Extrinsic self-healing asphalt materials

A mini review

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Review

Extrinsic self-healing asphalt materials: A mini review

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ABSTRACT

Self-healing is a biological phenomenon in which living organism responds to the suffered damage in a complex way. Inspired by the self-healing phenomenon in nature, various biomimetic healing methods rooted in intrinsic or extrinsic healing mechanisms have been explored. Research on novel self-healing asphalt materials with intelligent response is at the cutting-edge of materials science and offers a potential strategy for building long-life and low-carbon asphalt concrete infrastructure. This paper describes the progress of research on extrinsic self-healing asphalt materials and makes a clear distinction between intrinsic and extrinsic self-healing. The asphalt self-healing mechanism is interpreted by capillary flow theory, phase field theory, molecular diffusion theory and surface energy theory form various perspective. The extrinsic self-healing strategies including thermal induced healing and rejuvenator induced healing are proposed to enhance the healing level of cracked asphalt materials. A brief review of the methods including fracture-healing test and fatigue-healing test for assessing the efficacy of different extrinsic healing methods is presented. The thermal induced healing method bring high crack repair efficiency for asphalt concrete and the rejuvenator induced healing strategy not only improve the healing ratio of cracked asphalt concrete but also regenerate the ageing asphalt in situ. Important lessons for prospective research on the creation of novel self-healing asphalt materials are highlighted.

1. Introduction

Asphalt concrete, which is primarily composed of asphalt binder and stone aggregates, has been widely used in the building of road networks due to its excellent performance (García et al., 2010; Li et al., 2019; Menozzi et al., 2015; Yang et al., 2023). Nevertheless, micro-cracks and aging fatally occur in asphalt pavement due to the cumulative effects of UV irradiation, oxidation, water erosion, temperature variation and traffic loading (Hu et al., 2020; Li, J. et al., 2022b; Menapace and Masad, 2018; Polo-Mendoza et al., 2022; Sun et al., 2021; Yang, C. et al., 2022). If the maintenance treatment is not conducted on asphalt pavement timely, the micro-crack expands and degenerates into macro-crack, which will shorten the service duration and affect the concrete framework stability and traffic security. Nowadays, conventional maintenance treatments face a series of serious challenges including resource scarcity, energy reliance and greenhouse gas (GHG) and volatile organic compounds (VOCs) emission (Cui et al., 2021; Gong et al., 2023; Li et al., 2023; Lv et al., 2023; Ma et al., 2021; Xie et al., 2023; Yu et al., 2018). Hence, extend the service life of asphalt pavement can minimize the need for additional constructions while decreasing the maintenance cost and GHG and VOCs emission.

The utilization of self-healing, a naturally occurring phenomenon originating from biological systems, presents a promising approach for the repair of cracks in asphalt materials. To date, the scholars have put considerable efforts in self-healing research from soft polymeric materials (Kang et al., 2018) to ceramics (Ozaki et al., 2016), cementitious (Huang et al., 2016) and bituminous materials (Anupam et al., 2022).

Asphalt, as a representative viscoelastic substance, can autogenously repair the micro-crack during rest periods, which is regarded as intrinsic healing of asphalt (García, 2012; Qiu et al., 2011; Sun et al., 2018b; Sun et al., 2020; Zhang, L. et al., 2018). However, the attainment of the optimal intrinsic healing state is unfeasible in practical service

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environment due to unstoppable traffic flow and uncontrollable meteorological condition, which make asphalt binder lack the ability to repair the micro-cracks. Therefore, extrinsic healing methods have been introduced to improve the crack repair efficacy of asphalt materials.

This article developed a profound and extensive comprehension of the self-healing mechanism of asphalt and introduced advanced extrinsic healing strategies for asphalt materials. The concept of extrinsic healing is a noteworthy and forward-thinking idea that holds considerable promise for achieving sustainable pavement maintenance in a low-carbon environment.

2. Self-healing definition and mechanism of asphalt materials

2.1. Definition of asphalt self-healing

Self-healing is one of the significant features of biology, and it has become a hot spot of research in various countries to introduce the concept of biology into polymer materials to form intelligent materials with self-healing performance. As early as in the mid-eighties, in order to repair invisible microcrack, ensure the safety of polymer materials and extend the service life, the U.S. military proposed the concept of self-healing materials (Jud et al., 1981). The so-called self-healing refers to the principle of mimicking the damage healing of living organisms, once the material has defects, it has the ability of self-recovery in the absence of external action, which is called self-healing. It includes two aspects of meaning: the first has the ability of self-diagnosis, that is, the system can make some kind of response when the external action produces cracks or damage, sensing such cracks or damage; the second has the function of self-repair. After sensing the damage, the healing agent starts to repair and complete the restoration of material properties and structure, the core of self-healing is energy supply and material replenishment.

Polymers can be classified in a variety of ways depending based on classification. According to the structure of polymerization, they can be divided into reticulated polymers (thermosetting polymers) and chain polymers (thermoplastic polymers). Thermosetting polymer units connected into a network, at high temperatures is still not melted, and will not be deformed, has a strong resistance to high temperatures. Smart materials with self-healing properties are also categorized as thermoplastic and thermoset on the same basis. Thermoplastic polymer units are connected into chains, usually melt when heated, have plasticity, harden and form when cooled, and can be reused; thermosetting polymer units are connected into a network, and can be reused (Wu et al., 2008).

There are many different healing methods for thermoplastic materials, and the corresponding healing mechanisms are also different, with the main ones including mutual diffusion, photoinduction, recombination of chain segments and reversible bond formation (Jud and Kausch, 1979). Amorphous, semi-crystalline, block copolymers and fiber composites are self-healing by mutual diffusion. The specific process is the same two pieces of polymer closely together, heating temperature to the polymer above the glass transition temperature, with the diffusion of molecules, the interface at the interface of the material gradually disappears, the mechanical properties of the material is gradually enhanced, until the crack is completely healed. The healing time required for this healing method is affected by pressure as well as temperature, and for self-healing of polymers by molecular diffusion, a five-step healing mechanism of surface rearrangement, surface proximity, wetting, diffusion, and random distribution was proposed by Wool and O'Connor (Wool and O'connor, 1981) and it's acknowledged by scholars.

Owing to the complexity of the chemical component and microstructure of asphalt, the asphalt cannot be defined as single thermoplastic materials. The self-healing process is considered a double healing superposition behavior, which involves complex physical and chemical actions. Motivated from the self-healing phenomenon observed in polymers, self-healing of asphalt can be characterized as the progress of sealing crack interfaces through contact points and the restoration of initial properties under favorable environmental conditions (Anupam et al., 2022; Ayar et al., 2016; Gonzalez-Torre and Norambuena-Contreras, 2020; Li et al., 2021; Liang et al., 2021; Sun, D. et al., 2018).

2.2. Mechanisms of asphalt self-healing

The self-healing of asphalt materials is influenced by various factors, including asphalt composition, structure, ageing level, damage degree, ambient moisture, repair temperature and time (Ayar et al., 2016; Lv et al., 2017; Sun, D. et al., 2018; Tabaković and Schlangen, 2016; Varma et al., 2021). It is imperative to investigate the intrinsic mechanism of asphalt self-healing behavior in order to attain a comprehensive understanding of its complexities.

A thorough comprehension of the self-healing mechanism is the key point to precisely characterize and evaluate asphalt self-healing. Generally, as shown in Fig. 1, four predominant self-healing theories consisting of capillary flow theory (García, 2012; Zhang, L. et al., 2018), phase field theory (Hou et al., 2015; Kringos et al., 2011), molecular diffusion theory (Bhasin et al., 2011; Yu et al., 2020) and surface energy theory (Lytton et al., 1993; Si et al., 2002) are adopted to explain the healing of asphalt materials.

The theory of capillary flow is proposed at macroscopic level and the establishment condition is that asphalt binder can exhibit near-Newtonian fluid behavior under elevated temperatures. Therefore, it presupposes that when the ambient temperature exceeds the transition temperature of Newtonian fluid, asphalt at the crack interface show self-healing behavior under molecular interdiffusion after sufficient contact via the capillary flow, which is conducive to the restore of mechanical strength. The capillary flow theory explains the healing mechanism of asphalt binder at high temperatures on a macroscopic scale, but fails to provide a corresponding elucidation for the healing of asphalt at low temperatures.

The phase field theory establishes the relations between the asphalt self-healing phenomenon and its micro-structure evolution by using atomic force microscopy (AFM) analysis. It states that from the perspective of thermodynamics, asphalt self-healing can be interpreted as a recombination process of material-phase field. The stress concentration region at the interface of two phases is prone to the development and subsequent repair of micro-cracks. The completion of asphalt healing is attributed to the wetting of the interface between the intact and cracked phases, which is caused by the surface energy between them. The phase field theory is a theoretical framework that investigates the alterations in the microstructure of asphalt materials throughout the duration of cracking and healing. This theory can be employed to elucidate the mechanisms underlying the propagation of cracks and the subsequent healing processes. Nevertheless, there is an ongoing debate regarding the formation principle and composition of the bee-like structure found in asphalt binder. This has resulted in the phase field theory being insufficient in providing a complete explanation for the self-healing behavior of asphalt.

The Molecular diffusion theory characterizes the asphalt self-healing behavior from molecular level. The three-stage healing theory of asphalt cracks has been widely accepted, namely, (1) the closure of macro crack via the coagulation stress and asphalt movement; (2) the closure of micro crack by wetting and adhesion of crack interface; (3) the restore of mechanical property through the molecular diffusion at crack interface (Phillips, 1998). Current studies on molecular diffusion theory are based on molecular dynamics simulations, and it is still impossible to track the observation of molecular diffusion in asphalt by imaging techniques.

The surface energy theory is proposed in the fracture mechanics field and it states that the reduction of surface energy serves as the impetus for the self-healing behavior of asphalt (Lytton et al., 1993; Si et al., 2002). The process of asphalt cracking and healing is associated with the reduction of crack surface energy through the variation of crack

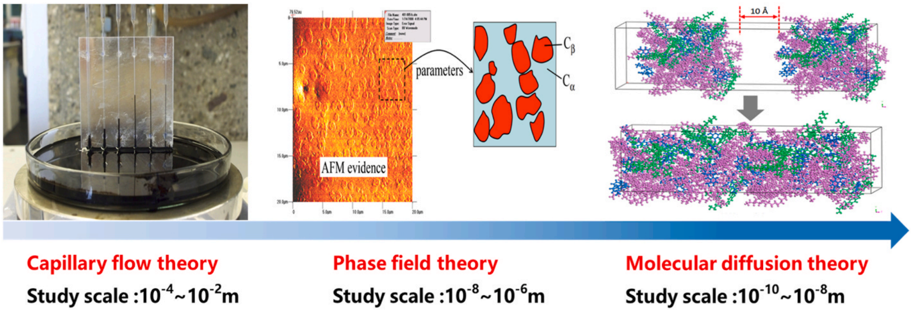

Fig. 1. Multiple-scale interpretation of the self-healing mechanism of asphalt. Capillary flow theory (García, 2012) , phase field theory (Kringos, 2009) and molecular diffusion theory (Sun, D. et al., 2016).

interfaces in the area. The healing rate was determined by the nonpolar (Lifschitz-Van der Waals) and polar (Lewis acid-base) components (Little et al., 1999). While the surface energy theory can categorize the process and factors that affect asphalt healing based on theoretical formulas, it requires substantial experimental data to corroborate its claims. In summary, a plausible approach to comprehend the self-healing mechanism of asphalt at various stages and scales is to appropriately integrate the four theories.

3. Recent strategies for achieving extrinsic healing of asphalt materials

According to the intrinsic healing mechanisms of asphalt, it can be inferred that the flow and diffusion of asphalt play a crucial role in the process of crack closure. The impact of viscosity on the flow and diffusion of asphalt is a significant consideration. Therefore, decreasing asphalt viscosity to enhance its flow properties is a crucial factor in the extrinsic healing of asphalt.

Asphalt is a viscoelastic material that exhibits temperature sensitivity and displays obvious reduction in viscosity when subjected to high temperatures. The solar radiation is uncontrollable and unable to provide on-demand healing for the cracked asphalt. Therefore, the implementation of regulated heat supply system for asphalt is beneficial in facilitating timely crack repair. Asphalt as multicomponent mixture loses its light component and thus has high viscosity under the ageing action. Related studies indicated that the active agent can be added into asphalt to restore the balance of light component ratio and lower the viscosity of asphalt (Behnood, 2019; Ji et al., 2017; Zahoor et al., 2021). Nevertheless, direct spraying of rejuvenator on asphalt pavement can only penetrate the surface layer of pavement and fails to meet the requirement of whole area healing. Besides, the spayed rejuvenator reduces the skid resistance of the pavement, which will drastically degrade the vehicle security. Therefore, it is imperative to encapsulate the asphalt rejuvenator and incorporate into the asphalt concrete and subsequently release it on demand to speed up crack healing.

3.1. *Extrinsic self-healing*

Extrinsic self-healing is developed based on energy provision or healing agent supply to the damaged asphalt to facilitate the repair of structural damage. The extrinsic healing for asphalt materials can be defined as providing healing energy or supply healing agent for cracked asphalt materials to improve its healing efficiency. The extrinsic self-healing enables the asphalt materials to react to the incidence of multiple cracking events and repair multiple cracks concurrently. Drawing inspiration from the hyperthermia technology and drug capsule developed by humans (shown in Fig. 2), heat energy via external activation or supply rejuvenator within encapsulation carrier can be provided for cracked asphalt concrete to accelerate the repair process in time. Currently, the classification of extrinsic self-healing in asphalt materials encompasses two distinct categories, namely thermal induced self-healing and rejuvenator encapsulation induced self-healing.

3.2. *Thermally induced healing strategies*

The thermal induced self-healing approach encompasses two primary techniques: electromagnetic induction heating self-healing (Fu et al., 2023; García et al., 2009; Gómez-Meijide et al., 2018; Li et al., 2019; Liu et al., 2010; Menozzi et al., 2015) and microwave induced heating self-healing (Gallego et al., 2013; Liu et al., 2022; Lou et al.,

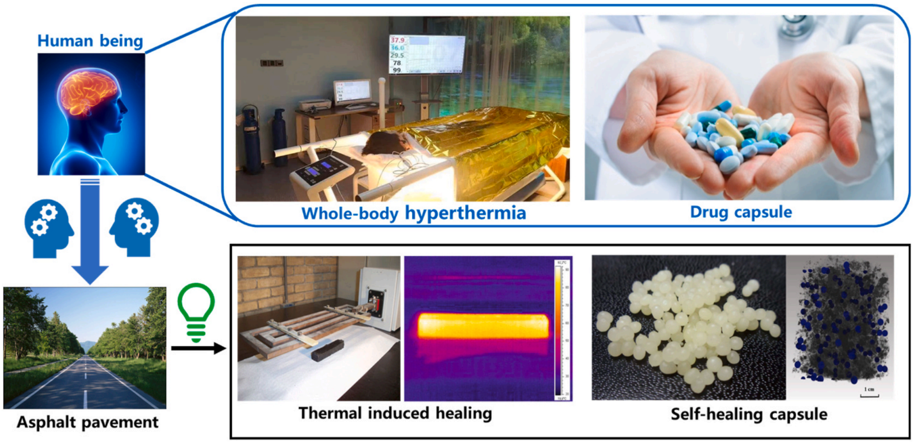

Fig. 2. Insights from medical treatment of human being to damage repair of asphalt pavement. Whole-body hyperthermia. Reprinted with permission from http://news.sohu.com. Drug capsules. Reprinted with permission from http://news.sohu.com. Thermal induced healing (García et al., 2010). Self-healing capsule (Norambuena-Contreras et al., 2019b).

2021). As shown in Fig. 3, proper dosage of conductive or microwave responsive substances are added into asphalt mixtures and then the resultant mixtures are subjected to thermal treatment through external stimulation (electromagnetic field or microwave, as shown Fig. 4) when micro cracks appear. The increase of asphalt temperature accelerates the flow ability of asphalt binder near the microcrack area which accelerates the closure of crack in asphalt concrete.

In 2009, Garcia et al. firstly introduced the electrically conductive fillers and fibers such as graphite and steel wool into asphalt mortar to increase the conductivity and explore the feasibility of induction heating (García et al., 2009). They proposed a four-stage conductivity mode for asphalt materials with conductive additives, as depicted in Fig. 5. Their investigation revealed that the percolation threshold was reached at an earlier stage when steel fibers were added, as compared to the addition of graphite. Meanwhile, it has been determined that there exists an optimal fiber content for every sand-asphalt ratio. If the fiber content surpasses this threshold, the mixture becomes challenging to produce and the electrical resistivity levels off. Moreover, it was discovered that the asphalt mortars containing three different quantities of steel wool exhibited the capability of induction heating while their temperature rise were observed. Subsequently, considerable academics-initiated investigations into the utilization of electromagnetic induction heating for asphalt materials. In 2013, Gallego et al. innovatively applied the microwave instead of electromagnetic induction to asphalt concrete containing steel wool and explored the healing property under different variables (Gallego et al., 2013). The study revealed that the most favorable proportion of steel wool employed in this research is approximately one-tenth of the quantity suggested for electromagnetic induction heating. Furthermore, the energy consumption of microwave devices is significantly lower than that of electromagnetic induction methods for achieving a comparable outcome. Since then, researchers have also begun to explore the effect of microwave heating on the healing properties of asphalt concrete. The thermal induced healing technology bring superior crack repair efficiency and muti-crack sealing potential for asphalt concrete. However, this technology requires the mixing of specified materials in the asphalt mixture and human intervention during its service life, which not only consumes a lot of plentiful power energy, but also produces masses of greenhouse gases during operation period.

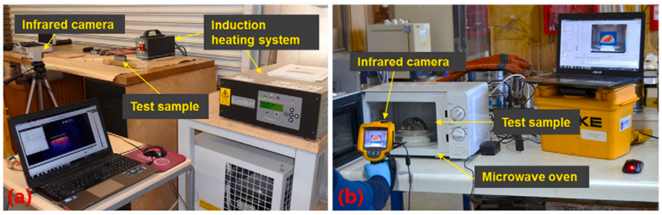

Fig. 4. Thermal induced healing technology: (a) electromagnetic induction heating healing and (b) microwave induction heating healing (Norambuena-Contreras and Garcia, 2016).

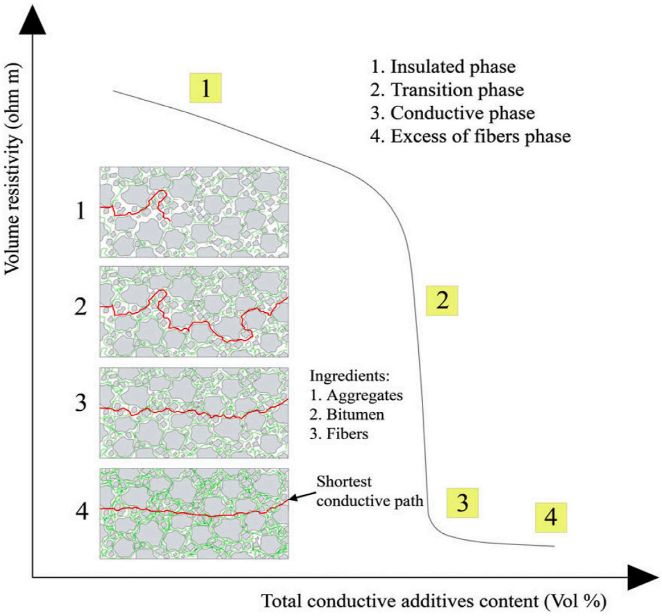

Fig. 5. The four-stage conductivity mode of asphalt materials with conductive additives (García et al., 2009).

3.3. Rejuvenator encapsulation induced healing strategies

The utilization of thermal-induced healing technology has the potential to enhance the efficiency of crack repair in asphalt concrete. Regrettably, this technology is incapable to address the ageing issue of asphalt materials in the actual service period. The utilization of the rejuvenator encapsulation induced healing strategy has the potential to facilitate both the repair process of cracked asphalt and the rejuvenation of aged asphalt in situ through the provision of light components (Gonzalez-Torre and Norambuena-Contreras, 2020; Li et al., 2021; Wan et al., 2022b). The proposed technique involves the encapsulation of asphalt rejuvenator within capsules or fibers (shown in Fig. 6), which are subsequently incorporated into asphalt mixtures. As illustrated in Fig. 7, in the event of micro-crack formation within the asphalt binder, the tip stress stemming from micro-crack will break the capsule and the inner rejuvenator will follow out and diffuse to crack zone. The rejuvenator fills in crack and softens the asphalt around the crack zone. The asphalt on both sides of the crack will diffuse and move, get along with the contact for molecular rearrangement, hence the crack is gradually closed and the mechanical performance of asphalt are gradually restored. The application of rejuvenator has the potential to mitigate the

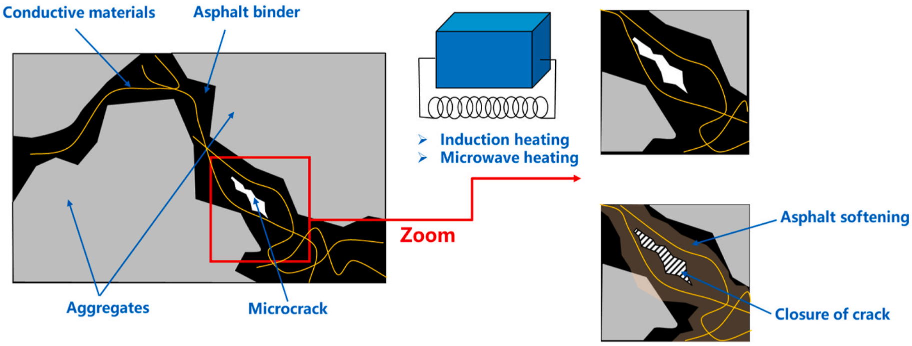

Fig. 3. The mechanism of thermal induced healing for asphalt.

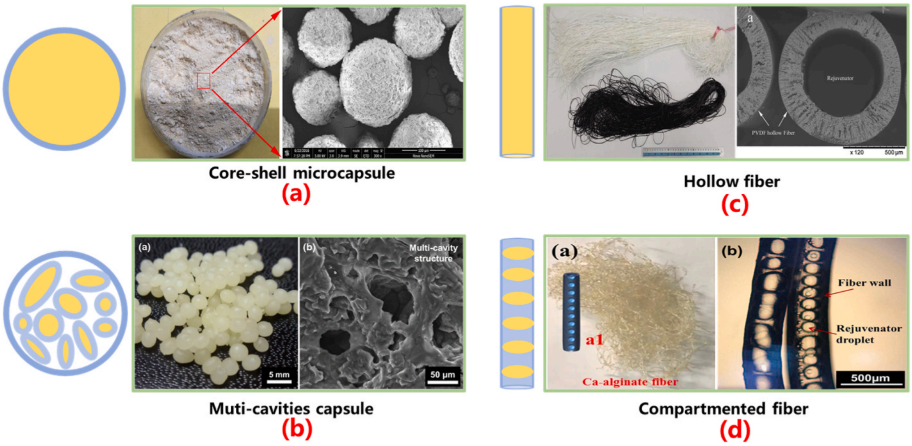

Fig. 6. The common forms of rejuvenator encapsulation. (a) Core-shell microcapsules (Sun et al., 2018a). (b) Muti-cavities capsule (Norambuena-Contreras et al., 2019a). (c) Hollow fiber (Guo et al., 2019). (d) Compartmented fiber (Shu et al., 2019).

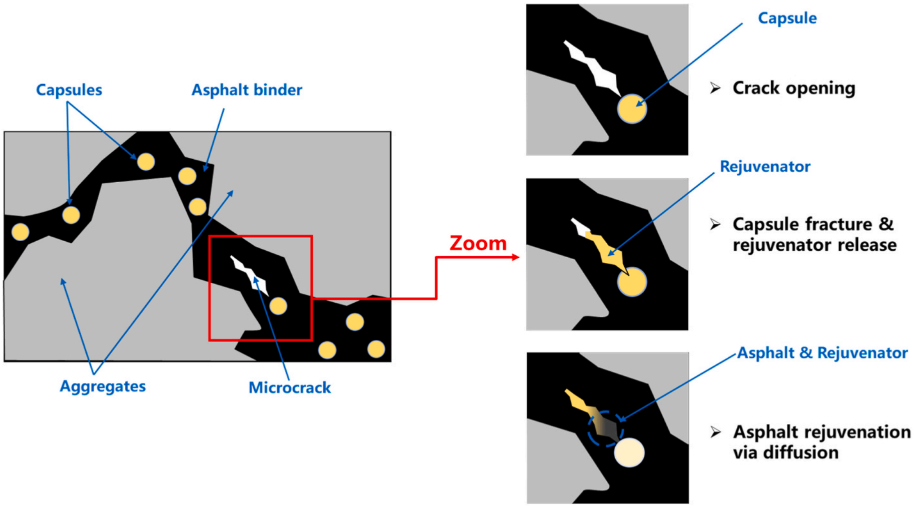

Fig. 7. The mechanism of rejuvenator induced healing (in capsule form) for asphalt (Tabaković and Schlangen, 2016).

stiffness of asphalt binder and speed up crack sealing. The proposed technique entails utilizing the capillary action of rejuvenator to remedy cracks and restore the deteriorated asphalt binder in the vicinity of the crack. Therefore, rejuvenator encapsulation induced healing is an intelligent and sustainable pre-maintenance methods for extending the service life of pavement.

3.3.1. Self-healing capsule

In 2010, Garcia et al. firstly applied the rejuvenator encapsulation technology to asphalt concrete (Garcia et al., 2010). They employed porous stone to absorb asphalt rejuvenator forming core materials and utilized an epoxy-cement matrix as shell materials to envelop the core, as shown in Fig. 8. The prepared capsules exhibited exceptional thermal and mechanical durability, enabling them to withstand the process of asphalt concrete preparation. The authors put forth the fundamental operational principle of the stone-epoxy-cement capsule in asphalt concrete. Specifically, when the stress experienced by the capsules embedded within the asphalt mixture surpasses a certain threshold, the capsules will fracture and discharge a portion of the rejuvenator, thereby restoring the initial characteristics of the asphalt. The effective

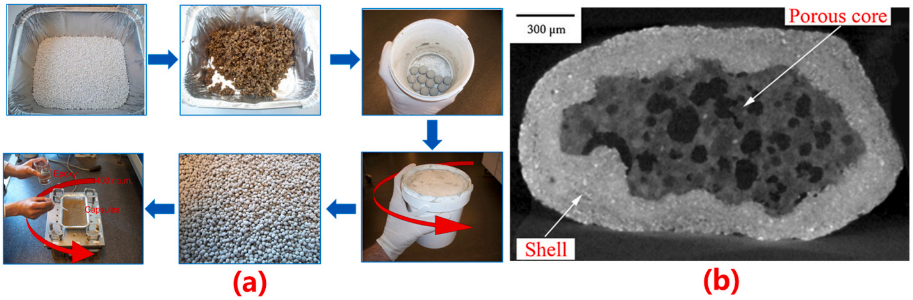

Fig. 8. The fabrication process of stone-epoxy-cement capsule (a) and its CT scan image (b) (Garcia et al., 2010).

implementation of rejuvenator encapsulation within asphalt concrete represents an initial stride towards the development of intelligent pavements.

However, the incorporation of stone-epoxy-cement capsule has been observed to significantly decrease the modulus of asphalt concrete, rendering it more prone to permanent deformation. Additionally, the oil present in the porous sand exhibits limited flow into the asphalt mastic, thereby restricting its ability to enhance the self-healing characteristics of asphalt concrete. Therefore, the researchers developed novel encapsulation carriers for loading asphalt rejuvenators.

Presently, the incorporation of healing agent within polymer capsules is being utilized to enhance the healing effectiveness of asphalt materials. The in-situ polymerization method is utilized to synthesize core-shell microcapsule with micrometers size. The present study has opted for polymer materials, namely melamine-formaldehyde (MF) (Aguirre et al., 2016; Sun et al., 2015), methanol-melamine-formaldehyde (MMF) (Su and Schlangen, 2012; Wang, Y.-Y. et al., 2022), urea-formaldehyde (UF) (Li et al., 2015; Wang and Hao, 2021) and melamine-urea-formaldehyde (MUF) (Sun et al., 2015, 2017a), polyurethane (PU) (Tan et al., 2020), isophorone diisocyanate (IPDI) (Chen et al., 2023; Ji et al., 2021), high methylether melamine–formaldehyde (HMMM) (Tian et al., 2020; Yang, P. et al., 2022) to serve as shell materials. The asphalt rejuvenator is used as core material. The multi-cavities capsule is fabricated by the iron-exchange principle and the orifice-bath method. The calcium alginate is employed as wall material, while the vegetable oil is selected as asphalt rejuvenator and is encapsulated in the cavities within the capsule (Al-Mansoori et al., 2018b; Bao et al., 2020; Micaelo et al., 2016; Norambuena-Contreras et al., 2019a; Ruiz-Riancho et al., 2021a; Wan et al., 2022a; Zhang et al., 2019).

The core-shell microcapsules show intelligent response to microcrack within asphalt binder and open the door for smart maintenance of asphalt pavement. However, compared with multi-cavities capsules, there are some limitations for core-shell microcapsules.

(a) Synthesis condition. The capsules with multiple cavities are produced using the orifice-bath technique under mild reaction conditions, whereas the core-shell microcapsules are predominantly synthesized via the in-situ polymerization method under strict reaction conditions. Moreover, the raw material utilized in the production of multi-cavity capsules is environmentally friendly, whereas the synthetic raw material utilized in the production of core-shell microcapsules has negative impacts on the environment.

(b) Rejuvenator loading content. The multi-cavities capsules (mm size) own plentiful inner cavities structure and the healing agent is embedded in separate cavities. Conversely, the microcapsules (μm size) own conventional core-shell structure where the entire rejuvenating substance is contained within the shell. Due to the size advantage and distinctive structure, the multi-cavities capsules outperform core-shell microcapsules in rejuvenator encapsulation capacity.

(c) Rejuvenator release pattern. The multi-cavities capsules release the encapsulated rejuvenator in a gradual manner when subjected to the external loading, while the core-shell microcapsule tend to break under the action of microcrack tip-stress, leading to the sudden release of the entire rejuvenator at once. The release mechanism of rejuvenator in core-shell microcapsule is intelligent by sensing the onset and spread of micro-crack. However, the single-use release pattern has a limited functional lifespan and lacks the ability to facilitate healing of multiple cracks. Moreover, the issue of matching the strength of microcapsules and microcrack tip stress poses a challenge in guaranteeing the timely release of the healing agent within the microcapsules. The activation mechanism of the rejuvenator release of multi-cavity capsules involves the accumulation action of cyclic compressive loading, which may fail to achieve the immediate smart healing objective, but can effectively accomplish the long-term healing goal by gradually releasing the healing agent.

(d) Impacts on the pavement performance. The fracture of microcapsules occurs due to tip stress and results in the formation of micro-pores within the asphalt binder. This process has the potential to negatively impact the stability of the pavement structure. The capsules with multiple cavities and appropriate strength can release the rejuvenator that is encapsulated within them without rupturing, due to the elastic contraction-expansion pattern. This process does not have adverse impact on the performance of the pavement.

3.3.2. *Self-healing fiber*

Inspired by human blood vessels, the polymer fibers are also commonly used to encapsulate asphalt rejuvenator to improve the self-healing properties of asphalt. The fiber can be categorized as hollow fiber and compartmented fiber based on the inner structure. As shown in Fig. 9, the wet-spinning method is commonly employed in the preparation of the hollow fiber. The Polyvinylidene fluoride resin (PVDF) is used as the wall material, and the oily rejuvenator is selected as the healing agent (Guo et al., 2019; Qing Wang et al., 2021; Su et al., 2019; Zhang, X.-L. et al., 2018). The compartmented fiber is fabricated by the wet-spinning method (Tabaković et al., 2016; Zaremotekhases et al., 2020) or microfluidic technology (Li, Y. et al., 2022; Shu et al., 2018). The calcium alginate serves as the wall material, while the commercial rejuvenator and vegetable oil are selected as the healing agents.

As presented in Fig. 10, upon exposure to stress at the micro-crack tip, the whole rejuvenator in hollow fiber will follow out and can only heal the micro-crack for one time. The compartmented fiber incorporates rejuvenator within discrete chambers, which can be gradually released upon microcrack activation, thereby conferring multiple healing capabilities to asphalt materials. One notable difference between hollow and compartmented fibers is their respective single-crack healing capabilities and the former excel later. This can be attributed to the greater amount of rejuvenator stored in the hollow fibers, as well as their unique pattern of releasing all rejuvenator at once. However, compartmented fibers demonstrate superior multi-crack healing capability and long-term healing potential compared to hollow fibers due to the presence of internal isolated chambers that contain healing agents.

4. Assessment of extrinsic healing level of asphalt materials

The evaluation of the healing level of bituminous materials typically involves the assessments of their self-healing capacity, crack repair status, mechanical functionality, and chemical characteristics.

4.1. *Visual observation*

The topic of visually monitoring the process of crack repair has been a prominent area of research within the field of self-healing. Scholars have endeavored to investigate the healing process of asphalt cracks through various scales of observation. Comprehensive visualization of the microcrack change process was carried out by imaging and microscopy techniques. The qualitative characterization of asphalt materials before and after extrinsic healing treatment has been extensively studied through the analysis of the camera photos (Liu et al., 2013; Sun et al., 2017a), CT reconstruction images (García, 2012; Micaelo et al., 2016) and fluorescence microscope (FM) pictures (Sun et al., 2017a), as shown in Fig. 11. These results confirmed that the asphalt crack exhibited a distinct closure state after the extrinsic healing intervention.

4.2. *Improved healing level for asphalt materials*

The results of visual observation show that asphalt exhibits a higher potential for effective crack repair following extrinsic healing treatment

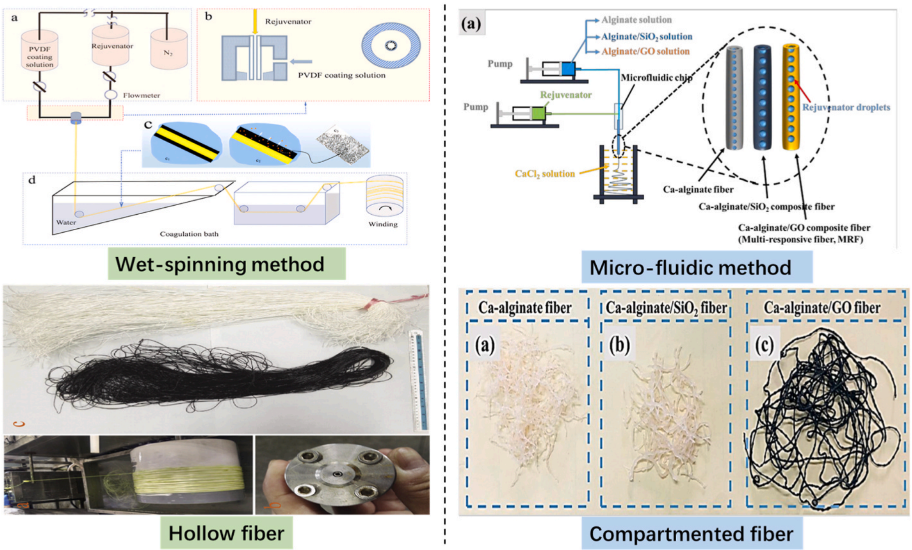

Fig. 9. The common fabrication methods of hollow fiber and compartmented fiber. (Left) wet-spinning method and hollow fiber (Zhang, X.-L. et al., 2018), (Right) micro-fluidic method and compartmented fiber (Shu, B. et al., 2019).

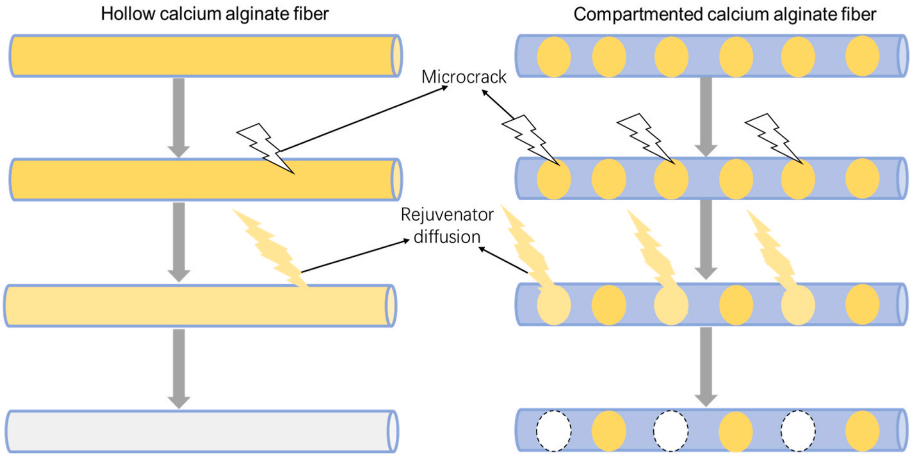

Fig. 10. The rejuvenator release mechanisms of hollow and compartmented fiber (Wan et al., 2022b).

compared with plain asphalt specimen. Nevertheless, it should be noted that achieving visual closure of cracks does not necessarily ensure the full restoration of the mechanical properties of asphalt mixture. Therefore, it is imperative to assess the healing efficiency of asphalt materials from mechanical standpoint.

The efficiency of extrinsic healing strategies in promoting the self-healing capacity of asphalt necessitates the use of appropriate methodologies for its evaluation. Self-healing assessment methods in the laboratory can be classified into fracture-healing tests and fatigue-healing tests based on the extent of damage (Li et al., 2021; Varma et al., 2021), as depicted in Fig. 12. The fracture-healing tests are conducted to assess the healing ratio of the two observable crack surfaces of the test specimens. This is achieved through providing intervals of rest to gradually heal the apparent visible cracks and restore their mechanical attributes. The fatigue-healing tests have been devised to investigate the healing of microcracks in undamaged specimens during the repetitive fatigue load procedure, which better simulates the asphalt pavement under actual service conditions.

4.2.1. *Evaluation of healing ratio of asphalt mixtures via thermal induced healing treatment*

The strength recovery is a metric utilized to evaluate the healing efficiency of asphalt concrete following thermal induced treatment. The three-point bending (3 PB) test (Liu et al., 2011; Xu et al., 2022) and semi-circular bending (SCB) (Fu et al., 2022; Norambuena-Contreras, 2017) test are usually conducted on asphalt concrete with conductive materials to obtain the strength recovery ratio. The asphalt concrete with steel fiber exhibits a favorable capacity for self-healing upon exposure to electromagnetic induction heating, and the maximum strength recovery ratio can reach 77.9% (Liu et al., 2013). Moreover, the process of electromagnetic induction heating can be iterated up to five times on asphalt mixtures beam in the event of crack formation, without compromising the healing efficacy of the fractured beams. The fatigue life of asphalt concrete is determined through the application of the four-point bending (4 PB) fatigue-healing-fatigue test subsequent multiple cycles of electromagnetic induction heating. The study conducted by Liu et al. investigated the induction healing effect of porous asphalt concrete. The experimental procedure involved subjecting the material to four cycles of damage loading, induction heating, and resting. The results indicated that the final fatigue life of the beam was 277720, with a corresponding fatigue life extension ratio of 190% (Liu et al., 2012).

A discernible thermal gradient is present in the asphalt specimens subjected to electromagnetic induction heating. The temperature differential between the uppermost and lowermost portions of the

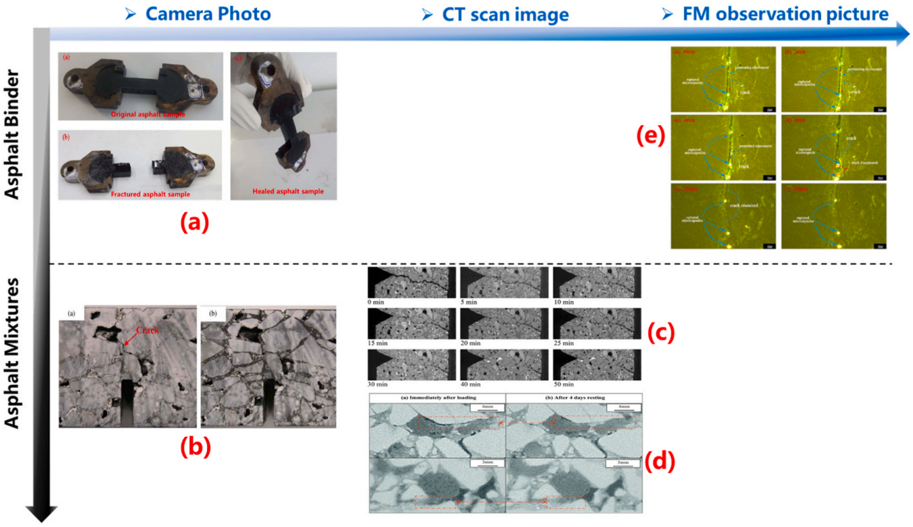

Fig. 11. The multiscale observation methods for crack repair process. (a) Fracture and healing morphologies of asphalt binder with 3 wt % microcapsules (Sun et al., 2017a). (b) Fractured beam photo before and after induction heating (Liu et al., 2013). (c) CT scan reconstruction images of asphalt mixtures beam through the induction healing process (García, 2012). (d) CT scan images of asphalt mixtures with capsules before and after healing process (Micaelo et al., 2016). (e) Fluorescence microscopic images of crack evolution of asphalt binder with microcapsules (Sun et al., 2017a).

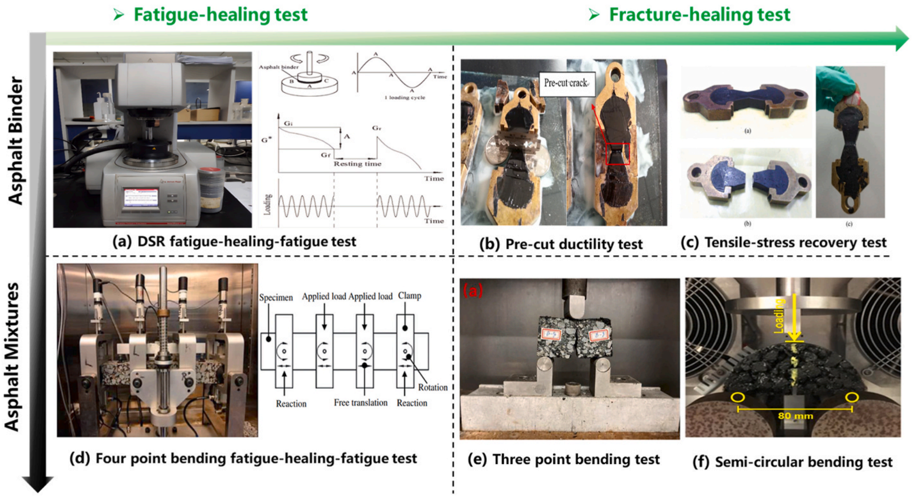

Fig. 12. Self-healing evaluation methods for asphalt materials in laboratory. Test for asphalt binder: (a) DSR fatigue-healing-fatigue test (Sun et al., 2017b; Tan et al., 2020). (b) Pre-cut ductility test (Xue et al., 2017).(c) tensile stress recovery test (Shu, B. et al., 2018). Test for asphalt mixtures: (d) Four-point bending fatigue-healing-fatigue test (Liu et al., 2012). (e) Three-point bending test (Wan et al., 2022a). (f) Semi-circular bending test (Xu, S. et al., 2019).

specimen exhibits an increase in proportion to the duration of heating, and the resulting gradient temperature distribution engenders a corresponding gradient in the healing process. In contrast, microwave induction heating induces a more homogeneous healing of cracks in asphalt concrete. The study found that the dense asphalt mixtures containing steel fiber exhibit a greater effective heating depth exceeding 10 cm following microwave heating, surpassing the maximum heating depth of 4.8 cm observed with electromagnetic induction heating (Liu et al., 2018). Compared with electromagnetic induction heating, the microwave induction heating can make asphalt concrete obtain higher healing level. The healing level of asphalt concrete with steel wool fiber after 40 s microwave induction heating can reach 93%, which is much higher than that of concrete beam with steel wool fiber after 40s electromagnetic induction heating (58%) (Norambuena-Contreras and Garcia, 2016).

The healing level of damaged asphalt concrete via thermal induced healing methods were shown in Table 1. The healing ratio is related with the asphalt mixture types, additive responsive materials, healing evaluation method and healing index. The positive outcomes of utilizing electromagnetic induction heating and microwave induction heating in laboratory settings suggest that thermal induced heating has potential as a viable method for in situ heating of asphalt layers. In contrast to conventional maintenance techniques employed during the onset of macro-damage, the utilization of thermal induced self-healing technology can significantly expedite the mending of microcracks during their initial formation.

4.2.2. Assessment of healing level of asphalt concrete via rejuvenator induced treatment

The thermal induced healing method bring excellent healing efficiency and superior healing level for asphalt concrete. However, it fails to tackle the challenge of asphalt ageing. This unavoidable drawback limits the large-scale application of the thermal induced heating technology. The rejuvenator encapsulation induced healing with dual function was born at the right time. Along with assisting in the restoration of the damaged asphalt, it also can renew the aged asphalt binder

Table 1
Healing level of asphalt concrete via thermal induced healing methods.

Matrix Material	Responsive Material	Healing Methods	Healing Assessment Method	Healing index	Healing ratio	Reference
Porous asphalt concrete (PA 0/16)	Steel wool (8%,v/v% of asphalt)	EIH	ITS test	Stiffness recovery ratio	99.1%	Liu et al. (2011)
Asphalt concrete	Steel wool (8%,v/v% of asphalt)	EIH	3 PB test	Strength recovery ratio	73.6%	Dai et al. (2013)
Asphalt concrete	Steel wool (6%,v/v% of asphalt)	EIH	3 PB test	Strength recovery ratio	60%	García et al. (2013)
Asphalt concrete	Steel particle (6%, v/v% of asphalt)	EIH	ITF test	Fatigue life extension ratio	31%	Menozzi et al. (2015)
Dense Asphalt concrete	Metal grit (4%, v/v% of asphalt mixtures)	EIH	3 PB test	Strength recovery ratio	92.3%	Gómez-Meijide et al. (2016)
Porous asphalt concrete	Aluminum fiber (5.0%v/v% of asphalt)	EIH	SCB test	Strength recovery ratio	72%	Pamulapati et al. (2017)
Asphalt concrete	Steel grit (4%, v/v% of asphalt mixtures)	EIH	3 PB test	Strength recovery ratio	66.7%	Gómez-Meijide et al. (2018)
Asphalt concrete (AC-13)	Steel wool (6%,v/v% of asphalt)	EIH	3 PB test	Strength recovery ratio	75%	Li et al. (2019)
Asphalt concrete (AC-13)	Waste steel shaving& Steel wool fiber (8%,v/v% of asphalt)	EIH	3 PB test	Strength recovery ratio	57%	Fu et al. (2022)
Asphalt concrete (AC-16)	Steel fiber (2%, v/v% of asphalt)	MIH	SCB test	Strength recovery ratio	95%	Norambuena-Contreras and Garcia (2016)
Asphalt concrete (AC-13)	Steel fiber (6%, v/v% of asphalt)	MIH	SCB test	Strength recovery ratio	89%	Sun, Y. et al. (2016)
Asphalt concrete (SMA-13)	Ni–Zn ferrite powder	MIH	3 PB test	Strength recovery ratio	65%	Zhu et al. (2017)
Dense Asphalt concrete	Carbon black (10%, v/v% of asphalt)	MIH	SCB test	Strength recovery ratio	89%	Jahanbakhsh et al. (2018)
Asphalt concrete	Steel fiber (4%, v/v% of asphalt)	MIH	SCB test	Strength recovery ratio	62%	González et al. (2019)
Asphalt concrete (OGFC-13)	Steel Slag (80%, v/v% of asphalt)	MIH	3 PB test	Strength recovery ratio	90.2%	Lou et al. (2021)
Asphalt concrete (OGFC-16)	Steel Slag (4.75–9.5 mm) (100%, v/v % of asphalt)	MIH	SCB test	Fracture energy recovery ratio	57.6%	Liu et al. (2022)

Notes: 1. EIH = electromagnetic induction healing, MIH = microwave induction healing.
2. 3 PB = three-point bending, 4 PB = four-point bending, SCB = semi-circular bending.
3. ITS = indirect tensile stiffness, ITF = indirect tensile fatigue.

on-site by supplying healing agent.

(1) Healing level of asphalt binder or mixtures with core-shell microcapsules

The microcapsule (μm size) is usually added into asphalt binder to measure the healing ratio. The fracture-healing test such as pre-cut ductility test and tensile-stress recovery test are performed on asphalt binder containing capsules. Compared with blank asphalt samples, the asphalt binder with microcapsules can obtain better healing level due to the release of the rejuvenator from the microcapsules. Asphalt binder with microcapsules (0.5 wt%) has a maximum healing level (ductility recovery ratio) that could reach 90.3% (Xue et al., 2017). Additionally, the DSR fatigue-healing-fatigue test is used to assess the fatigue life recovery ratio of asphalt binder containing microcapsules. Due to the release of the healing agent, the asphalt binder containing microcapsules exhibits a greater fatigue life recovery ratio than the asphalt binder without them (Sun et al., 2015; Sun et al., 2019; Wang and Hao, 2021; Zhang, H. et al., 2018). As the microcapsules are incorporated into asphalt mixtures, the 4 PB fatigue-healing-fatigue examination is conducted on asphalt concrete beams for ascertaining the level of fatigue recuperation. The finding suggested that the fatigue life of asphalt mixtures with 3% of microcapsules (150270) was twice as long as the fatigue life of asphalt mixtures without microcapsules (76080). Besides, the fatigue life of asphalt mixtures with microcapsules decreased with the increase of healing cycle (Sun et al., 2018a).

(2) Healing assessment of asphalt concrete with multi-cavities capsules

The multi-cavities capsules (mm size) are commonly incorporated as part of fine aggregates into asphalt mixtures. The healing efficiency of asphalt concrete with multi-cavities capsules are assessed through the 3 PB test or SCB test. The fracture-healing-fracture tests, as depicted in Fig. 13, are commonly conducted by researchers to assess the impact of capsules on the healing efficiency of asphalt concrete. Numerous studies revealed that the capsule size (Ruiz-Riancho et al., 2021b), capsule addition amount (Norambuena-Contreras et al., 2019a), aggregates gradation (Garcia-Hernández et al., 2020), loading cycles (Bao et al., 2020), healing temperature (Al-Mansoori et al., 2018a) and healing time (Norambuena-Contreras et al., 2019b) have impacts on the healing ratios of asphalt mixtures containing multi-cavities capsules. The recommend capsules addition amount is 0.5% of the mass of asphalt mixtures. Compared with non-capsule asphalt concrete, asphalt concretes with the capsules own higher healing levels (Al-Mansoori et al., 2017; Bao et al., 2021; Garcia-Hernández et al., 2020; Norambuena-Contreras et al., 2019b; Wan et al., 2022a; Wang, H. et al., 2022b; Xu et al., 2018; Yu et al., 2022; Zhang et al., 2022). The max healing level (strength recovery ratio) of asphalt mixtures with capsules (0.5 wt%) can reach 92.7% after cyclic compression loading (Zhang et al., 2019).

The correlation between the healing efficiency of asphalt concrete and the discharge of healing agents from multi-cavity capsules is significant. The healing ratio of asphalt concrete with capsules has shown gradual improvement with the increase in loading cycles. This suggests that multi-cavity capsules exhibit gradient release behavior, thereby conferring upon asphalt concrete with capsules the ability to sustain continued healing.

The gradual improvement of the healing agent release ratio in multi-cavity capsules has been observed with increasing compression loading cycles, as reported in previous studies (Bao et al., 2021;

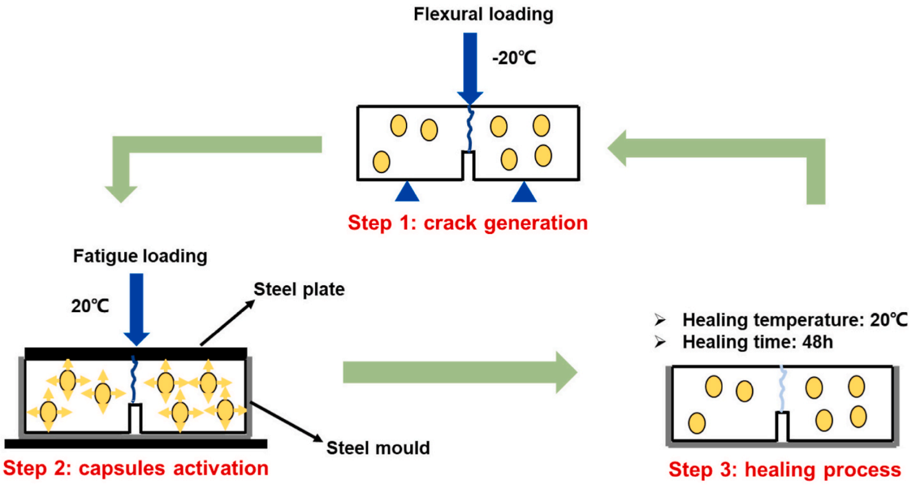

Fig. 13. The procedure of fracture-healing-facture test (Wan et al., 2022a).

Garcia-Hernández et al., 2020; Rao et al., 2021; Wang, H. et al., 2022a). This sustained release characteristic of multi-cavity capsules has the potential to provide a multi-crack repair function for asphalt pavement.

(3) Healing ratio of asphalt binder or mixtures with self-healing fiber

The self-healing fiber can be cut into small bars with different lengths and added into asphalt binder or asphalt mixtures to evaluate the healing effect. The healing efficiency of asphalt binder containing fiber is evaluated by the tension test. The max healing ratio of asphalt binder with hollow polyvinylidene tetrafluoroethylene (PVDF) fiber can reach 75% (Qing Wang et al., 2021). The study reveals that the maximum healing ratio of asphalt binder can be achieved up to 82.8% with the incorporation of calcium alginate hollow fiber at a dosage of 5%, surpassing the healing ratio of test asphalt with compartmented fiber, which was recorded at 75.4% (Shu et al., 2019).

The assessment of the healing capacity of asphalt mixtures containing fiber is conducted through either the 3 PB test (Shu et al., 2021) or SCB test (Tabaković et al., 2017). The incorporation of fiber in asphalt concrete results in a significantly elevated healing ratio in comparison to that of plain asphalt concrete. The maximum healing ratio achievable by asphalt concrete with calcium alginate fiber can reach 68.8% (Shu, B. et al., 2019). Besides, the asphalt concrete with Ca-alginate fiber shows higher healing level under saline and alkali water containing Na^+ service environment than acid water service environment (Shu et al., 2020).

The enhanced healing level of asphalt materials highly depends on the release rejuvenator from fiber. It is vital to understand the rejuvenator release mechanism of self-healing fiber. As shown in Fig. 14, from the microscopic point of view it reveals the compartment fiber to improve the mechanism of asphalt self-healing ability, the self-repair process can be roughly divided into: (1) asphalt internal cracks lead to fiber rupture, (2) the rejuvenator inside the fiber release and fill the cracks in the capillary action, (3) the rejuvenator wetting asphalt around crack zone, (4) rejuvenator in the asphalt of the rapid diffusion of the asphalt viscosity decreases dramatically, (5) the rapid flow of asphalt to the cracked area and (6) cracks disappeared and the asphalt performance restores.

The healing levels of asphalt materials via rejuvenator induced healing methods are shown in Table 2. Under the evaluation mode of fatigue-healing (fatigue-healing-fatigue test via DSR, 4 PB test via UTM), the addition of core-shell capsules of muti-cavity capsules can aid asphalt materials in the extension of fatigue life. Under the evaluation mode of fracture-healing (ductility test, 3 PB test and SCB test), the incorporation of self-healing capsules or fibers help asphalt materials obtain various degree of strength recovery. In summary, the rejuvenator induced healing strategy can improve healing level of asphalt materials and expand the fatigue life.

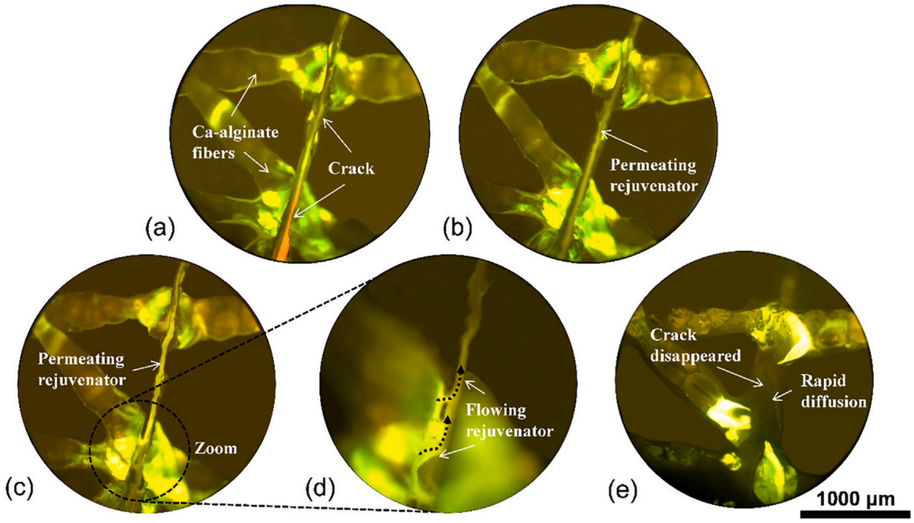

Fig. 14. The rejuvenator release mechanism of self-healing fiber.

Table 2
Healing ratios of asphalt materials via rejuvenator induced healing methods.

Matrix Material	Functional Material	Healing Assessment Method	Healing index	Healing ratio	Reference
Asphalt	UF microcapsule	Ductility test	Ductility recovery ratio	39.45%	Li et al. (2015)
Asphalt	UF microcapsule	Fatigue-healing-fatigue test	Complex modulus recovery ratio	97.5%	Xue et al. (2017)
Asphalt	MUF microcapsule	Ductility tensile test	Tensile strength recovery ratio	83.8%	Sun et al. (2017a)
Asphalt mixtures (AC-10)	MUF microcapsule	4 PB test	Fatigue life recovery ratio	60.08%	(Sun et al., 2018a)
Asphalt	MF microcapsule	Fatigue-healing-fatigue test	Fatigue life extension ratio	39%	Sun et al. (2015)
Asphalt	MMF microcapsule	Fatigue-healing-fatigue test	Complex modulus recovery ratio	27.6%	(Wang, Y.-Y. et al., 2022)
Asphalt	PU microcapsule	Fatigue-healing-fatigue test	Fatigue life recovery ratio	40.9%	Tan et al. (2020)
Asphalt mixtures (AC-13) (SMA-13)	IDPI microcapsule	3 PB	Strength recovery ratio	AC: 95% SMA: 73%	Chen et al. (2023)
Asphalt	HMMM microcapsule	Force ductility test	Tensile flexibility recovery ratio	52%	Tian et al. (2020)
Asphalt	Ca-alginate microcapsule	Ductility tensile test	Tensile stress recovery ratio	79.89%	Shu, B. et al. (2018)
Asphalt mastic	Ca-alginate muti-cavity capsule	3 PB test	Strength recovery ratio	95%	Yamaç et al. (2021)
Asphalt mortar	Ca-alginate muti-cavity capsule	3 PB test	Strength recovery ratio	40%	(Xu et al., 2019)
Asphalt mixtures (AC-13)	Ca-alginate muti-cavity capsule	3 PB test	Strength recovery ratio	52.93%	Al-Mansoori et al. (2017)
Asphalt mixtures (AC-13)	Ca-alginate muti-cavity capsule	3 PB test	Fracture energy recovery ratio	180.2%	Zhang et al. (2019)
Asphalt mixtures (SMA-14)	Ca-alginate muti-cavity capsule	3 PB test	Strength recovery ratio	52.93%	Norambuena-Contreras et al. (2019b)
Asphalt mixtures (PAC)	Ca-alginate muti-cavity capsule	SCB test	Strength recovery ratio	19.3%	Xu, S. et al. (2019)
Asphalt binder	Ca-alginate hollow fiber	Tension test	Tensile strength recovery ratio	80%	Guo et al. (2019)
Asphalt	Ca-alginate hollow fiber	Tension test	Tensile stress recovery ratio	82.5%	(Shu et al., 2019)
Asphalt	Ca-alginate compartmented fiber	Tension test	Tensile stress recovery ratio	75.4%	(Shu et al., 2019)
Asphalt mixtures	Ca-alginate fiber	3 PB test	Strength recovery ratio	91%	Zaremotekhases et al. (2020)
Asphalt mixtures (AC-13)	Ca-alginate compartmented fiber	3 PB test	Strength recovery ratio	72.5%	(Shu et al., 2020)

Notes: 1. UF = urea-formaldehyde, MUF = methanol-melamine-formaldehyde, MF = melamine-formaldehyde, MMF = methanol-melamine-formaldehyde, PU = polyurethane, IPDI = isophorone diisocyanate, HMMM = methyl etherified melamine formaldehyde, Ca-alginate = calcium alginate.

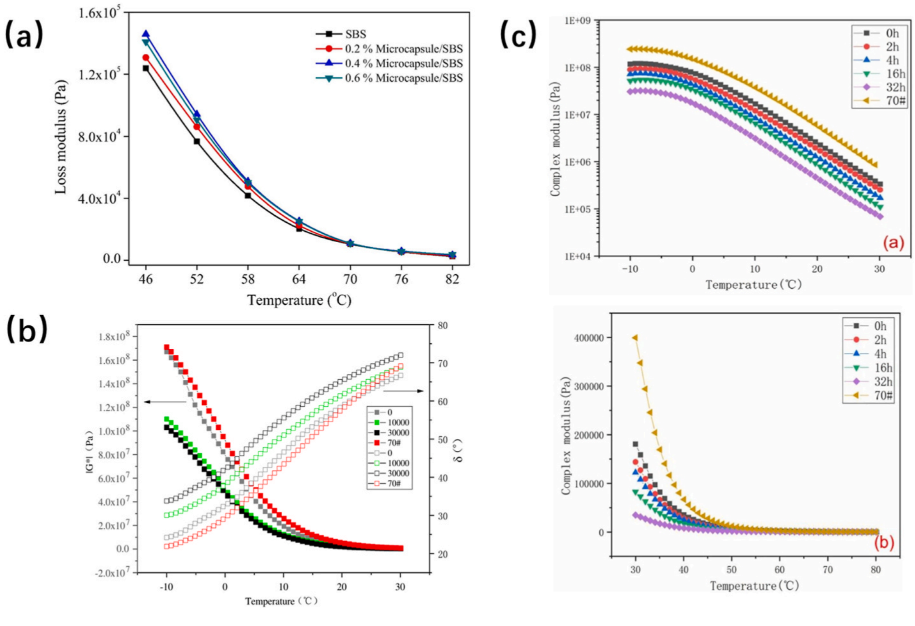

Fig. 15. (a) The loss modulus of SBS modified asphalt binder containing different dosage of UF microcapsules after healing accomplish (Li et al., 2020), (b) the complex modulus and phase angel of asphalt binder extracted from asphalt mixtures with Ca-alginate capsules after different cycles of loading (Bao et al., 2021), (c) the complex modulus of asphalt binder extracted from asphalt mixtures with Ca-alginate capsules after different time of cyclic loading via wheel tracking test (Rao et al., 2021).

4.3. Evaluation of regeneration effect of rejuvenator released from capsule or fiber

The distinct advantage of rejuvenator induced healing method is the rejuvenator released from encapsulation carrier (capsule and fiber) can revitalize the aged asphalt via the provision of light components, while the thermal induced healing can only accelerate the crack repair process through the generated heat energy. Consequently, it is imperative to examine the regenerative impact of the released rejuvenator from capsule or fiber on asphalt.

4.3.1. Evaluation of the regeneration effect based on rheological property

The rejuvenator released from capsule or fiber flow and diffuse into asphalt binder and improve its flow ability which can be evaluated via the rheological property. The complex modulus (G*) is usually employed to assess the flow ability of asphalt binder, and lower G* represents better flow ability. The phase angel(δ) is usually represented the ratio of viscosity component and elastic component. When the rejuvenator with viscosity component flow into asphalt, the viscosity component ratio will increase, which corresponds to a rise of δ. Hence, the G* and δ of asphalt binder will decrease and increase respectively when the released rejuvenator flow and diffuse into the binder.

Compared with blank aged asphalt binder samples, the G* and δ of asphalt binder containing microcapsule decreases and increases apparently due to the softening effect of rejuvenator (Sun et al., 2019; Sun et al., 2018a; Wang, Y.-Y. et al., 2022). As shown in Fig. 15(a), with the addition of UF microcapsules, the loss modulus of asphalt binder increases apparently. This can be explained by the fact that when pressure from outside sources damages or cracks microcapsules in asphalt binder, the encapsulated rejuvenator leaks out and mixes with SBS-modified asphalt and improves the viscosity component ratio of asphalt. Meanwhile, the asphalt binder obtained from asphalt concrete containing multi-cavity capsules exhibited decreased G* and increased δ values after undergoing various loading cycles, in comparison to the asphalt binder extracted from asphalt concrete without capsules after loading, as shown in Fig. 15(b) (Bao et al., 2021). The same tendency was confirmed by the following research (Rao et al., 2021), as presented in Fig. 15(c). The rejuvenator can be released from encapsulation carrier and flow into asphalt binder, which soften it and adjust the viscosity component ratio and finally improve the rheological performance.

4.3.2. Characterization of the regeneration effect by SARA fractions

The categorization of asphalt binders can be based on the polarity of their components, which can be classified into four distinct groups: saturated, aromatic, resin, and asphaltene (SARA) (Li, J. et al., 2022a; Shi et al., 2017). The aging process of asphalt binder results in the conversion of its saturated and aromatic components into asphaltene and resin, leading to a reduction in the quantity of light components. The decrease in content of light components (saturated and aromatic) negatively impacts the ability of asphalt to heal cracks.

The healing agent (commercial rejuvenator and vegetable oil) consists of abound light components, and can balance the light component fraction of asphalt and thus restore the aged asphalt binder (Ji et al., 2017; Shu, B. et al., 2020). Hence, the variation of SARA components can be used to assess the regeneration effect of rejuvenator induced healing technology. Wang et al. explored the SARA fractions variation of extracted asphalt binder from asphalt concrete with different multi-cavities capsules after 10000 cycles of compression loading at 0.6 MPa, 1.0 MPa and 1.4 MPa respectively, and found that the three types of rejuvenators (vegetable oil, waste cooking oil and industrial rejuvenator) released from the capsules increase the light component content of asphalt binder, as depicted in Fig. 16 (Wang, H. et al., 2022b).

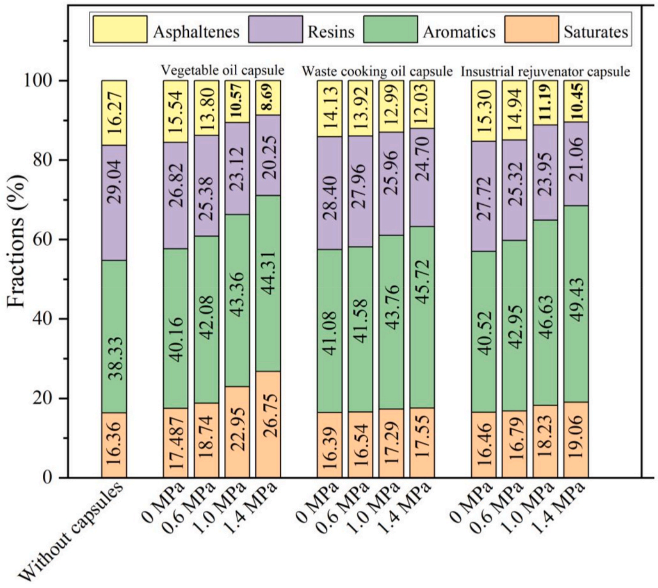

Fig. 16. The SARA component variation of the extracted asphalt binder after 10000 cycles of compression loading at 0.6 MPa, 1.0 MPa and 1.4 MPa respectively (Wang, H. et al., 2022b).

5. Summary and prospects

5.1. Summary

The healing capacity of asphalt pavements has a significant impact on their durability and service life. A comprehensive understanding of this capacity and methods for its improvement can be seen as an effective step towards achieving the goal of developing sustainable asphalt pavements. Considering the low inherent healing capacity of asphalt under natural conditions, this paper provides an overview of extrinsic healing strategy for asphalt materials. The following conclusions can be drawn:

1. A comprehensive understanding of the self-healing mechanism is the key point to precisely characterize and evaluate the asphalt self-healing. The capillary flow theory, phase field theory and molecular diffusion theory explain asphalt self-healing progressively from the macro-scale to the micro-scale. The surface energy theory rooted in fracture mechanics field proposes that the reduction of surface energy serves as the impetus for the self-healing behavior of asphalt. It is challenging to fully elucidate asphalt's self-healing mechanism using a single theory. The self-healing mechanism of asphalt at different repair stages and at different repair scales can be reliably and completely explained by a reasonable fusion of these theories.
2. Self-healing ability, as an inherent property of asphalt, has a great potential to extend the service life of asphalt pavements. In order to achieve efficient asphalt healing, innovative ideas such as thermally induced healing and rejuvenator encapsulation induced healing have achieved significant results in the laboratory. The thermal induced healing technology bring superior crack repair efficiency and muti-crack sealing potential for asphalt concrete. However, this technology requires the mixing of specified materials in the asphalt mixture and human intervention during its service life, which also generates harmful gases and accelerates the rate of asphalt ageing due to the heating process. The rejuvenator encapsulation induced healing technology can not only repair the microcrack but also regenerate the ageing asphalt in situ via the support of encapsulated rejuvenator. Nevertheless, this technology brings excellent curing effectiveness for damaged asphalt materials under moderate healing environment. In real service condition, the healing ratio of self-

healing capsules or fibers may be inferior to laboratory results. Besides, the control of fabrication cost and research on large-scale production technology of self-healing capsules or fibers still have huge room.
3. The search for reasonably general healing evaluation methods and metrics is essential to characterize the healing capacity of asphalt materials under the action of exogenous healing methods. Currently, a variety of evaluation methods and metrics have been used for different research subjects such as asphalt mastic, asphalt mortar, and asphalt concrete, and the differences in healing levels do not support the superiority of the same healing technique.

5.2. Prospect and recommendation

The extrinsic healing strategy including thermally induced healing and rejuvenator encapsulation induced healing have been successfully applied in asphalt materials (binder, mortar, and mixtures) in laboratory scale to improve the healing level, but there are huge room for them to improve.

1. In the context of low carbon maintenance, the utilization of recycle materials with conductive or microwave absorption properties are beneficial to the sustainable asphalt pavement via thermal induced healing technology. Meanwhile, energy-saving, and efficient electromagnetic induction and microwave transmission vehicles need to be developed urgently.
2. Optimization of the capsule and fiber preparation process is required to achieve production with controlled performance. Meanwhile, the production efficiency of capsules and fiber is relatively low, and industrial manufacturing requires further research.
3. The current release pattern of healing agent from carrier (capsule & fiber) is a passive and uncontrollable stress-induced release that is not compatible with the complex service condition. Considering the living environment of rejuvenator carrier is asphalt concrete, external remote triggers such as magnetic fields and microwaves are suitable for the active controlled release of healing agent in responsive capsules. Multi-responsive release modes based on responsive capsules may realize the on-demand release goal in asphalt pavement in the future.
4. Thermal induced healing technology and rejuvenator induced healing technology each have their own advantages and disadvantages, and the synergistic effect of them is to be explored, which is conducive to the realization of synergistic healing of asphalt materials.

The implementation of self-healing asphalt materials has been proposed as a potential solution for the restoration of structural damage caused by the combined impact of repeated loading and environmental factors. Extrinsic self-healing is developed based on energy provision or healing agent supply to the damaged asphalt to facilitate the repair of structural damage. These functions enable the asphalt materials to react to the incidence of multiple cracking events and repair multiple cracks concurrently. Therefore, the implementation of exogenous healing techniques for the purpose of promoting self-healing of cracks is highly advantageous in the context of pavement preventive maintenance. This review focus on the extrinsic healing strategy and the healing level of thermal induced method and rejuvenator induced method for asphalt materials, the effect of extrinsic healing method on the pavement performance of asphalt concrete is not mentioned. Collaborative efforts are required to address the aforementioned factors in order to facilitate the implementation of extrinsic self-healing asphalt concrete in engineering applications. This would result in a substantial contribution towards the advancement of sustainable and low-carbon asphalt concrete infrastructure.

CRediT authorship contribution statement

Pei Wan: Conceptualization, Methodology, Writing – original draft. **Shaopeng Wu:** Supervision, Writing – review & editing. **Quantao Liu:** Project administration, Formal analysis, Writing – review & editing. **Huan Wang:** Formal analysis. **Xing Gong:** Formal analysis. **Zenggang Zhao:** Formal analysis. **Shi Xu:** Writing – review & editing. **Jian Jiang:** Writing – review & editing. **Lulu Fan:** Writing – review & editing. **Liangliang Tu:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the publication of this paper.

Data availability

Data will be made available on request.

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References

Aguirre, M.A., Hassan, M.M., Shirzad, S., Daly, W.H., Mohammad, L.N., 2016. Micro-encapsulation of asphalt rejuvenators using melamine-formaldehyde. Construct. Build. Mater. 114, 29–39.

Al-Mansoori, T., Micaelo, R., Artamendi, I., Norambuena-Contreras, J., Garcia, A., 2017. Microcapsules for self-healing of asphalt mixture without compromising mechanical performance. Construct. Build. Mater. 155, 1091–1100.

Al-Mansoori, T., Norambuena-Contreras, J., Garcia, A., 2018a. Effect of capsule addition and healing temperature on the self-healing potential of asphalt mixtures. Mater. Struct. 51 (2).

Al-Mansoori, T., Norambuena-Contreras, J., Micaelo, R., Garcia, A., 2018b. Self-healing of asphalt mastic by the action of polymeric capsules containing rejuvenators. Construct. Build. Mater. 161, 330–339.

Anupam, B.R., Sahoo, U.C., Chandrappa, A.K., 2022. A methodological review on self-healing asphalt pavements. Construct. Build. Mater. 321.

Ayar, P., Moreno-Navarro, F., Rubio-Gámez, M.C., 2016. The healing capability of asphalt pavements: a state of the art review. J. Clean. Prod. 113, 28–40.

Bao, S., Liu, Q., Li, H., Zhang, L., Maria Barbieri, D., 2021. Investigation of the release and self-healing properties of calcium alginate capsules in asphalt concrete under cyclic compression loading. J. Mater. Civ. Eng. 33 (1).

Bao, S., Liu, Q., Rao, W., Yu, X., Zhang, L., 2020. Synthesis and characterization of calcium alginate-attapulgite composite capsules for long term asphalt self-healing. Construct. Build. Mater. 265.

Behnood, A., 2019. Application of rejuvenators to improve the rheological and mechanical properties of asphalt binders and mixtures: a review. J. Clean. Prod. 231, 171–182.

Bhasin, A., Bommavaram, R., Greenfield, M.L., Little, D.N., 2011. Use of molecular dynamics to investigate self-healing mechanisms in asphalt binders. J. Mater. Civ. Eng. 23 (4), 485–492.

Chen, Y., Ji, X., Si, B., Zhang, Z., Shao, D., Zhu, S., He, S., 2023. Investigation on self-healing performance of asphalt mixture containing microcapsules and survival behaviour of microcapsules. Int. J. Pavement Eng. 24 (1).

Cui, P., Wu, S., Xiao, Y., Hu, R., Yang, T., 2021. Environmental performance and functional analysis of chip seals with recycled basic oxygen furnace slag as aggregate. J. Hazard Mater. 405, 124441.

Dai, Q., Wang, Z., Mohd Hasan, M.R., 2013. Investigation of induction healing effects on electrically conductive asphalt mastic and asphalt concrete beams through fracture-healing tests. Construct. Build. Mater. 49, 729–737.

Fu, C., Liu, K., Liu, Q., Zhang, Z., Oeser, M., 2022. A sustainable inductive healing asphalt mixture for solving gradient healing behavior. J. Clean. Prod. 370.

Fu, C., Wang, F., Liu, K., Liu, Q., Liu, P., Oeser, M., 2023. Inductive asphalt pavement layers for improving electromagnetic heating performance. Int. J. Pavement Eng. 24 (1).

Gallego, J., del Val, M.A., Contreras, V., Páez, A., 2013. Heating asphalt mixtures with microwaves to promote self-healing. Construct. Build. Mater. 42, 1–4.

Garcia-Hernández, A., Salih, S., Ruiz-Riancho, I., Norambuena-Contreras, J., Hudson-Griffiths, R., Gomez-Meijide, B., 2020. Self-healing of reflective cracks in asphalt mixtures by the action of encapsulated agents. Construct. Build. Mater. 252.

García, Á., 2012. Self-healing of open cracks in asphalt mastic. Fuel 93, 264–272.

García, A., Bueno, M., Norambuena-Contreras, J., Partl, M.N., 2013. Induction healing of dense asphalt concrete. Construct. Build. Mater. 49, 1–7.

García, Á., Schlangen, E., van de Ven, M., Liu, Q., 2009. Electrical conductivity of asphalt mortar containing conductive fibers and fillers. Construct. Build. Mater. 23 (10), 3175–3181.

Garcia, A., Schlangen, E., van de Ven, M., Sierra-Beltran, G., 2010. Preparation of capsules containing rejuvenators for their use in asphalt concrete. J. Hazard Mater. 184 (1–3), 603–611.

García, Á., Schlangen, E., van de Ven, M., van Vliet, D., 2010. Induction heating of mastic containing conductive fibers and fillers. Mater. Struct. 44 (2), 499–508.

Gómez-Meijide, B., Ajam, H., Lastra-González, P., Garcia, A., 2016. Effect of air voids content on asphalt self-healing via induction and infrared heating. Construct. Build. Mater. 126, 957–966.

Gómez-Meijide, B., Ajam, H., Lastra-González, P., Garcia, A., 2018. Effect of ageing and RAP content on the induction healing properties of asphalt mixtures. Construct. Build. Mater. 179, 468–476.

Gong, X., Liu, Q., Wang, H., Wan, P., Chen, S., Wu, J., Wu, S., 2023. Synthesis of environmental-curable CO2-based polyurethane and its enhancement on properties of asphalt binder. J. Clean. Prod. 384.

Gonzalez-Torre, I., Norambuena-Contreras, J., 2020. Recent advances on self-healing of bituminous materials by the action of encapsulated rejuvenators. Construct. Build. Mater. 258.

González, A., Valderrama, J., Norambuena-Contreras, J., 2019. Microwave crack healing on conventional and modified asphalt mixtures with different additives: an experimental approach. Road Mater. Pavement Des. 20 (Suppl. 1), S149–S162.

Guo, Y.-D., Xie, X.-M., Su, J.-F., Mu, R., Wang, X.-F., Jin, H.-P., Fang, Y., Ding, Z., Lv, L.-Y., Han, N.-X., 2019. Mechanical experiment evaluation of the microvascular self-healing capability of bitumen using hollow fibers containing oily rejuvenator. Construct. Build. Mater. 225, 1026–1035.

Hou, Y., Wang, L., Pauli, T., Sun, W., 2015. Investigation of the asphalt self-healing mechanism using a phase-field model. J. Mater. Civ. Eng. 27 (3), 04014118.

Hu, Z., Zhang, H., Wang, S., Xu, T., 2020. Thermal-oxidative aging mechanism of asphalt binder based on isothermal thermal analysis at the SARA level. Construct. Build. Mater. 255.

Huang, H.L., Ye, G., Qian, C.X., Schlangen, E., 2016. Self-healing in cementitious materials: materials, methods and service conditions. Mater. Des. 92, 499–511.

Jahanbakhsh, H., Karimi, M.M., Jahangiri, B., Nejad, F.M., 2018. Induction heating and healing of carbon black modified asphalt concrete under microwave radiation. Construct. Build. Mater. 174, 656–666.

Ji, J., Yao, H., Suo, Z., You, Z., Li, H., Xu, S., Sun, L., 2017. Effectiveness of vegetable oils as rejuvenators for aged asphalt binders. J. Mater. Civ. Eng. 29 (3).

Ji, X., Li, J., Hua, W., Hu, Y., Si, B., Chen, B., 2021. Preparation and performance of microcapsules for asphalt pavements using interfacial polymerization. Construct. Build. Mater. 289.

Jud, K., Kausch, H., 1979. Load transfer through chain molecules after interpenetration at interfaces. Polym. Bull. 1, 697–707.

Jud, K., Kausch, H., Williams, J., 1981. Fracture mechanics studies of crack healing and welding of polymers. J. Mater. Sci. 16, 204–210.

Kang, J.H., Son, D., Wang, G.J.N., Liu, Y.X., Lopez, J., Kim, Y., Oh, J.Y., Katsumata, T., Mun, J.W., Lee, Y., Jin, L.H., Tok, J.B.H., Bao, Z.N., 2018. Tough and water-insensitive self-healing elastomer for robust electronic skin. Adv. Mater. 30 (13).

Kringos, N., 2009. A finite element based chemo-mechanics model to simulate healing of bituminous materials. In: International Workshop Chemo Mechanics of Bituminous Materials. Delft, The Netherlands. 9-11 June 2009, pp. 69–75.

Kringos, N., Schmets, A., Scarpas, A., Pauli, T., 2011. Towards an understanding of the self-healing capacity of asphaltic mixtures. Heron 56 (1/2), 45–74.

Li, H., Yu, J., Wu, S., Liu, Q., Li, B., Li, Y., Wu, Y., 2019. Study on the gradient heating and healing behaviors of asphalt concrete induced by induction heating. Construct. Build. Mater. 208, 638–645.

Li, J., Xing, X.Y., Hou, X.D., Wang, T., Wang, J.Y., Xiao, F.P., 2022a. Determination of SARA fractions in asphalts by mid-infrared spectroscopy and multivariate calibration. Measurement 198.

Li, J., Yang, S., Muhammad, Y., Sahibzada, M., Zhu, Z., Liu, T., Liao, S., 2020. Fabrication and application of polyurea formaldehyde-bioasphalt microcapsules as a secondary modifier for the preparation of high self-healing rate SBS modified asphalt. Construct. Build. Mater. 246.

Li, J., Yu, J., Wu, S., Xie, J., 2022b. The mechanical resistance of asphalt mixture with steel slag to deformation and skid degradation based on laboratory accelerated heavy loading test. Materials 15 (3).

Li, R., Zhou, T., Pei, J., 2015. Design, preparation and properties of microcapsules containing rejuvenator for asphalt. Construct. Build. Mater. 99, 143–149.

Li, X., Wu, S., Wang, F., You, L., Yang, C., Cui, P., Zhang, X., 2023. Quantitative assessments of GHG and VOCs emissions of asphalt pavement contained steel slag. Construct. Build. Mater. 369.

Li, Y., Hao, P., Li, N., 2022. Preparation and properties of a novel rejuvenator-loaded fiber for asphalt pavement. Construct. Build. Mater. 324.

Li, Y., Hao, P., Zhang, M., 2021. Fabrication, characterization and assessment of the capsules containing rejuvenator for improving the self-healing performance of asphalt materials: a review. J. Clean. Prod. 287.

Liang, B., Lan, F., Shi, K., Qian, G., Liu, Z., Zheng, J., 2021. Review on the self-healing of asphalt materials: mechanism, affecting factors, assessments and improvements. Construct. Build. Mater. 266.

Little, D.N., Lytton, R.L., Williams, D., Kim, Y.R., 1999. An analysis of the mechanism of microdamage healing based on the application of micromechanics first principles of fracture and healing. J. Assoc. Asphalt Paving Technol. 68.

Liu, J., Zhang, T., Guo, H., Wang, Z., Wang, X., 2022. Evaluation of self-healing properties of asphalt mixture containing steel slag under microwave heating: mechanical, thermal transfer and voids microstructural characteristics. J. Clean. Prod. 342.

Liu, Q., Chen, C., Li, B., Sun, Y., Li, H., 2018. Heating characteristics and induced healing efficiencies of asphalt mixture via induction and microwave heating. Materials (Basel) 11 (6).

Liu, Q., García, Á., Schlangen, E., Ven, M.v.d., 2011. Induction healing of asphalt mastic and porous asphalt concrete. Construct. Build. Mater. 25 (9), 3746–3752.

Liu, Q., Schlangen, E., García, Á., van de Ven, M., 2010. Induction heating of electrically conductive porous asphalt concrete. Construct. Build. Mater. 24 (7), 1207–1213.

Liu, Q., Schlangen, E., van de Ven, M., 2013. Induction healing of porous asphalt concrete beams on an elastic foundation. J. Mater. Civ. Eng. 25 (7), 880–885.

Liu, Q., Schlangen, E., van de Ven, M., van Bochove, G., van Montfort, J., 2012. Evaluation of the induction healing effect of porous asphalt concrete through four point bending fatigue test. Construct. Build. Mater. 29, 403–409.

Lou, B., Sha, A., Barbieri, D.M., Liu, Z., Zhang, F., Jiang, W., Hoff, I., 2021. Characterization and microwave healing properties of different asphalt mixtures suffered freeze-thaw damage. J. Clean. Prod. 320.

Lv, Q., Huang, W., Zhu, X., Xiao, F., 2017. On the investigation of self-healing behavior of bitumen and its influencing factors. Mater. Des. 117, 7–17.

Lv, Y., Wu, S., Li, N., Cui, P., Wang, H., Amirkhanian, S., Zhao, Z., 2023. Performance and VOCs emission inhibition of environmentally friendly rubber modified asphalt with UiO-66 MOFs. J. Clean. Prod. 385.

Lytton, R.L., Uzan, J., Fernando, E.G., Roque, R., Hiltunen, D., Stoffels, S.M., 1993. Development and Validation of Performance Prediction Models and Specifications for Asphalt Binders and Paving Mixes. Strategic Highway Research Program, Washington, DC.

Ma, F., Dong, W., Fu, Z., Wang, R., Huang, Y., Liu, J., 2021. Life cycle assessment of greenhouse gas emissions from asphalt pavement maintenance: a case study in China. J. Clean. Prod. 288.

Menapace, I., Masad, E., 2018. The influence of moisture on the evolution of the microstructure of asphalt binders with aging. Road. Mater. Pavement. 21 (2), 331–346.

Menozzi, A., Garcia, A., Partl, M.N., Tebaldi, G., Schuetz, P., 2015. Induction healing of fatigue damage in asphalt test samples. Construct. Build. Mater. 74, 162–168.

Micaelo, R., Al-Mansoori, T., Garcia, A., 2016. Study of the mechanical properties and self-healing ability of asphalt mixture containing calcium-alginate capsules. Construct. Build. Mater. 123, 734–744.

Norambuena-Contreras, J., 2017. Influence of the microwave heating time on the self-healing properties of asphalt mixtures. Appl. Sci. (Basel) 7 (10).

Norambuena-Contreras, J., Garcia, A., 2016. Self-healing of asphalt mixture by microwave and induction heating. Mater. Des. 106, 404–414.

Norambuena-Contreras, J., Liu, Q., Zhang, L., Wu, S., Yalcin, E., Garcia, A., 2019a. Influence of encapsulated sunflower oil on the mechanical and self-healing properties of dense-graded asphalt mixtures. Mater. Struct. 52 (4).

Norambuena-Contreras, J., Yalcin, E., Hudson-Griffiths, R., García, A., 2019b. Mechanical and self-healing properties of stone mastic asphalt containing encapsulated rejuvenators. J. Mater. Civ. Eng. 31 (5).

Ozaki, S., Osada, T., Nakao, W., 2016. Finite element analysis of the damage and healing behavior of self-healing ceramic materials. Int. J. Solid Struct. 100, 307–318.

Pamulapati, Y., Elseifi, M.A., Cooper, S.B., Mohammad, L.N., Elbagalati, O., 2017. Evaluation of self-healing of asphalt concrete through induction heating and metallic fibers. Construct. Build. Mater. 146, 66–75.

Phillips, M., 1998. Multi-step models for fatigue and healing, and binder properties involved in healing. In: Eurobitume workshop on performance related properties for bituminous binders, Luxembourg.

Polo-Mendoza, R., Martinez-Arguelles, G., Walubita, L.F., Moreno-Navarro, F., Giustozzi, F., Fuentes, L., Navarro-Donado, T., 2022. Ultraviolet ageing of bituminous materials: a comprehensive literature review from 2011 to 2022. Construct. Build. Mater. 350.

Qing Wang, L., Feng Su, J., Gao, X., 2021. Observation of the microstructure and shape of self-healing microvascular in asphalt. Construct. Build. Mater. 290.

Qiu, J., van de Ven, M.F.C., Wu, S.P., Yu, J.Y., Molenaar, A.A.A., 2011. Investigating self healing behaviour of pure bitumen using Dynamic Shear Rheometer. Fuel 90 (8), 2710–2720.

Rao, W., Liu, Q., Yu, X., Wan, P., Wang, H., Song, J., Ye, Q., 2021. Efficient preparation and characterization of calcium alginate-attapulgite composite capsules for asphalt self-healing. Construct. Build. Mater. 299.

Ruiz-Riancho, N., Garcia, A., Grossegger, D., Saadoon, T., Hudson-Griffiths, R., 2021a. Properties of Ca-alginate capsules to maximise asphalt self-healing properties. Construct. Build. Mater. 284.

Ruiz-Riancho, N., Saadoon, T., Garcia, A., Grossegger, D., Hudson-Griffiths, R., 2021b. Optimisation of self-healing properties for asphalts containing encapsulated oil to mitigate reflective cracking and maximize skid and rutting resistance. Construct. Build. Mater. 300.

Shi, H.Q., Xu, T., Zhou, P., Jiang, R.L., 2017. Combustion properties of saturates, aromatics, resins, and asphaltenes in asphalt binder. Construct. Build. Mater. 136, 515–523.

Shu, B., Bao, S., Wu, S., Dong, L., Li, C., Yang, X., Norambuena-Contreras, J., Liu, Q., Wang, Q., 2019a. Synthesis and effect of encapsulating rejuvenator fiber on the performance of asphalt mixture. Materials (Basel) 12 (8).

Shu, B., Guo, L., Qiu, B., Yang, T., Sun, T., Qiu, W., Zhou, M., Song, P., Li, Y., Maria Barbieri, D., Wu, S., 2021. Effect of encapsulation combined with microwave heating on self-healing performance of asphalt mixture. J. Renew. Mater. 9 (10), 1781–1794.

Shu, B., Wu, S., Dong, L., Norambuena-Contreras, J., Li, Y., Li, C., Yang, X., Liu, Q., Wang, Q., Wang, F., Barbieri, D.M., Yuan, M., Bao, S., Zhou, M., Zeng, G., 2020a. Self-healing capability of asphalt mixture containing polymeric composite fibers under acid and saline-alkali water solutions. J. Clean. Prod. 268.

Shu, B., Wu, S., Dong, L., Norambuena-Contreras, J., Yang, X., Li, C., Liu, Q., Wang, Q., 2019b. Microfluidic synthesis of polymeric fibers containing rejuvenating agent for asphalt self-healing. Construct. Build. Mater. 219, 176–183.

Shu, B., Wu, S., Dong, L., Wang, Q., Liu, Q., 2018a. Microfluidic synthesis of ca-alginate microcapsules for self-healing of bituminous binder. Materials (Basel) 11 (4).

Shu, B., Zhang, L., Wu, S., Dong, L., Liu, Q., Wang, Q., 2018b. Synthesis and characterization of compartmented Ca-alginate/silica self-healing fibers containing bituminous rejuvenator. Construct. Build. Mater. 190, 623–631.

Shu, B., Zhou, M., Yang, T., Li, Y., Ma, Y., Liu, K., Bao, S., Barbieri, D.M., Wu, S., 2020b. The properties of different healing agents considering the micro-self-healing process of asphalt with encapsulations. Materials (Basel) 14 (1).

Si, Z., Little, D., Lytton, R., 2002. Characterization of microdamage and healing of asphalt concrete mixtures. J. Mater. Civ. Eng. 14 (6), 461–470.

Su, J.-F., Schlangen, E., 2012. Synthesis and physicochemical properties of high compact microcapsules containing rejuvenator applied in asphalt. Chem. Eng. J. 198–199, 289–300.

Su, J.-F., Zhang, X.-L., Guo, Y.-D., Wang, X.-F., Li, F.-L., Fang, Y., Ding, Z., Han, N.-X., 2019. Experimental observation of the vascular self-healing hollow fibers containing rejuvenator states in bitumen. Construct. Build. Mater. 201, 715–727.

Sun, D., Hu, J., Zhu, X., 2015. Size optimization and self-healing evaluation of microcapsules in asphalt binder. Colloid Polym. Sci. 293 (12), 3505–3516.

Sun, D., Li, B., Tian, Y., Lu, T., Zhu, X., Sun, G., Gilabert, F.A., 2019. Aided regeneration system of aged asphalt binder based on microcapsule technology. Construct. Build. Mater. 201, 571–579.

Sun, D., Li, B., Ye, F., Zhu, X., Lu, T., Tian, Y., 2018a. Fatigue behavior of microcapsule-induced self-healing asphalt concrete. J. Clean. Prod. 188, 466–476.

Sun, D., Lin, T., Zhu, X., Tian, Y., Liu, F., 2016. Indices for self-healing performance assessments based on molecular dynamics simulation of asphalt binders. Comput. Mater. Sci. 114, 86–93.

Sun, D., Pang, Q., Zhu, X., Tian, Y., Lu, T., Yang, Y., 2017a. Enhanced self-healing process of sustainable asphalt materials containing microcapsules. ACS Sustain. Chem. Eng. 5 (11), 9881–9893.

Sun, D., Sun, G., Zhu, X., Guarin, A., Li, B., Dai, Z., Ling, J., 2018. A comprehensive review on self-healing of asphalt materials: mechanism, model, characterization and enhancement. Adv. Colloid. Interfac. 256, 65–93.

Sun, D., Sun, G., Zhu, X., Ye, F., Xu, J., 2018b. Intrinsic temperature sensitive self-healing character of asphalt binders based on molecular dynamics simulations. Fuel 211, 609–620.

Sun, D., Yu, F., Li, L., Lin, T., Zhu, X.Y., 2017b. Effect of chemical composition and structure of asphalt binders on self-healing. Construct. Build. Mater. 133, 495–501.

Sun, G., Ma, J., Sun, D., Li, B., Ling, S., Lu, T., 2020. Influence of thermal oxidative aging on temperature induced self-healing transition of polymer modified bitumens. Mater. Des. 192.

Sun, G., Ma, J., Sun, D., Yu, F., 2021. Influence of weather accelerated ageing on healing temperature sensitivity of asphalts. J. Clean. Prod. 281.

Sun, Y., Wu, S., Liu, Q., Li, B., Fang, H., Ye, Q., 2016. The healing properties of asphalt mixtures suffered moisture damage. Construct. Build. Mater. 127, 418–424.

Tabaković, A., Post, W., Cantero, D., Copuroglu, O., Garcia, S.J., Schlangen, E., 2016. The reinforcement and healing of asphalt mastic mixtures by rejuvenator encapsulation in alginate compartmented fibres. Smart Mater. Struct. 25 (8).

Tabaković, A., Schlangen, E., 2016. Self-healing technology for asphalt pavements. Self-Heal. Mater. 285–306.

Tabaković, A., Schuyffel, L., Karač, A., Schlangen, E., 2017. An evaluation of the efficiency of compartmented alginate fibres encapsulating a rejuvenator as an asphalt pavement healing system. Appl. Sci (Basel) 7 (7).

Tan, X., Zhang, J., Guo, D., Sun, G., Zhou, Y., Zhang, W., Guan, Y., 2020. Preparation, characterization and repeated repair ability evaluation of asphalt-based crack sealant containing microencapsulated epoxy resin and curing agent. Construct. Build. Mater. 256.

Tian, Y., Zheng, M., Li, P., Zhang, J., Qiao, R., Cheng, C., Xu, H., 2020. Preparation and characterization of self-healing microcapsules of asphalt. Construct. Build. Mater. 263.

Varma, R., Balieu, R., Kringos, N., 2021. A state-of-the-art review on self-healing in asphalt materials: mechanical testing and analysis approaches. Construct. Build. Mater. 310.

Wan, P., Wu, S., Liu, Q., Wang, H., Zhao, F., Wu, J., Niu, Y., Ye, Q., 2022a. Sustained-release calcium alginate/diatomite capsules for sustainable self-healing asphalt concrete. J. Clean. Prod. 372.

Wan, P., Wu, S., Liu, Q., Zou, Y., Zhao, Z., Chen, S., 2022b. Recent advances in calcium alginate hydrogels encapsulating rejuvenator for asphalt self-healing. J. Road. Eng. 2 (3), 181–220.

Wang, H., Liu, Q., Wu, J., Wan, P., Zhao, F., 2022a. Self-healing performance of asphalt concrete with ca-alginate capsules under low service temperature conditions. Polymers (Basel) 15 (1).

Wang, H., Yuan, M., Wu, J., Wan, P., Liu, Q., 2022b. Self-healing properties of asphalt concrete with calcium alginate capsules containing different healing agents. Materials (Basel) 15 (16).

Wang, Y.-Y., Tan, Y.-Q., Lv, H.-J., Han, M.-Z., 2022c. Evaluation of rheological and self-healing properties of asphalt containing microcapsules modified with graphene. Construct. Build. Mater. 357.

Wang, Y., Hao, P., 2021. Rheological and fatigue-healing durability of asphalt containing synthesized microcapsules with refined waste oil core. Construct. Build. Mater. 274.

Wool, R., O'connor, K., 1981. A theory crack healing in polymers. J. Appl. Phys. 52 (10), 5953–5963.

Wu, D.Y., Meure, S., Solomon, D., 2008. Self-healing polymeric materials: a review of recent developments. Prog. Polym. Sci. 33 (5), 479–522.

Xie, J., Chen, J., Hu, L., Wu, S., Wang, Z., Li, M., Yang, C., 2023. Preparation, thermochromic properties and temperature controlling ability of novel pellets in ultra-thin wearing course. Construct. Build. Mater. 389.

Xu, H., Wu, S., Chen, A., Zou, Y., 2022. Influence of erosion factors (time, depths and environment) on induction heating asphalt concrete and its mechanism. J. Clean. Prod. 363.

Xu, S., Liu, X., Tabakovic, A., Schlangen, E., 2019a. Investigation of the potential use of calcium alginate capsules for self-healing in porous asphalt concrete. Materials (Basel) 12 (1).

Xu, S., Tabaković, A., Liu, X., Palin, D., Schlangen, E., 2019b. Optimization of the calcium alginate capsules for self-healing asphalt. Appl. Sci (Basel) 9 (3).

Xu, S., Tabaković, A., Liu, X., Schlangen, E., 2018. Calcium alginate capsules encapsulating rejuvenator as healing system for asphalt mastic. Construct. Build. Mater. 169, 379–387.

Xue, B., Wang, H., Pei, J., Li, R., Zhang, J., Fan, Z., 2017. Study on self-healing microcapsule containing rejuvenator for asphalt. Construct. Build. Mater. 135, 641–649.

Yamaç, Ö.E., Yilmaz, M., Yalçın, E., Kök, B.V., Norambuena-Contreras, J., Garcia, A., 2021. Self-healing of asphalt mastic using capsules containing waste oils. Construct. Build. Mater. 270.

Yang, C., Wu, S., Cui, P., Amirkhanian, S., Zhao, Z., Wang, F., Zhang, L., Wei, M., Zhou, X., Xie, J., 2022. Performance characterization and enhancement mechanism of recycled asphalt mixtures involving high RAP content and steel slag. J. Clean. Prod. 336.

Yang, C., Wu, S., Xie, J., Amirkhanian, S., Zhao, Z., Xu, H., Wang, F., Zhang, L., 2023. Development of blending model for RAP and virgin asphalt in recycled asphalt mixtures via a micron-Fe_3O_4 tracer. J. Clean. Prod. 383.

Yang, P., Gao, X., Wang, S., Su, J.-F., Wang, L.-Q., 2022. Novel waterproof bituminous coating using self-healing microcapsules containing ultraviolet light curing agent. Construct. Build. Mater. 329.

Yu, B., Wang, S., Gu, X., 2018. Estimation and uncertainty analysis of energy consumption and CO_2 emission of asphalt pavement maintenance. J. Clean. Prod. 189, 326–333.

Yu, T., Zhang, H., Wang, Y., 2020. Multi-gradient analysis of temperature self-healing of asphalt nano-cracks based on molecular simulation. Construct. Build. Mater. 250.

Yu, X., Liu, Q., Wan, P., Song, J., Wang, H., Zhao, F., Wang, Y., Wu, J., 2022. Effect of ageing on self-healing properties of asphalt concrete containing calcium alginate/attapulgite composite capsules. Materials (Basel) 15 (4).

Zahoor, M., Nizamuddin, S., Madapusi, S., Giustozzi, F., 2021. Sustainable asphalt rejuvenation using waste cooking oil: a comprehensive review. J. Clean. Prod. 278.

Zaremotekhases, F., Idris, I.I., Hassan, M.M., Mohammad, L.N., Negulescu, I.I., 2020. Effect of sodium alginate fibers encapsulating rejuvenators on the self-healing capability and cracking resistance of asphalt mixtures. J. Mater. Civ. Eng. 32 (12).

Zhang, H., Bai, Y., Cheng, F., 2018. Rheological and self-healing properties of asphalt binder containing microcapsules. Construct. Build. Mater. 187, 138–148.

Zhang, L., Hoff, I., Zhang, X., Yang, C., 2022. Investigation of the self-healing and rejuvenating properties of aged asphalt mixture containing multi-cavity Ca-alginate capsules. Construct. Build. Mater. 361.

Zhang, L., Liu, Q., Li, H., Norambuena-Contreras, J., Wu, S., Bao, S., Shu, B., 2019. Synthesis and characterization of multi-cavity Ca-alginate capsules used for self-healing in asphalt mixtures. Construct. Build. Mater. 211, 298–307.

Zhang, L., Liu, Q., Wu, S., Rao, Y., Sun, Y., Xie, J., Pan, P., 2018. Investigation of the flow and self-healing properties of UV aged asphalt binders. Construct. Build. Mater. 174, 401–409.

Zhang, X.-L., Su, J.-F., Guo, Y.-D., Wang, X.-Y., Fang, Y., Ding, Z., Han, N.-X., 2018. Novel vascular self-nourishing and self-healing hollow fibers containing oily rejuvenator for bitumen. Construct. Build. Mater. 183, 150–162.

Zhu, X., Cai, Y., Zhong, S., Zhu, J., Zhao, H., 2017. Self-healing efficiency of ferrite-filled asphalt mixture after microwave irradiation. Construct. Build. Mater. 141, 12–22.