (steel wool, steel fibre and carbon fibre) as microwave-absorbing materials. They reported significant improvements in healing capacity and mechanical characteristics of the mixture containing fibres, but freeze–thaw cycles had a notably negative impact. As shown in Fig. 14, steel fibre exhibits the most robust impact on the fracture behaviour of the mixtures as it was less affected by moisture and freeze–thaw effects compared to carbon fibres and steel wool. Carbon fibre shows the least resistance to fracture



(a) The crack initiation stage (b) The creak propagation stage (c) The fracture failure stage

Fig. 14 The strain cloud diagram at the end of various stages [8]

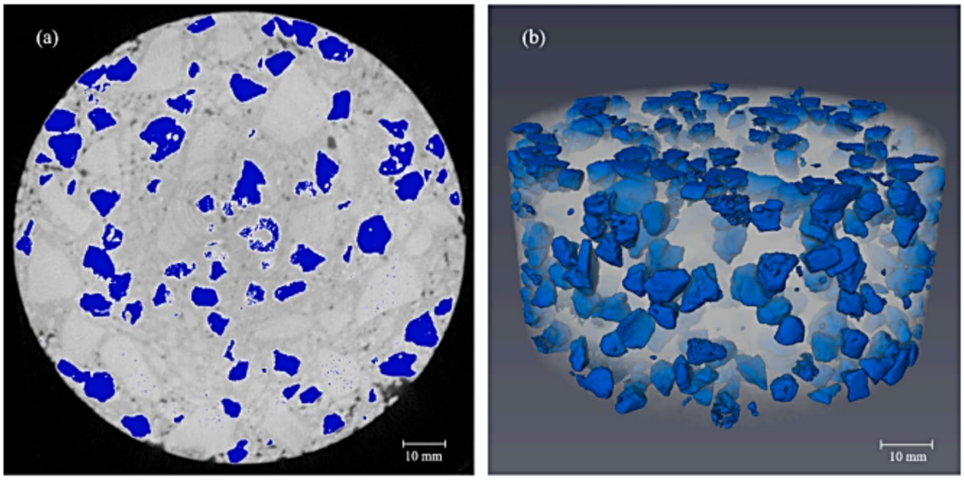


Fig. 15 Steel slag distribution of: **a** 2D, and **b** 3D [120]

and freeze–thaw damage. Typically, peak strain corresponds to the initiation of macrocracks but in this study, the macrocrack initiation location happened before the peak load. In this sense, steel fiber > steel wool > carbon fibre can be used to rank these regarding fibre reinforcement in asphalt mixtures.

In the investigation by Liu et al. [120], asphalt mixtures were modified with steel slag instead of limestone, and subjected to microwave heating. The high metal oxide content of steel slag enables effective wave absorption. Despite having a larger fracture energy healing rate according to the self-healing index (FEHR) when compared to traditional mixtures, steel slag asphalt mixtures did not exhibit a significant decrease in their initial strength. Samples with a greater steel slag content had superior self-healing abilities. According to CT scanning as shown in Fig. 15, the steel slag is evenly dispersed throughout the mixture. This dispersion can be seen in a specific area using two-dimensional photographs, while its overall distribution in the mixtures can be seen using three-dimensional photos. Steel slag is distributed evenly throughout the mixture, whether it is in the top, middle, lower, outside or inside.

Loureiro et al. [121] conducted a study to evaluate the effect of microwave heating on mixtures containing steel wool fibres (SWF), a combination of steel slag and steel wool (SS) fibres, and mixtures without fibres. The research revealed that the use of SS and SWF gave the optimum self-healing capacity with superior heating temperatures during the heating cycles and semi-circular bending test, showing remarkable recovery of strength after a complete fracture. Conversely, inferior fracture test results were obtained for the mixtures without SS. After heating cycles and the four-point bending fatigue test, both the conventional mixture and those with SS and SWF, exhibited high healing indexes, with approximately 150% recovery of fatigue life after two cycles of healing.

Yang et al. [122] conducted an assessment of the static magnetic and chemical composition of steel slag comprising various particle sizes. The study revealed that steel slag exhibits narrow S-type magnetic hysteresis loops, indicating its low coercivity with a magnetically soft nature. Particle diameters ranging from 9.5 to 16 mm, had optimum static magnetic characteristics and Fe content, with a coercivity gain and saturation magnetization of 148.09 Oe and 2.13 emu/g, respectively. In comparison to the inclusion of reclaimed asphalt pavement (RAP), the use of larger-sized steel slag particles in recycled asphalt mixtures resulted in enhanced healing efficiency and depth, as well as an elevated induced temperature rise. The efficacy of healing was enhanced as particle size increased, exhibiting an inverse relationship with the dosage of reclaimed asphalt pavement (RAP).

Based on research, it appears that these metallic fillers have more irregular shapes than virgin steel wool fibres, primarily wider widths. However, these wider elements can also form electrically conductive channels, which enhance asphalt mixtures' specific heat capacity and thermal conductivity [123]. Nevertheless, while mixing, these metallic wastes have a tendency to cluster, which reduces the maximum volumetric quantity that can be added. Another viable option is to use steel slag in place of traditional coarse aggregates (such granite or limestone), as its presence can enhance the performance of the mixture as a whole as well as improve healing outcomes. Nevertheless, studies have also been reported [96] that mixtures with metallic wastes have a diminished healing performance but they still represent affordable and sustainable materials [44].

5.3. Additives as healing agents

Increasing the self-healing properties of bitumen itself can also improve the ability of asphalt pavements to heal cracks. Modified bitumen can be polymer (SBS, HDPE, crumb rubber, PPA, PE) or comprised of nanomaterials. The type and quantity of modifiers used, determine how well polymer-modified asphalt self-heals. When a crack in asphalt that has been treated with nanomaterials, the tip of the crack attracts the nanoparticles, this stopping the crack from spreading and help it mend. Lv et al. [83] studied the self-healing of asphalt with various modifiers including HDPE, SBS, Gilsonite and TB. The results in terms of methylene plus methyl hydrogen to carbon (MMHC) ratio, healing index (HI_1), and viscosity are summarized in Table 2. The content and type of modifier had a substantial effect on the asphalt self-healing

Table 2 Various testing results [83]

Binder type	Binder ID	Viscosity @135 °C (Pa. s)	Healing index (%)	MMHC
Modified binder (modified from binder A)	5.0% TB	850	39.61	2.3374
	10.0% TB	930	34.93	2.3509
	20.0% TB	1148	24.22	2.3723
	2.0% HDPE	965	43.91	2.3285
	8.0% HDPE	1354	17.25	2.3387
	4.0% Gilsonite	823	40.42	2.3289
	8.0% Gilsonite	1696	29.00	2.3283
	12.0% Gilsonite	2165	19.53	2.3271
	Pure SBS modifier	NA	NA	2.0242
	1.5% SBS	947	26.63	2.3339
	3.0% SBS	1320	24.59	2.3300
	4.5% SBS	2509	23.58	2.3227
Base binder	A	515	41.40	2.3351
	B	847	33.51	2.3383
	C	1233	15.35	2.3700
	D	692	35.71	2.3293
	E	731	29.58	2.3400
	F	797	24.85	2.3538

according to the results of the Binder Bond Strength (BBS) test. Interestingly, an increase in the content of the modifier reduced the self-healing of the base binder, regardless of additive type. It was found that the MMHC ratio was insufficient to describe the healing of modified asphalt, although it was good for evaluating the healing of base binder. In contrast, with basic and modified asphalt, rotational viscosity at 135 °C can predict healing characteristics.

Liu et al. [97] studied the viability of using polyphosphoric acid (PPA) and waste engine oil (WEO) to enhance fatigue resistance and self-healing. Regarding additives containing 1% PPA and 4% WEO, 2% PPA, and 2% WEO, respectively, fatigue life was substantially extended by 1150% and 1000% over the original asphalt. Regardless of PPA concentration, asphalt modified with 6% WEO showed a significant improvement in dissipated energy, modulus and fatigue life recovery, compared to the original asphalt. Healing indicators increased significantly with healing time for the original asphalt in comparison with modified asphalt. This was because recovery occurred in a short time for most of the damage in modified asphalt.

Sun et al. [96] systematically examined how bio-oil regeneration and aging affected the evolution of self-healing behaviour in terminal blend (TB) rubberized asphalt and pure asphalt, across a wide temperature range. As shown in Fig. 16, intricate self-healing, evolution behaviour was caused by the impact of various temperatures on the flow properties and elastic recovery (ER) of rejuvenated or aged asphalts. The self-healing process at all measured temperatures, was dominated by the flow capacity of newly generated asphalts, according to the proposed ER-flow self-healing theory. For the aged asphalt, the process was dominated by the ability of ER in the viscoelastic zone, the process dominated by the flow ability in parallel with the increase in temperature. In contrast to long-term aging, climate aging had a more significant impact on the self-healing of virgin asphalt and less of an effect on TB asphalt. An increase in bio-oil content, increased the recovery percentage of rejuvenated asphalts, peaking when 4%wt. Overall, the self-healing of aged asphalts was only partially recovered by bio-oil regeneration. Through the use of molecular simulations, Xin-wen and Zhao-hui [124] were able to uncover the self-healing mechanism of bio-oil recycled asphalt (BRA) proposing that the process was primarily driven by elastic recovery at lower temperatures and viscous flow at higher temperatures.

The use of carbon nanotube as an asphalt healing additive, has been investigated by various researchers. Santagata [125] reported a significant change in the fatigue performance of asphalt when the CNT content approaches 1%. CNTs can increase softening points and decrease the penetration and ductility of asphalt binders, according to Wang et al.'s evaluation [126]. Ibrahim [127] evaluated the rheological characteristics of bitumen with CNTs, the results showing that low-temperature cracking resistance, high-temperature rutting resistance and fatigue resistance, all increased. After analysing the impact of various road preparation techniques, Faramarzi concluded that CNTs

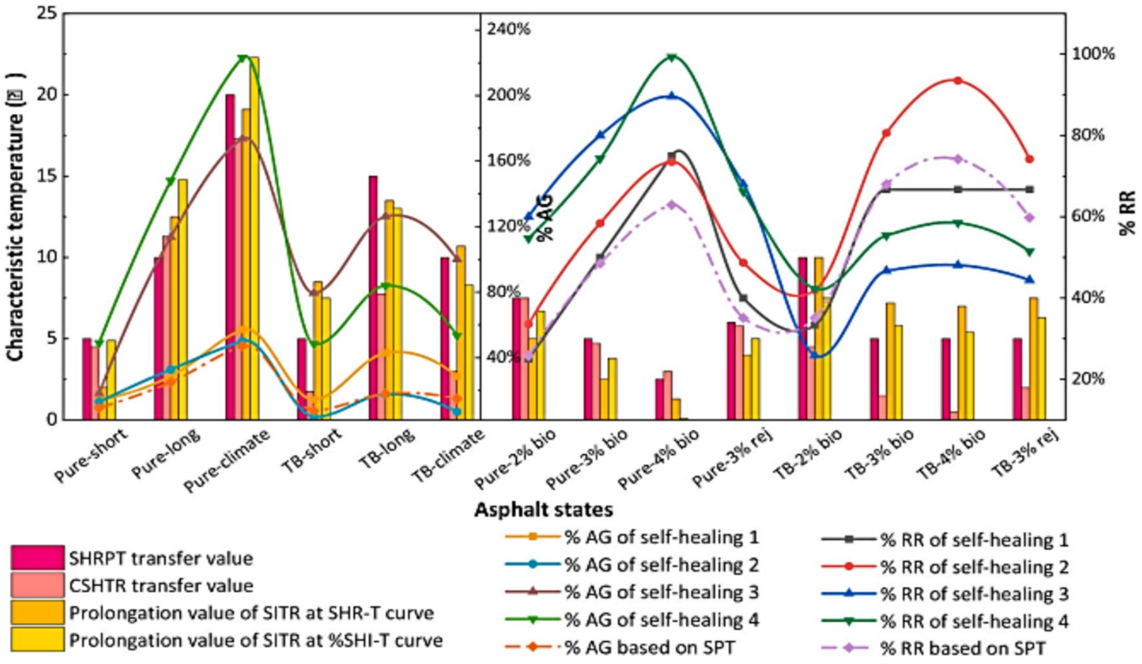


Fig. 16 Effects of regeneration and aging within a wide range of temperatures [96]

could lower pavement maintenance costs [128, 129]. Zhang et al. [86] studied the use of multi-walled carbon nanotubes (MCNT) in asphalt binders, finding that physically blended bitumen and MCNT were agglomerated when the content of MCNT was higher than 1.5%. However, an increase in MCNT, degraded and increased both low and high-temperature rheological characteristics, respectively, according to the findings of master curves. The flow behaviour index was lowered by the use of MCNT and hence increased the initial temperature of healing. At room temperature, no variations in the healing effects were obtained, though 1.5% content MCNT exhibited the best healing efficiency when modified asphalt are healed at their respective healing temperatures. It is worth noting that the modification process between CNTs and bitumen is limited, despite the fact that CNTs can reinforce and enhance bitumen's ability to mend itself. In asphalt, it is still difficult to produce a homogenous dispersion without agglomerating [130, 131]. An excessive amount of CNTs can aggregate and generate a stress concentration, which makes asphalt more prone to cracking and degrades bitumen characteristics [132]. Thus, in order for the nanomodified asphalts to fulfil the fundamental requirements and quicken the self-healing processes, CNT content needs to be kept within a suitable range.

Apostolidis et al. [133] investigated the ability of asphalt without aggregates, to induce healing as part of asphalt concrete where inductive particles are spread, substantially affecting the behaviour of asphalt pavements. The electrical conductivity of asphalt mortar significantly improved when steel fibres were used as opposed to iron powder. Furthermore, thermal conductivity exhibited a slight increase when using a combination of iron powder and steel fibres in the mortars, compared to the use of only steel fibres as conductive particles. The incorporation of iron powder and steel fibres resulted in an enhancement in tensile strength and an extension of fatigue life. Ultimately, on the introduction of iron powder, asphalt mortars exhibited similar induction healing capabilities as mortars containing steel fibres. The maximum efficiency in induction heating for mortars were obtained when iron powder is mixed with steel fibers.

Novel approaches

Mazzoni et al. [98] compared bitumen and corresponding mastics in terms of thixotropy, self-healing and fatigue. They used a Dynamic Shear Rheometer (DSR) to analyse the data, based on a novel test technique that had previously been used for bitumen, the results indicating that bituminous mastics can be analysed using this approach. Finding that individual filler particles could not repair themselves; they established that the addition of aged bitumen significantly improved the overall fatigue performance of virgin bitumen/mastic, this pointing to important advantages when combined with recycled mixtures that include recycled asphalt aggregates. Favourable interactions between long polymer chains of unaged asphalt and short polymer chains of aged asphalt, were found to be responsible for this as it creates an internal network capable of providing greater elasticity and interdiffusion.

A cutting-edge maintenance technique for asphalt pavements, automatic induction self-healing treatment (AI-SHT), effectively heals cracks when inductive particles are mixed into the asphalt. The metallic components of the bridge serve as the inductive materials. Liu et al. [134] examined the engineering viability and financial benefits of applying AI-SHT to steel deck asphalt pavement (SDAP). To investigate the effects of self-healing, the magnetic circuit principle was proposed. A reduced form of SDAP was used to test fractures and induction self-healing. AC–13 asphalt concrete was used for SDAP which was 1 km × 3.75 m × 6 cm in length × width × depth. The area of the induction coil for the proposed AI–SHT was 0.09 m2. Table 3 compares the self-healing outcomes between SDAP and the traditional "mill and overlay" method (IHAP) when the AI-SHT was used. The

Table 3 Comparison of strength recovery rates of IHAP and SDAP [134]

Types of AI–SHT	Type and content of induction materials (by the volume v.%or mass m.% of asphalt	Maximum rate of strength recovery	Total consumption of induction energy	Optimum healing temperature
Liu et al. [135]	Steel fibers (6 v.%)	Less than 78%	1 kW·h	–
Liu et al. [135]	Steel wool fibers (6 v.%)	65.70%	0.69 kW·h	100 °C
Li et al. [136]	Steel fibers (6 v.%)	75.00%	0.12 kW·h	–
Sun et al. [137]	Steel slag (coarse aggregate) Steel fibers (6 v.%)	11.56% 80.80%	0.06 kW·h	80 °C
Pamulapati et al. [138]	Aluminium (5.0 m.%)	72.00%	–	110 °C
	Steel fibers (2.5–5.0 m.%)	62.00%		
Liu et al. [139]	Waste steel shavings (11.2 m.%)	78.70%	0.50 kW·h	85 °C
Liu et al. [134]	Steel bridge deck	89.50%	0.08 kW·h	120 °C

information about the IHAP's strength recovery rate was obtained from earlier investigations. As shown in Table 3, the SDAP's maximum rate of strength recovery was higher than IHAP's. SDAP's maximum rate of strength recovery was 89.5%, but IHAP was limited to 81%. Comparatively speaking to its use on IHAP, AI-SHT's applied to SDAP consumed less induction energy. The primary explanation was that the SDAP served as a heat source and decreased resistance to the magnetic field in the circuit. In comparison to IHAP, the rate of strength recovery of SDAP, was significantly higher in this situation because SDAP's heating performance was superior to that of IHAP.

Sun et al. [63] developed a formula of activation energy as an indication of self-healing, according to Arrhenius' law, this clearly distinguishing the self-healing effectiveness of asphalt mixtures. Healing activation energy serves as the minimum energy required for time-dependent strength gains and rates as well as the time-dependent healing capability of various asphalt mastics.

Field investigations

The first induction-heating asphalt pavement was used in the Netherlands in December 2010 [140], and it has continued to function successfully up to this point. A 400-m test section of induction healing pavement was also laid in the Chinese province of Guangdong in 2018 [141]. The Dutch experimental pavement underwent its first induction heating treatment in June 2014, the results showing that ravelling resistance and healing ratios were both good [142]. The Netherlands could save about 90 million euros annually and increase the lifespan of its roads by 50% if all of its roads were replaced with induction-heated pavements, according to calculations. If only 10% of the roads are rebuilt with induction healing pavement, China could also save 1000 billion RMB in maintenance costs, according to the same computation [140]. On the other hand, asphalt pavement aging cannot be stopped by induction heating technology. As the servicing process progresses, the pavement's susceptibility to cracks will increase and the healing temperature will be higher than that used previously. If a homogenous mixture with the fewest possible steel wool clusters is required, mixing should last for five minutes. When regular asphalt pavement is applied, it takes longer to mix [140, 143]. Heating effectiveness is also constrained; 5 kms takes one hour to heat because it takes 26.4 s for the temperature of the road surface to rise from 5 to 85 degrees Celsius [144]. To ensure heating rates and maintenance schedules for large-scale induction equipment, more research is necessary. In porous asphalt pavements, ravelling is one of the main flaws. A Rotating Surface Abrasion test was used by Liu et al. [145] to examine how induction heating unravelled porous asphalt on field samples. The results showed that induction heating increases the resistance to ravelling and that healing works best when administered early.

Some research has addressed field work of asphalt mixtures in a lab setting without considering the actual circumstances of the asphalt mixture [146, 147]. Using Dynamic Shear Rheometer (DSR) and Fourier transform infrared spectroscopy (FT-IR) testing, Yin et al. [148] investigated asphalt over a service life of 9–22 months. They discovered that because of its proximity to oxygen, sunlight and a greater temperature, the pavement surface aged more quickly than at lower depths. Wu et al. [149] used fatigue, indirect tensile strength and FT-IR tests to assess asphalt mixtures over a 10-year service life. The findings revealed that although the pavement's top layers could have been able to lessen the impact on the lower layers of the asphalt, the influence was minimal. The lowest portions at about 90 mm deep, may be impacted by 10-year field aging. Li et al. [150] investigated the impact on bitumen modified with stacked double hydroxide asphalt mixes. Their findings indicated that aging severity decreased as depth increased. It was also discovered that aging could have an impact up to a depth of just 10 mm following 4 years of service life. Comparing the findings of the aforementioned investigations reveals disagreement over the degree to which field aging affects the depth of the mixtures, as well as a variety of effects at that depth. Adding to this, Mirzamojeni et al. [151] also studied the self-healing of field-aged asphalt. Three sections of asphalt pavement with service lives of 7, 10 and 11 years were examined using FT-IR. A core hole was made through the centre of the asphalt layers, the Semi-Circular Bending (SCB) test used to gauge their capacity for self-healing. Figure 17 shows the results, these findings illustrate that aging-related variations in asphalt layer thickness can have an impact on self-healing. With an 11-year service life, the healing index of the surface and the layer's depth, varied by around 10%. It was also found that the index of self-healing of the centre portion of the asphalt layers, remained essentially constant and equal to 35% over a period of 7 to 11 years.

Sustainability evaluation

The predominant focus of existing research is on augmenting the fundamental ability of asphalt to self-repair. Very limited attention has been devoted to systematically evaluating the environmental implications and sustainability aspects associated with these self-healing techniques. For induction-heated asphalt, environmental sustainability was studied by Lizasoain-Arteaga et al. [152], who carried out a life cycle assessment (LCA). They found that induction heating was superior to traditional maintenance methods through the

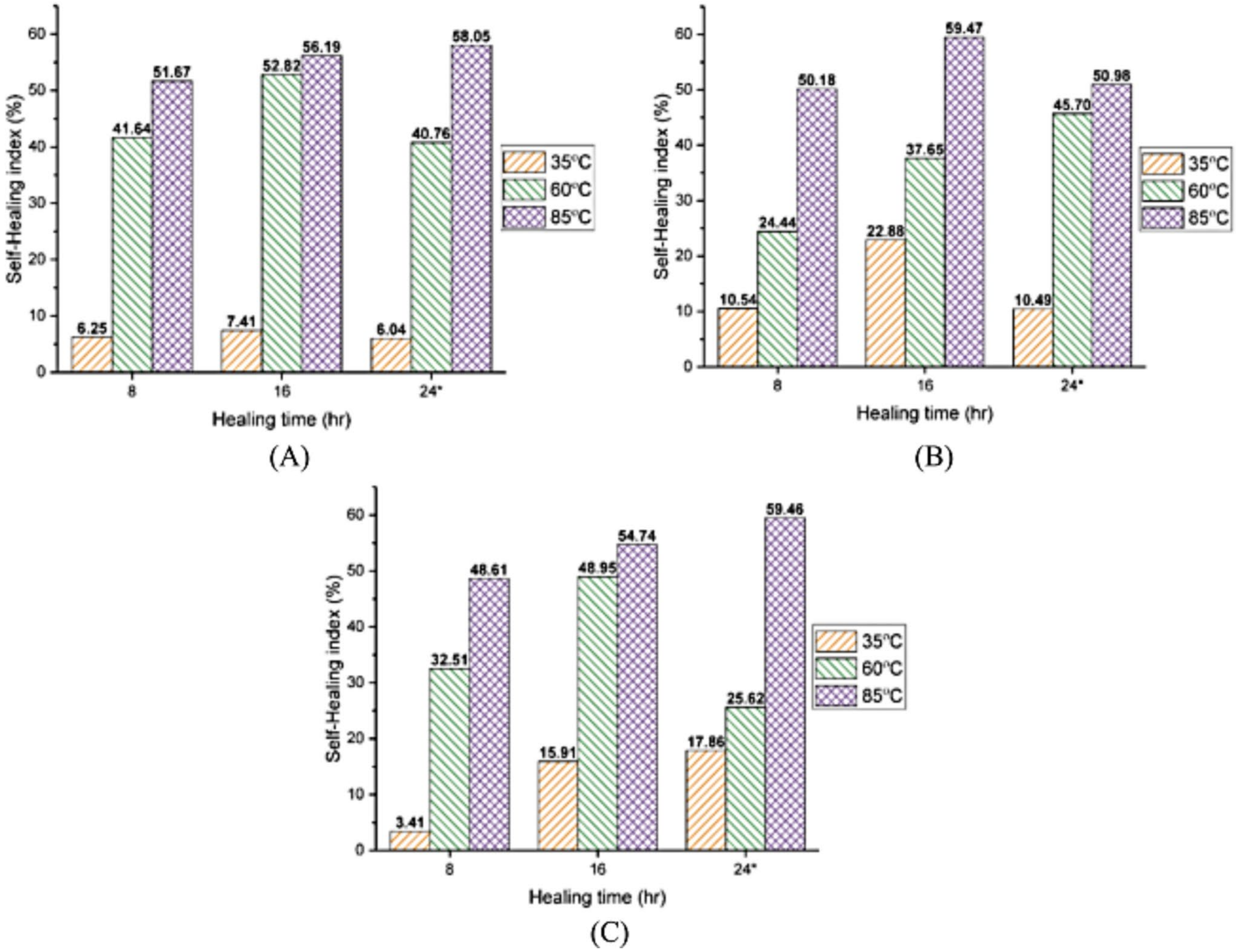


Fig. 17 Self-healing index with various service lives: **A** 7 years, **B** 10 years, and **C** 11 years [151]

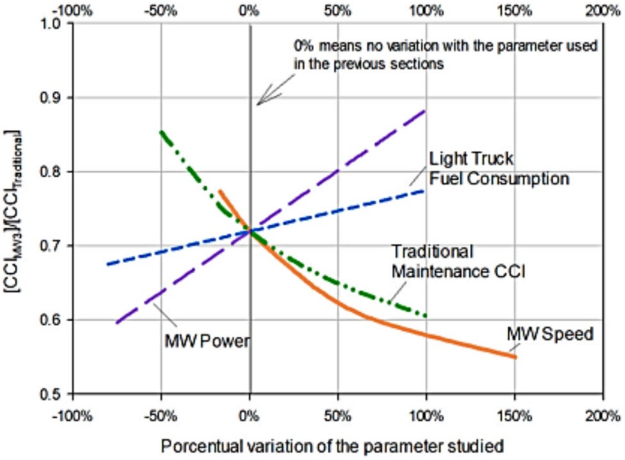


Fig. 18 CCI sensitivity results [154]

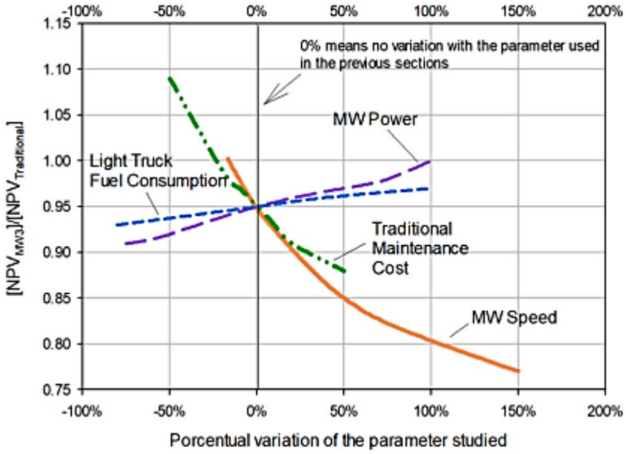


Fig. 19 Cost sensitivity results [154]

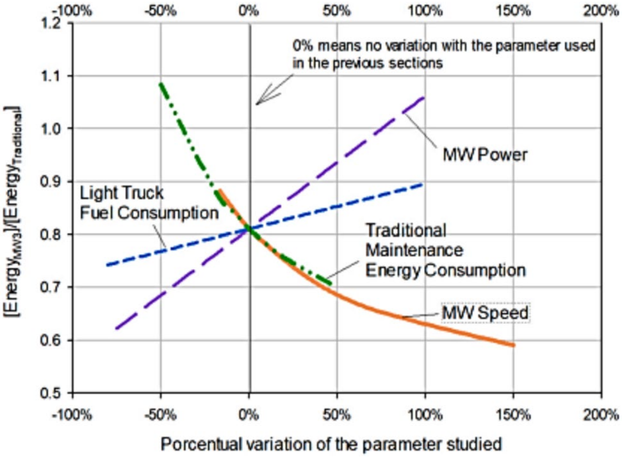


Fig. 20 Energy consumption sensitivity results [154]

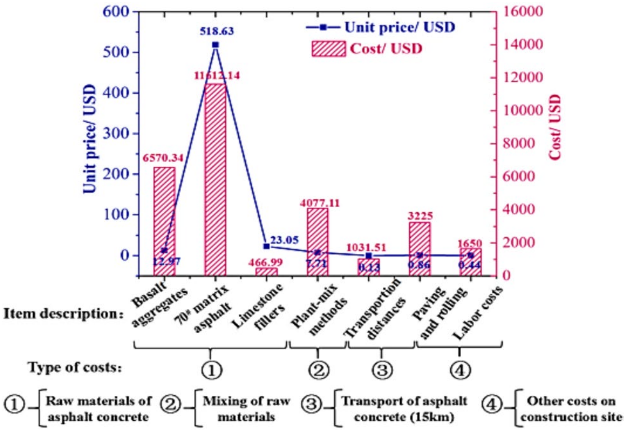


Fig. 21 Required expenses for the development of the SDAP [155]

analysis of 12 of 17 categories of environmental effects, this method creating the least traffic disruption as it is fast and less intensive maintenance. Rodríguez-Alloza et al. [153] carried out a comparison between microwave heating self-healing (MWHSH) and traditional methods using a multiple input–output LCA. Their results showed that cost and greenhouse gas emissions were reduced by about 32%, and 16%, respectively for a bidirectional road modified with steel slag.

Recently, Nalbandian et al. [154] studied the sustainability of MWHSH as applied to various scenarios, the results shown in Figs. 18, 19, 20. In comparison to full traditional maintenance during the lifetime of asphalt pavements, MWHSHT provided economic indicators, material consumption, feedstock energy and energy consumption. It is suggested that the adoption of MWHSHT in pavement maintenance offers numerous advantages over traditional methods. It results in reduced energy consumption, feedstock energy and use of materials, leading to improved economic indicators and enhanced pavement sustainability throughout its life cycle. MWHSHT can enhance social, environmental and economic sustainability, surpassing the effectiveness of sole reliance on conventional methods. The results in terms of climate change indicator (CCI) sensitivity analysis indicated that CCI is very sensitive to the power and speed of microwaves. CCI was reduced from 72 to 67%-60% by increasing the speed of the microwave device from 0.4–0.67 m/min and reducing the heating time to 1 min. In terms of cost-sensitive analysis, the results indicated that the most critical parameters are speed of the microwave device and the cost of traditional maintenance, both of which can drastically change the results. The rate of fuel consumption and heating of microwave devices had negligible impacts. Costs were reduced from 95 to 89% or 83% by reducing the heating time to 1 min or increasing the speed of the microwave device to 0.67 m/min. Energy sensitivity analysis showed a similar result to CCI, the main impact parameters on energy consumption identified as traditional maintenance activities, speed, power and heating of microwave devices. Reducing microwave heating power by 50% and 75% would reduce energy consumption by about 12% and 50%, respectively, although the latter is unlikely to occur in practice.

Liu et al. [134] conducted an extensive economic analysis comparing traditional "mill and overlay" methods with AI–SHT (Artificial Intelligence-Self-Healing Technology) for the Sustainable Development of Asphalt Pavement (SDAP). Figure 21 shows the expenses required to calculate the costs of the traditional method. Figure 22 indicates that the use of AI–SHT significantly reduces the required frequency of "mill and overlay", over a 30-year lifespan of asphalt concrete layers. The use of AI–SHT compared to the traditional maintenance method, resulted in an 88.75%

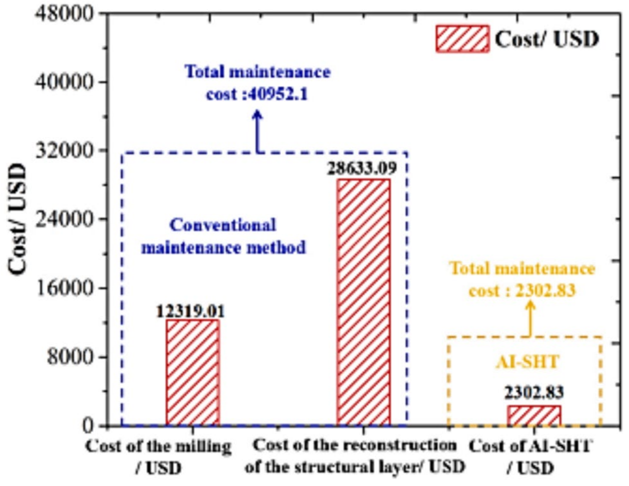


Fig. 22 Comparison of costs of developed and traditional methods [134]

reduction in maintenance costs, showcasing its substantial economic benefits.

Conclusions

The integration of self-healing capabilities can prolong the lifespan of asphalt pavements and promote sustainable pavement solutions. The self-healing behaviour of asphalt involves multiple scales and can be analysed using surface energy theory, molecular diffusion theory, phase field theory and capillary flow theory. However, a comprehensive understanding of the self-healing mechanisms of asphalt would require synthesizing these theories to explain various healing phases and scales effectively. The use of capsules is vital to enhance asphalt self-healing without compromising the pavement's overall behaviour. Induction heating and microwave heating are effective methods for repairing asphalt cracks, microwave heating in particular, offering more uniform results, regardless of the heating time, thereby promoting consistent crack healing. The efficiency of healing assessments can significantly vary depending on the test technique, procedure, healing conditions and evaluation criteria used. These techniques nevertheless, satisfy the fundamental requirements for an asphalt mixture despite having some detrimental impact on some areas of the performance of the road.

Moisture has an impact on the asphalt binder's ability to repair. Moisture inhibits both immediate and time-dependent healing by lowering cohesion and raising activation energy, implying that it is essential to evaluate the impact of moisture on different self-healing systems. Recently, cost-effective and less-contaminated core materials like waste cooking oil, vegetable oil and sunflower oil, have gained popularity as substitutes for conventional rejuvenators. To enhance asphalt healing, polymers, steel wool and steel slag can be incorporated using either induction or microwave-based methods. Induction heating, though rapid, may result in non-uniform heating for asphalt mixtures with steel fibres, while microwave heating is slower but provides more homogeneous results. The hybrid healing method may revive aging binder and effectively repair cracks, leading to greater long-lasting healing in asphalt. Using automatic induction was found to be an effective and economical method, but further studies are required to confirm the results.

Recommendations

The concept of self-healing pavements remains a growing area of research. As potential future research areas, the following points are recommended:

1 The ability of healing agents to accomplish repeated healing still raises serious questions which is restricting their use. More research is needed to determine how fibres and empty capsules affect the mechanical characteristics of these pavements.

2 Additional research is required to assess the influence of thickness and type of capsule with type of asphalt, on the efficiency of healing agents. The aim would be to develop an optimal capsule design, thereby facilitating their widespread adoption.

3 Field research is scarce so more research is essential to evaluate the behaviour of healed pavements under real-world conditions.

4 Although both microwave and induction methods can repair asphalt cracks, it is important to qualify the optimal healing time.

5 Although cost and environmental benefits analyses have suggested noticeable positive outcomes, the studies on this subject are limited meaning that further studies are necessary. Further research is required concerning the cost and availability of modified materials, the combination of original asphalt with microcapsule reinforcement, and the energy consumption of microwave and electromagnetic induction methods.

6 Even though they are created using the same encapsulating technique, capsules have some variation in their physical and chemical characteristics. Future efforts should focus on enhancing and standardizing the method for evaluating the effectiveness of healing and facilitating the analysis of results and comparisons between different studies.

7 The potential health risk from exposure to radiation, is one of the significant issues with microwave healing. According to the WHO, microwave radiation exposure can damage human tissue. Before using it in the field, appropriate safety precautions, regulations and rules should be imposed.

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Declarations

Conflict of interest On behalf of all authors, the corresponding author declares that there is no conflict of interest.

Ethical approval The authors declare that they have not submitted the manuscript to any other journal for simultaneous consideration. The work is original and not published elsewhere**.**

Informed consent There are no human or animal subjects in this article, and informed consent is not applicable.

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