Al-Rafidain Journal of Engineering Sciences

Journal homepage https://rjes.iq/index.php/rjes

ISSN 3005-3153 (Online)

Self-Healing in Asphalt Pavements for Enhanced Road Sustainability: Opportunities and challenges

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ARTICLE INFO

Article history:

Received	14-05-2026
Revised	14-05-2026,
Accepted	18-06-2026,
Available online	19-06-2026

Keywords:

Asphalt
Encapsulation
Healing Technology
Regeneration agents
Rejuvenator
Self-healing

ABSTRACT

Self-healing is a characteristic obtained by the asphalt mixture through production or operational conditions, the application of paving, or by modification of the components constituting the asphalt mixture. The asphalt binder is a hydrocarbon material composed of carbon chains that are bonded together to form the asphalt structure. The chemical composition of the asphalt binder can be modified, and the carbon chains enhanced to mitigate the deterioration resulting from the ageing of the asphalt binder and the volatility of its constituents. This is achieved by using an asphalt binder with a softer penetration grade and a high concentration of low molecular weight components, hence reducing volatility-induced ageing. Alternatively, the capability of the asphalt mixture for self-healing can be achieved through the incorporation of components that repair damage and rebuild cracks in the asphalt pavement, such as regeneration agents, steel fibres, or other materials.

1. Introduction

The movement of people and things is made easier by road networks, which is an essential social and economic function. For the nation's and its regions' social, economic, and political existence, the road network's operational condition is essential. 16.3 million kilometers make up the world's road network[1]. [2], 3.1 million are in China, 4.4 million are in the USA, and 5 million are in the EU. [3]. The asphalt pavement self-healing method potentially revolutionize conventional production techniques that have persisted for more than a century[2]. The design of asphalt pavement has been improved using self-healing technology during the past decade [3], [4], [5]. Technology of Self-healing offers alternative approach to maintenance of road by implementation of a built-in mechanism to heal the pavement damage by repairing the cracks autonomously. The impartial of self-healing technology is to enable or enhance the local or overall recovery of material systems after damage. Allowing or assisting material systems to recover after damage is the primary objective of self-healing technology.

It attempts to minimize damage severity and prolong or restore the service life of the affected pavement parts [6], [7], [8]. By partially mending their own microcracks, asphalt pavements can reduce fatigue damage and increase service life. Bitumen's inherent

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https://doi.org/10.61268/qmnm2391

healing properties as well as additional technologies that promote or accelerate healing are the sources of this self-healing[9], [10], [11]. Generally speaking, self-repair of asphalt mixtures include healing and sealing fractures, regaining the paving's strength, and restoring its shape. Depending on the degree of damage, the healing period, and the viscosity of the bonding asphalt, this process can be completed automatically[12],[13]. Additionally, ingredients like regenerative agents contained in capsules that are included of the asphalt mixture's composition can be employed to help or expedite the self-healing process[14], [15]

Out of all the modified bitumens examined, a regular soft bitumen was shown to be the most effective healer. Ionomers, supermolecular rubbers, and nanoparticles are examples of novel self-healing modifiers for example are not entirely advantageous for the self-healing improvement of bituminous materials after examining the changes in the material properties and the self-healing capabilities due to modifications.

The rejuvenator encapsulation methodology rejuvenates aged binder by restoring its chemical, physical, and mechanical characteristics prior to ageing. This technique represents a further advantageous form of self-healing. Researchers have shown that several types of rejuvenator containing capsules can be fabricated and that these capsules provide sufficient mechanical and thermal durability to withstand degradation in asphalt concrete pavement [16], [17], [18]. The asphalt rejuvenator is able to penetrate the pavement structure up to 2 cm due to the asphalt concrete surface layer rejuvenation.; therefore, microcracks located deeper within the pavement cannot be effectively repaired. Furthermore, such methods need on-site construction activities, which lead to traffic congestion, the need for additional new materials and an increase in CO_2 emissions[19]

[6] used calcium-alginate fibers as compartmented carriers that contained a rejuvenator, a healing agent for asphalt binder. This method made it possible to add rejuvenators to asphalt concrete mixtures in a regulated manner. A porous asphalt (PA) mixture was subjected to a Four-Point Bending Fatigue Test to determine the implanted healing system's efficacy. So the researcher reached to that the mechanical and thermal characteristics of the compartmented fibers were adequate to withstand the compaction and mixing processes of asphalt. In addition to that, the PA mixture with 5% of compartmented alginate fibers in a 70 to 30 rejuvenator to alginate ratio exhibited significant enhancement in strength, stiffness, and healing capacity as compared to the controlled mixture (i.e., PA without fibers). Microscopic investigations were also performed using Environmental Scanning Electron Microscopy (ESEM). The ESEM revealed an enhancement of internal alginate network within the capsules, indicating that the rejuvenating material is distributed in the internal structure of the porous matrix rather than being within the structure of single-shell capsule (as illustrated in Fig. 1).

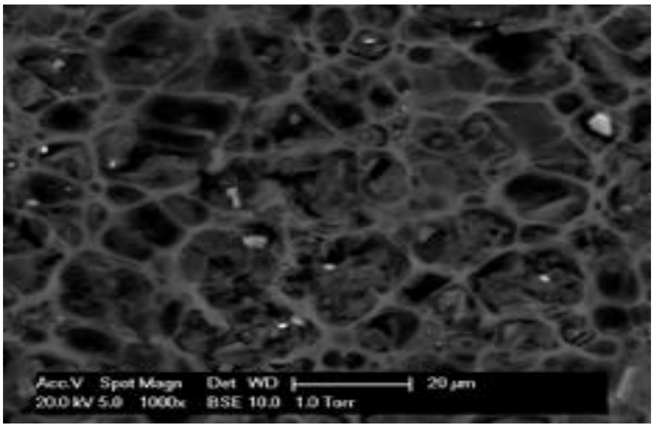

Figure 1. The cross-sectional ESEM images of calcium alginate capsules [12]

Behnia and H. Reis [20] Disk-shaped Compact Tension (DCT) experiments were used to evaluate the self-healing ability of asphalt concrete exposed to thermally induced damage. After eight freezing cycles, the study looked at how resting time affected the asphalt concrete specimens' ability to recover themselves. DCT outcomes (as illustrated in Fig. 2) revealed that the specimens with 12 hours of resting time exhibited a significant reduction in fracture severity because of repeated cooling cycles, indicating approximately 100% self-healing of thermally induced fractures in the asphalt concrete material. [2] expected improve calcium alginate capsules used with binder self-healing. The capsules of calcium alginate different alginate/rejuvenator (A/R) ratios were made, and their thermal stability and mechanical properties were assessed using compression testing and thermo gravimetric analysis (TGA). Depending on the collective investigation of thermal resistance and mechanical performance, the capsule with 30/70 value of A/R ratio illustrated an optimum formulation.

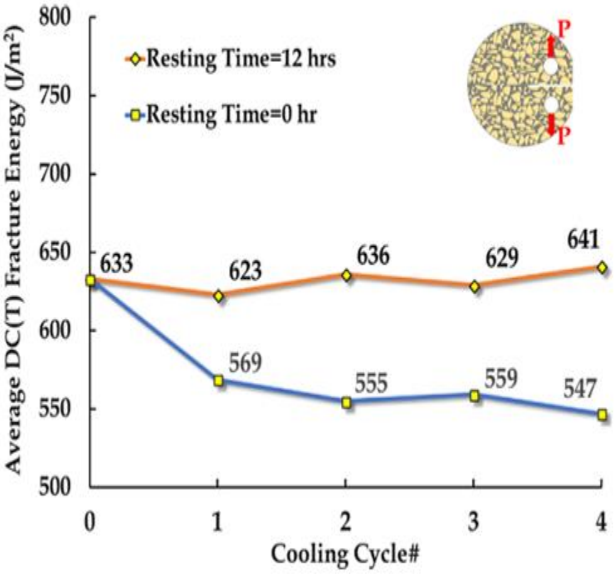

Figure 2. Effect of Resting Time between Cooling Cycles on Fracture Energy of Asphalt Concrete Materials [13].

[21] investigated that calcium alginate capsules affected porous asphalt mixes' ability to repair. They observed that the cracks in porous asphalt mixes may be repaired using calcium alginate capsules. The impact of capsules which fracture resistance for porous asphalt pavement was assessed using semi-circular bending (SCB) tests. Indirect tensile stiffness modulus (ITSM) measurements used to study the impact of the capsules on the stiffness of the porous asphalt pavement. The outcomes of the investigation showed that calcium alginate capsules improved porous asphalt concrete's healing capacity without compromising its functionality.

[22] efficiently produced calcium alginate capsules. Fig. 3. The calcium alginate capsules lack the usual core-shell structure and instead have a distinctive porous structure, with tiny rejuvenator droplets enclosed by porous media within the shell, according to the X-ray tomography image of the capsule. Thermogravimetric analysis (TGA) and micro compressive tests were used to assess the thermal stability and compressive resistance of the capsules. It proved that the calcium alginate capsules are resistant to the construction of asphalt pavement. Additionally, a three-point bending test and healing program on asphalt mastic beams were used to assess the healing result of these capsules. The findings demonstrated that asphalt mastic beams with calcium alginate capsules were appreciably more capable of healing than reference beams.

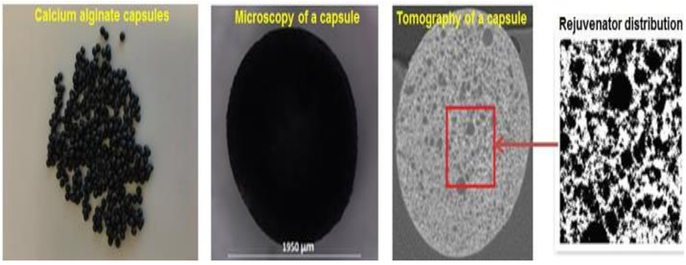

Figure 3. Calcium alginate capsules prepared by Xu et al. [15]

[23] studied the healing properties of asphalt concrete following loading cycles at various pressures using capsules containing several healing agents. For the initial time, the effect of loading pressure on calcium alginate capsules' ability to mend themselves was examined. In comparison to standard asphalt mixtures without capsules, it was discovered that asphalt mixtures containing various capsules showed increased quantities of light-weight components in binder. The concentration of light components inside the asphalt binder increased as a result of the capsules releasing more healing agents due to the increased loading pressure. [24] used a molecular dynamics model to explain how the self-healing properties of asphalt are impacted by temperature. The best healing temperature range for asphalt was found to be between 40.3 and 48.7 degrees Celsius using differential

scanning calorimetry (DSC). [25] examined the asphalt's capillary flow at different healing temperatures. Results showed that asphalt's surface energy and contact angle reduction with temperature, leading to immediate capillary flow. When paired with the additional pressure brought on by the temperature rise, asphalt's ability to mend itself is greatly increased. Asphalt pavements' self-healing mechanism is temperature-dependent and viscosity-driven. [26] demonstrated the bituminous materials' self-healing duration and temperature dependence, showing that greater healing occurs with longer healing times and higher healing temperatures.[27] examined the rheological characteristics of binders treated with organoclay, specifically their fatigue characteristics. During fatigue testing using a dynamic shear rheometer, the dissipated energy impression, ratio of dissipated energy variation, and plateau value (PV) energy were measured. It was shown that utilizing more organoclay and lowering strain levels led to higher fatigue resistance and lower PV values. [28] proposed replacing natural coarse aggregate in asphalt mixtures with electric arc furnace slag (EAFS) to create a sustainable alternative. Mechanical properties such as Marshall stability were investigated to determine self-healing effectiveness. The results showed that using EAFS in the asphalt mixture saves significant time and energy. EAFS not only achieved the highest healing results, but it also improved the mechanical properties of the mixtures. Using up to 30% of one or two sieve sizes of steel slag in place of coarse aggregate, and the findings showed that steel slag can improve the combinations' ability to heal [29]. [30] demonstrated both the fiber survival rate in the asphalt mixture and the encapsulation technique's proof of concept, which intricate embedding the fibers into the asphalt mastic mixture. Fibers including rejuvenator were created then evaluated by using Thermogravimetric Analysis (TGA) and Uniaxial Tensile Test (UTT) to demonstrate possible use of alginate as a rejuvenator encapsulating material , its capacity to endure the asphalt production process. The results of the testing demonstrated that the fibers had enough mechanical and thermal strength to endure the mixing and compaction of asphalt. The fibers' survival during the asphalt manufacturing process was confirmed by the CT scan of an asphalt mixture containing fibers, which demonstrated that the filaments were intact and undamaged. There are a lot of studies of earlier research on the self-healing properties of asphalt mixtures, but there aren't many approaches that connect the influencing factors and how they affect the road's lifespan. As a result, this study aimed to bridge this gap by offering a critical analysis of earlier studies with an emphasis on the role that self-healing components play in enhancing the asphalt mixture's performance.

2. Self-Healing Mechanism:

Aged bitumen undergoes oxidation through construction and service, converting bitumen oils to resins and resins to asphaltenes. This results in age-hardening and increased viscosity compared to new binder[31] [18]. Maltenes and saturates are components of specially designed cationic emulsions that are rejuvenators[32], [33] [2]. Its main function as a self-healing is to decrease stiffness and restore viscoelastic properties of oxidized asphalt. The longevity of the asphalt pavement could be increased by several decades with this process. However, cracks that begin at the base of the asphalt layer won't be corrected because this method only addresses the top part of the pavement. These problems can be fixed and the pavement can be healed overall by adding encapsulating rejuvenators to the asphalt pavement mix. This method's idea is that the capsules will burst and release the rejuvenator inside them due to the fracture energy at the pavement cracks. Large amounts of microcapsules added to the asphalt mix may lower pavement quality, which could lead to early pavement breakdown[34], [35] [14].

2.1. Self-healing without using additives:

Asphalt is a self-healing material[36]. By sealing tiny cracks that develop in the material during usage, asphalt pavement can regain its strength and stiffness when exposed to rest periods. Asphalt pavement develops cracks as a result of heavy traffic and bad weather. The asphalt pavement's capacity to self-repair is reduced by prolonged exposure to these circumstances. However, bitumen with a higher penetration value can restore a pavement's self-repair process[37]. Asphaltenes and maltenes (oils and resins) are combined to form asphalt binder.. At normal temperatures asphalt binder is a Visco-elastic material. As temperatures rise, the resins material that makes up the asphalt binder changes from solid to viscous, which contributes to the self-healing of the asphalt binder, as surface cracks close. However, this healing process does not affect a depth of 20-30 mm below the surface of the paving. This means that cracks at this depth do not heal and reappear on the surface when the temperature drops or due to traffic loads.

Asphalt pavements in cold or mild climates suffer from thermal cracking, resulting in transversely orientated, top-down cracks of varying lengths and widths on road surface. Thermal fatigue cracks often take various cooling cycles to form and spread across the pavement layer. Fig. 4 demonstrates that thermal stresses are greatest at the pavement surface due to the rate of temperature variation.

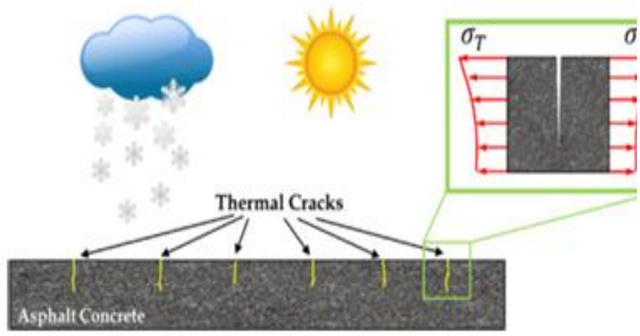

Figure 4. Typical Thermal Cracks in Asphalt Pavement [20].

Microcracks can heal themselves during the healing process, with elevated extended temperatures and rest times acting as driving forces for the self-healing mechanism (as shown in Fig. 5). Additionally, [10], [31]a number of researchers used self-healing CT scan images of asphalt binder samples at 70°C with varying healing times. They discovered that, over time, the repair process starts at the damage's surface and moves deeper, as seen in Figure (6).

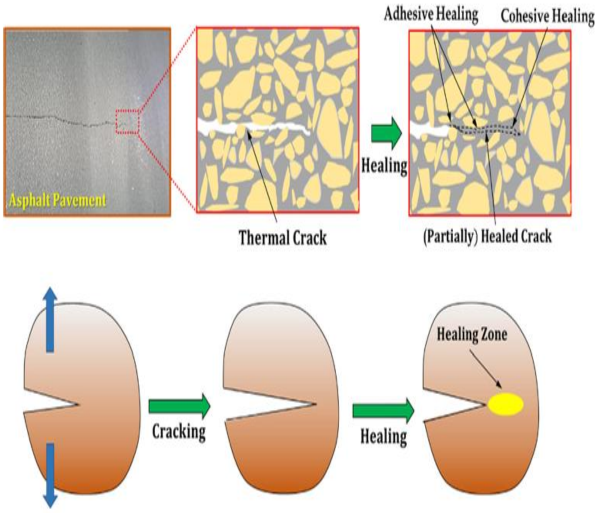

Figure 5. Schematic Illustration of Self-Healing of Thermal Cracks in Asphalt Pavements, including both Adhesive and Cohesive Healing Mechanisms occurring within the Healing Zone ahead of the Crack Tip [20]

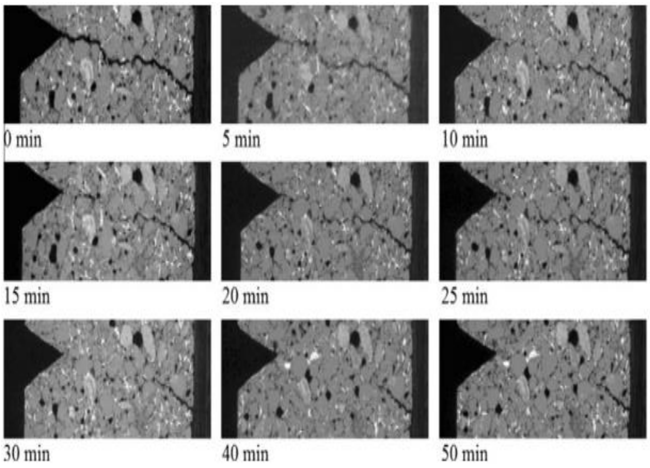

Figure 6. CT scan images of an asphalt beam during healing[10]

In adhesive healing (i.e., deboning between aggregate and mastic), the repair process initiated immediately after the damage or defect. For any successful self-healing system, it must be able to recognise damage and subsequently starting the proper repair mechanism [38]. Fischer [39] divides repair processes into two main sets, natural and synthetic self-healing, across a range of materials classes leading to determination of general rules and assumptions for designing new and application specified self-healing material schemes. Restoring the system's attributes to their initial state, that is, to its maximum potential, is known as attribute repair. Functional repair is a process of making the system work again. If complete implementation cannot be restored. When harm or degradation occurs in the asphalt mixture, self-healing begins by repairing the ensuing damage (due to ageing of the asphalt binder or traffic load), resulting from the chemical composition of bitumen. The unaged combination included an adequate amount of the maltene fraction, which helped repair cracks at both the meso- and macro-levels. However, as the mixture ages, the maltene component depletes, resulting in lower healing indices. After a period of damage, the asphalt binder gets more viscous, as more of the melanin converts to asphaltene, and the stiffness increases. As a result, there is a need to introduce materials that promote long-term self-healing, such as regeneration agents used by capsules or fibres. [40] investigates the properties of asphalt self-healing. Autogenous (intrinsic) healing and autonomic (extrinsic) healing are contrasted, and it is discovered that intrinsic healing is more promising. The study then investigates the use of models to evaluate the effectiveness of self-healing. The findings indicate that the self-healing process is significantly impacted with temperature and time.

2.2. Self-healing by using rejuvenators:

An efficient method to encapsulate and embed the rejuvenator into an asphalt pavement—that is, to revitalize the aged bitumen upon injury and then heal the damage—is to use a capsule healing system. Rejuvenators are designed cationic emulsions with maltenes and saturates. By changing the properties of the asphalt mix, a rejuvenator's main purpose is to reduce the stiffness of oxidized asphalt binder and flux the binder to increase pavement lifespan [41] . Reclamite, Paxole 1009, Cyclepave, , ACF Iterlene 1000, methanol microcapsules, epoxy microcapsules and nano materials are a few commercially available rejuvenating agents[31], [42], [43] . [44] found that a byproduct of waste cooking oil (WCO) can be employed as a binder rejuvenator.

Microcracks caused by temperature variations or traffic stresses can be sealed by asphalt paving. The aging binder is revitalized when the encapsulating rejuvenator is released (on demand). A crack discovers a microcapsule when it begins and grows. A rejuvenator, or healing agent, is released when the microcapsule is opened by the energy at crack. In order to heal a damage, the rejuvenator will soften the aged binder so that two cracked edges can come into contact and seal the crack.

Multi-cavity capsules and core-shell microcapsules make up the self-healing capsule. In-situ polymerization is the primary method used to create microcapsules with a core-shell structure (5~500 µm). Usually, asphalt rejuvenators contain melamine-formaldehyde (MF).[45], [46], methanol-melamine-formaldehyde (MMF)[47], [48], urea-formaldehyde (UF)[49], [50], or melamine-urea formaldehyde (MUF) shell materials[51], [52]. genetic capsules are films into which a Rejuvenator material is inserted to protect while preventing it from disintegrating. The Rejuvenator chemical is released when tile surfaces cracking due to variations in temperature or traffic load. The Rejuvenator agent is released to seal and repair the crack. Calcium capsules change colour and shape according to the quantity of Rejuvenator agent injected into them, as they get darker in colour with a more spherical shape with an increase in the regenerative agent as shown in Fig.7.

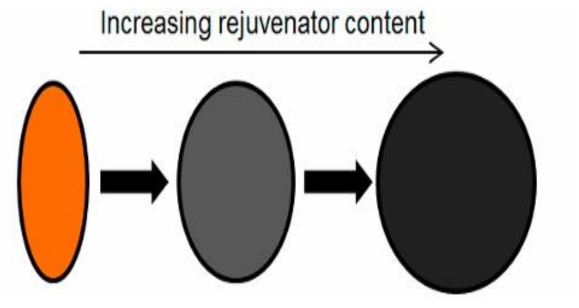

Figure 7. Microscopic images of capsules [11]

The compartmentalized fibres were created by spinning a rejuvenator emulsion suspended in a sodium alginate solution mixed with water [23]. To achieve this, Sodium alginate was dissolved in deionized water at a weight percentage of 6%. Simultaneously, the copolymer was dissolved in water at 70°C and mixed for 60 minutes to create a 2.5 weight percent poly (ethylene-alt-maleic anhydride) (PEMA) polymeric surfactant solution. To create a healing agent solution, PEMA was thawed in water and permitted to cool to room temperature (20±2°C). It was then mixed with 60% rejuvenator and 40% PEMA. Sodium alginate and PEMA/rejuvenator solutions were mixed in a rejuvenator/alginate 1/1.3 ratio. The solution mixed at 40 rpm for 20 seconds. To generate the rejuvenator-filled compartmented fibres (as shown in Fig. 7, The emulsion was spun using a standard wet spinning technique on a lab-scale, plunger-based wet spinning line [38], [39]. Fig. 8 shows compartmentalised alginate fibres.

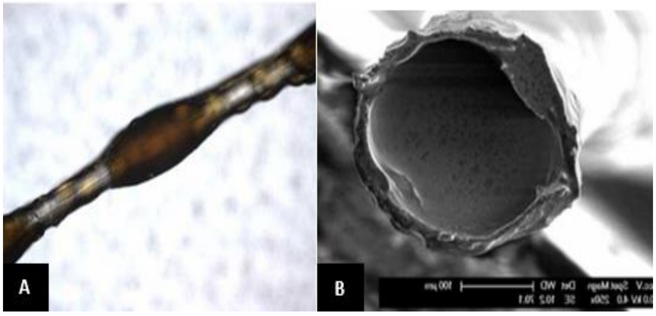

Figure 8. Compartmented Alginate Fibre: a) compartmented alginate fibre encapsulating rejuvenator [20], b) ESEM image of fibre cross section [15]

When employing fibre and capsules with an asphalt mixture, the fibres and capsules must resist pressure and not break during the procedure. As a result, some researchers proposed that the stress resistance should be one Newton higher than the aggregate used in asphalt mixtures [16].

In comparison to spherical microcapsules, this technique may have the following benefits:

- Alginate is an organic substance, so there are no risks to the environment or leaching.
- The alginate-compartmented fibers' high aspect ratio raises the possibility that the compartments may rupture and release more healing agents locally (i.e., rejuvenators).
- If alginate fibers are not damaged by fracture contact, they will eventually break down, releasing the rejuvenator while providing an alternative, self-healing trigger mechanism.

The healing agent is intended to be injected into the asphalt pavement by the embedding fibers and capsule. When a crack appears, the healing agent diffuses into aged bitumen, wets the crack surfaces, and softens aged binder, permitting it to flow and eventually cure the crack [11].

So, self-healing process occurs as follows, as shown in Fig. 9:

- Wet the two faces of the microcrack.
- Spreading the particles of the treated material on the two faces of the crack and distributing the material through the cracks to fill and treat.

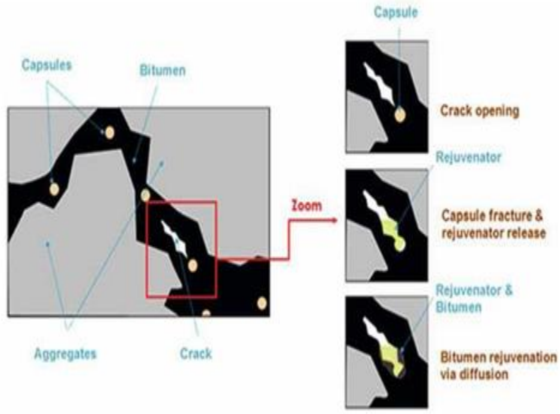

Figure 9. Rejuvenator encapsulation, a self-healing mechanism in asphalt mix [26]

Table (1): Healing studies on asphalt

References	Healing Technology	Test	Result
[6]	calcium-alginate fibres in a porous asphalt (PA) mix.	The 4-Point Bending Fatigue Test	improved strength, stiffness, and healing capabilities
[20]	Self-healing by asphalt binder characteristics	Disc-shaped Compact Tension (DCT) tests	decline in fracture of samples
[2]	calcium alginate capsules	thermogravimetric analysis (TGA)	Improve thermal stability and mechanical properties.
[21]	calcium alginate capsules in a porous asphalt (PA) mix.	Semi-circular bending (SCB) tests	enhance the healing capability of porous asphalt concrete
[22]	calcium alginate capsules	a three-point-bending test	Improve healing capability.
[23]	calcium alginate capsules	Dynamic shear rheometer	enhance asphalt concrete healing
[27]	Nanoparticles	dynamic shear rheometer	higher fatigue life
[28]	electric arc furnace slag (EAFS)	Marshall stability	improves the mixtures' mechanical properties.
[29]	steel slag	X-ray computed tomography (CT)	good wave absorption performance
[30]	alginate fibres	Thermogravimetric Analysis 19 (TGA) and Uniaxial Tensile Test (UTT)	This indicates the fibers resisted the asphalt manufacturing process.
[40]	Intrinsic Healing	X-ray computed tomography (CT)	The self-healing process is significantly impacted by temperature and time.
[53]	Microcapsules / microvasculars	The 3-Point Bending Test, X-ray tomography image.	30–90% healing, rejuvenates aged binder

3. Factor effect on asphalt mixtures self-healing:

Self-healing process in asphalt pavement influenced by a number of both internal and external factors:

- Nature of base binder used in pavements. The viscosity and chemical composition of binder used in manufacture of asphalt paving are crucial characteristics. Low asphaltene concentration with high aromatic/saturated asphalt increases self-healing qualities by reducing viscosity[54], [55], [56] .
- Density recovery, diffusion, and fatigue-life increase are all greatly accelerated by higher temperatures and longer rest periods, with declining returns and an ideal window [57], [58]
- Resting period ‹more load cycles prior to rest exacerbate microcracks and decrease future healing; intermittent loading with rest permits

modulus recovery and increases fatigue life[57], [58], [59] .

- Healing indices are lowered at the binder, interface, and mixture levels by water, salt solutions, freeze-thaw, and combination UV-pressure-salt aging. While most types of salt are harmful, some can very slightly aid in healing[60], [61], [62] .
- At the binder, mastic, and mixture scales, oxidative/weathering aging significantly impairs self-healing by increasing stiffness, molecular weight, and molecular mobility [63], [64], [65].

4. Advantages of self-healing:

A recent development in material technology is self-healing technology. It is altering the behavior of materials and signals a revolution in materials engineering. Including self-healing technology in the design process could revolutionise the processes involved in constructing and maintaining roads.

- Asphalt mixtures' fatigue life can be increased by self-healing; systems that use induction heating, encapsulated rejuvenators, or composites effectively improve fatigue resistance and postpone cracking [53], [66], [67].
- Self-healing pavements save maintenance costs, energy consumption, raw material consumption, and related CO2 emissions by decreasing fracture propagation and minimizing significant repairs[67], [68], [69].
- Under the right temperature and time circumstances, well-designed capsules or micro systems can achieve healing efficiencies of up to 80–90% of initial strength[70], [71], [72].
- The quantity of natural resources needed to maintain road systems can be decreased by using self-healing asphalt [53], [73].

5. Disadvantages of self-healing:

Regardless of the advantages of self-healing asphalt, there may be some concerns:

- Self-healing asphalt mixture is a new technology that is still in the development stage, so it is difficult to estimate its effectiveness in different conditions[74], [75].
- Self-healing asphalt uses more expensive components and technology, as well as production and installation processes, than ordinary asphalt [76], [77], [78].
- The processes for manufacturing self-healing asphalt mixtures may not be available everywhere; thus, producing this type of asphalt mixture poses a challenge in the asphalt pavement industry[75], [77].

6. Conclusion:

To create self-healing construction materials, it's important to consider both material structure and production methods. Implementing self-healing in asphalt concrete is challenging due to production conditions, structural properties of thermoplastic mixtures, and operating and climatic factors. The following conclusions are reached after this review examines asphalt's ability for self-healing:

- The essential goal of self-healing asphalt is to create a road with autonomic healing capabilities, extending its service life.
- Larger starting crack sizes result in higher healing percentages, despite having a higher healing volume constraint at the end. Samples with smaller initial crack diameters showed lower healing percentages.
- Asphalt mastic mixtures can be healed by alginate fibers encasing bitumen rejuvenators, thus represent the potential for the advancement of self-healing asphalt technology in the future.

- Higher temperatures promote quicker, more effective healing; the ideal range is close to the softening point; too low temperatures diminish benefit; longer rest periods enhance healing to an optimal degree; benefit plateaus or reverses with extended periods of time (age).
- Increasing the number of load cycles increases damage and decreases healing; adding rest intervals lengthens the fatigue life. Interface healing is hampered by water and many saline settings, but it may be somewhat aided by some carbonate environments.

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