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Novel approaches and materials for healing asphalt cracks

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Research paper - Subject review

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Premature cracks in an asphalt pavement may damage its intact structure, substantially decrease its load-bearing capacity, degrade its driving comfort and safety, and even lead to total pavement failure. This paper provides a detailed state-of-the-art review regarding the impact of new approaches and materials on the curing of asphalt cracking, along with an explanation of their advantages, deficiencies, improvement opportunities, and future perspectives. By providing this background information, this study intends to contribute to the discovery of ground-breaking technical solutions and cost-effective materials to remedy premature asphalt pavement cracks at the right place and time. Future studies are recommended to advance efforts to discover more effective, practical, cost-saving, sustainable, and eco-friendly methods and agents for healing asphalt cracks.

Key words:
self-healing, asphalt pavement, asphalt cracks, rejuvenator, heating

Pregledni rad

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Novi pristupi i materijali za sanaciju pukotina u asfaltu

Rana pojava pukotina na asfaltnom kolniku može oštetiti njegovu kvalitetu, značajno smanjiti nosivost, udobnost i sigurnost vožnje, pa čak dovesti i do potpunog kolapsa prometnice. Rad pruža detaljan pregled najnovijih pristupa i materijala za sanaciju pukotina u asfaltu, njihove prednosti i ograničenja, mogućnosti poboljšanja kvalitete asfaltnih površina te neke buduće perspektive. S tim u vezi, ovim radom autori žele pridonijeti u istraživanju i otkrivanju inovativnih tehničkih rješenja i ekonomičnih materijala za pravodobnu sanaciju ranih pukotina na asfaltnoj površini. Preporučuju se daljnja istraživanja kako bi se unaprijedili napori u otkrivanju učinkovitijih, praktičnijih, ekonomičnijih, održivih i ekološki prihvatljivih metoda i sredstava za sanaciju pukotina u asfaltu.

Ključne riječi:
samozacjeljivanje, asfaltna površina, pukotine na asfaltu, obnavljanje, zagrijavanje

1. Introduction

With the exponential growth in both passenger and freight transport on highways, governments and transportation agencies are required to meet increased driving expectations in terms of safety and comfort [1]. Hence, it is necessary to overcome the challenge of maintaining deteriorating pavement surfaces while struggling with scarce natural resources and financial cuts [2, 3]. Under normal circumstances, the first pavement surface maintenance is usually required within the first 8–12 years of construction [4]. Following this tentative period, typical distress emerging in road pavements includes rutting, shoving, stripping, ravelling, and cracking, all of which are caused by low-quality materials, poor mixture design, improper paving operation, inadequate pavement thickness, heavy traffic loads, moisture damage, and climatic conditions [5]. Although the continuous accumulation of distress driven by repetitive traffic loads is the primary reason behind crack progression, Roque et al. (2015) stated that most average wheel load applications do not significantly contribute to crack initiation, particularly during the early life of asphalt roads [6]. Instead, changes in the bituminous mixture properties throughout the life of the pavement that make the asphalt stiffer, more brittle, and less capable of healing may be one of the principal determinants of the initial cracking performance. Furthermore, some forms of asphalt cracking develop even in perfectly paved traffic-free roads owing to exposure to severe weather conditions. Hence, a thorough investigation of the underlying factors behind the initiation and progression of cracking and an elaborate inspection of the crack type classification are essential for determining which type of techniques and healing agents will be used to prevent pavement failure. However, this phenomenon and early damage have been underestimated and received little attention for a long time in the past. Beginning in the early 1990s, the substantial increase in traffic loads, traffic volumes, and tire pressure resulted in more early damages and cracks as well as additional detrimental distresses in asphalt pavements, and it is this issue that enforced pavement community to come up with the concept of "pavement preventive maintenance" [7]. Swift and scheduled pavement preventive maintenance is defined as a strategic program aimed at detecting light impairments and deteriorations, treating distress, decreasing the cost of routine maintenance and operation activities, and retarding progressive failure [8, 9]. Featured examples of preventive treatments include crack sealing, chip seals, slurry seals, microsurfacing, thin and/or ultrathin bituminous overlays, surface recycling (hot and cold in place), and installation of drainage facilities [10]. It should be noted that it is vital to select and apply the right treatment for the right-diagnosed deterioration at the right time.

This paper provides a brief overview of the characterisation of common asphalt cracks, describes the inductive factors behind cracking, and introduces recent maintenance techniques that have been applied and proposed. In addition, innovative materials and concepts that are globally utilised in pavement repair are discussed.

2. Common types of cracks

Transverse, longitudinal, edge, slippage, reflection, block, and fatigue cracking are the most prominent types of asphalt-pavement cracking. Transverse cracking may develop owing to thermal fluctuations in flexible pavement layers. Specifically, when the temperature-induced stresses are higher than the tensile strength of the asphalt material, thermal shrinkage provokes transverse cracking. Furthermore, asphalt courses consisting of binders with high consistency and hardness have been reported to be brittle and vulnerable to transverse cracking at low temperatures. Although this type of cracking is not originally related to the resilient modulus, indirect tensile strength, base-course thickness, and axle loading/tire pressures, heavy traffic may intensify existing cracks [11]. As illustrated in Figure 1.a, the transverse cracks were perpendicular to the centreline of the pavement, and the severity level was based on the width of the cracking. The severity of any transverse crack with a mean width less than or equal to 6 mm is considered "low", greater than 6 mm but less than 19 mm is considered "moderate" and greater than 19 mm is considered "high" [12]. Generally, low and moderately severe transverse cracking can be repaired with a sealant, but an asphalt layer with highly severe transverse cracking is usually removed and replaced with a new overlay.

As shown in Figure 1.b, longitudinal cracks generally emerge parallel to the centreline of the pavement. Generally considered as the precursors of fatigue cracking and/or structural failure, they are held accountable for allowing surface water infiltration and deteriorating pavement roughness. The most prominent factors contributing to this type of cracking are poor joint construction or location, cracks reflected from inferior layers, top-down cracking, segregation arising from defective/faulty paving operations, expansion of the clay subgrade, and differential settlement between embankment sections [13]. The air void content and particle size distribution also affect the permeability and crack resistance [14]. Both the severity level and maintenance approaches for the longitudinal cracking were identical to those for the transverse cracking. Roberts et al. (1996) stated that following a sealant to further prevent water penetration and ravelling, pavements with remedied low-and moderate–severe longitudinal cracks can serve satisfactorily for a long period under traffic loads [15].

Edge cracks also elongate and run in the direction of the carriageway; however, they mainly appear within the shoulder and emergency lanes of the pavement, as shown in Figure 1.c. This is attributed to the inadequate lateral support from the edges, insufficient compaction of the outer side of the road section, excessive consolidation of the underlying embankment material, poor drainage, soil drying, and heavy vegetation along the outside edge of the pavement. Fwa (2006) addressed that cracks without breakup or loss of materials is interpreted as "low severe" [12]. Cracks with limited breakup and loss of material up to 10 % is considered "moderate severe", whereas those with apparent breakup and loss of material greater than 10 % is considered "high severe". Based on the severity and extension of the edge cracks, the solution is to fill the cracks with asphalt

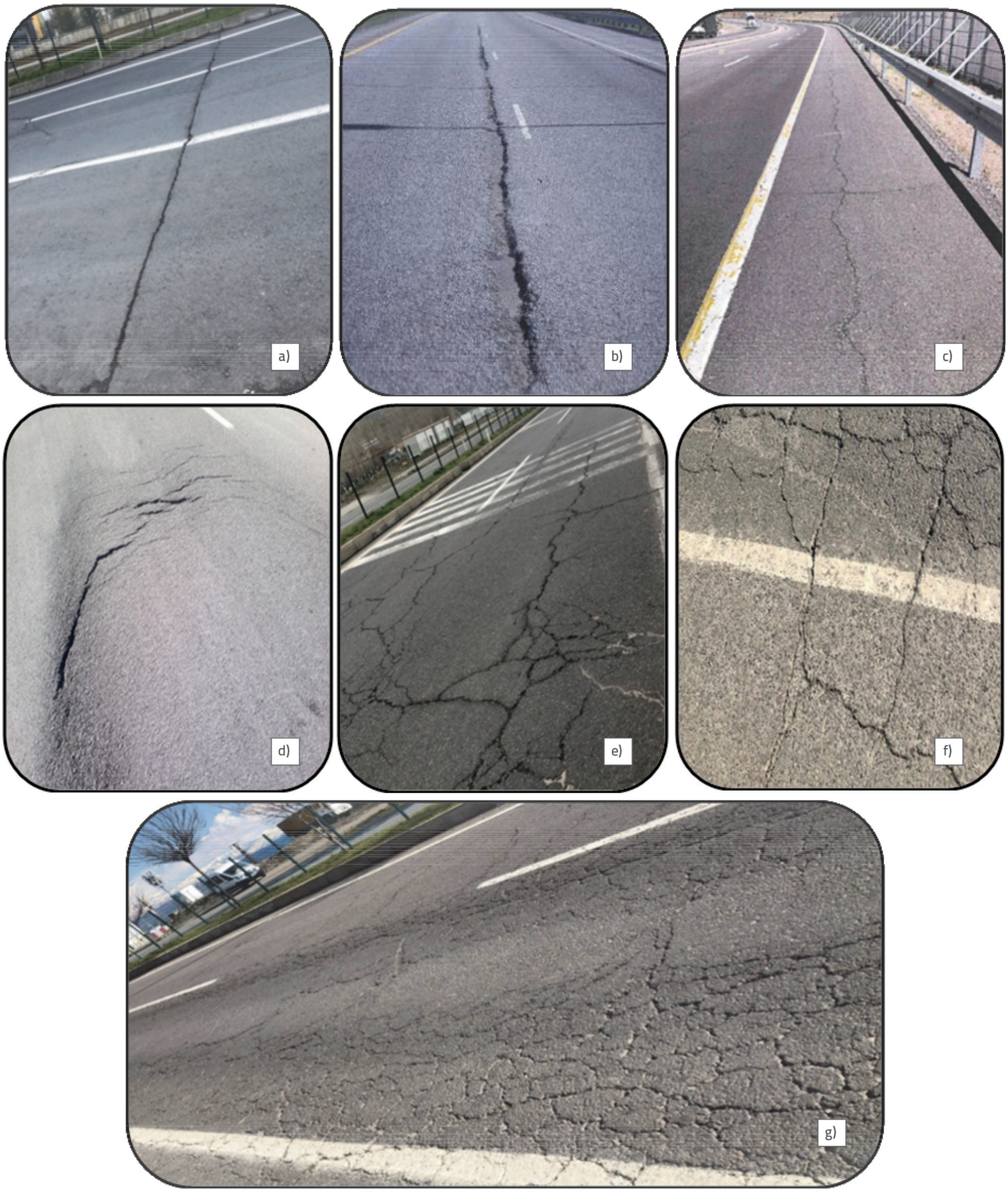

Figure 1. Asphalt cracks: a) Transverse cracking; b) Longitudinal cracking; c) Edge cracking; d) Slippage cracking; e) Reflection cracking; f) Block cracking; g) Fatigue cracking

emulsion slurry, remove nearby vegetation, improve drainage, and radically reconstruct the irreparable section as a last resort. As shown in Figure 1.d, slippage cracks are formed in a crescent shape (half-moon) and mainly occur in road sections where an effective bond is absent between the superposed asphalt layers. Improper bonds are primarily linked to defective tack coats, asphaltic aggregates with high sand content, the presence of dust, traces of clayey soil material, oil, dirt, and even surface water on the road to be paved. Considering the horizontal stresses driven by heavy traffic loads, special attention should be devoted to heavy braking pavement sections, such as intersections, pedestrian crossings, downhills, and uphills [4]. Pavements with slippage cracks are maintained by removing the affected section, cleaning the inferior layer, and applying a tack coat and a surface patch.

The reflection cracking shown in Figure 1.e was induced by the horizontal and vertical displacements of the underlying parts of an old asphaltic layer with discontinuity. Stress or strain concentrations due to traffic loads as well as shrinkage, contraction, expansion, and swelling due to severe environmental conditions are the main mechanisms behind displacements. This type of crack can also be caused by the distress propagating from the foundation or subgrade of the road and extending to the top surface. Roads with linear and confined reflective cracks can be repaired by crack sealing, whereas those with nonlinear and extensive cracks should be paved with a new asphaltic overlay. Performing other anti-reflective cracking techniques, such as binder-impregnated geotextiles, steel meshes with slurries, cold asphalt concrete overlays, and stress-absorbing membrane interlayers, yielded promising results in Poland [16]. Furthermore, the inclusion of specific binder modifiers, particularly crumb rubber, has been shown to increase pavement resistance to reflective cracks and water damage [12, 17].

Block cracking is a crisscrossing crack that splits a pavement surface into rectangular or square blocks, as shown in Figure 1.f [18]. The size of a typical cracked block generally ranges from 0.1 to 10 m^2. Even though there are distinctive mechanisms leading to the development of block cracking, the key contributors are the moisture level, fluctuations in temperature, progression of predecessor cracks (reflection cracking), and bituminous binder embrittlement. The lack of sufficient moisture in the aggregate during the first application or over time is another important factor. Extreme thermal conditions are known to significantly affect the expansion and contraction of bitumen, and freezing temperatures can result in the considerable shrinkage of coarse and fine aggregates. It should be noted that this type of cracking is not primarily associated with traffic; however, repetitive loading can exacerbate its severity. Small-sized block cracks are usually filled in and sealed with a hot-pour crack filler material, whereas large-scale cracks are fixed with a thin overlay.

The fatigue performance of bituminous materials is considered a cornerstone of asphalt mixture design in pavement engineering because it plays a direct role in the cracking behaviour and average lifespan of asphalt-paved roads [19, 20]. Fatigue cracks are caused by repetitive tire loads conducive to a set of interconnected, interlaced, and longitudinal cracks [12, 21]. They first ensue at the bottom of the bituminous layer, where the maximum tensile strains occur, and then propagate upward [22]. Once fatigue cracks reach the asphalt surface, they become very similar in appearance to an alligator's hide as evidenced in Figure 1.g; hence, they are also called "alligator cracking". This type of cracking is prominently related to the properties of the asphalt ingredients, overloading by heavy-duty vehicles, weakening of the subgrade or unbound layers, improper mixture design, and inadequate pavement thickness [4]. Cheng et al. (2002) reported that fatigue cracks are embedded within the bituminous binder and mortar or at the interface of the binder and aggregate [23]. However, it has been proven that the function of bitumen, and thereby mortar, in preventing fatigue crack initiation in the mixture is more pronounced than that of aggregates. Thus, reinforcing a straight binder with a modifier, grid, and anti-stripping agent is an effective approach at the design level to prevent fatigue cracking under repeated traffic loads [24]. Pavements with thin layers and poor subgrades, owing to their meager drainage systems, are also very vulnerable to fatigue cracking. In the case of local fatigue cracks, each asphaltic layer and unbound layers of the subgrade up to 60 cm should be removed and reconstructed along with proper drainage installation (full-depth patching technique). A new asphalt overlay that is structurally strong enough to withstand traffic loads should be placed over the entire pavement surface damaged by extensive fatigue cracking [4].

3. Recent materials and applications in Turkey

In Turkey, there are distinctive asphalt crack-curing materials with many different properties, which are grouped into cold- and hot-applied thermoplastic materials. Emulsion derivatives (bitumen emulsion and polymer-modified bitumen [PMB] emulsion) are cold-applied thermoplastic materials used to fill cracks. The self-settling of bitumen emulsion in cracks without any heat treatment is convenient during application. Owing to its low flexibility and high sensitivity to heat, it is suitable for curing passive cracks. A mixture consisting of bitumen, PMB, fibre, and rubber is an example of a hot-applied thermoplastic material. It is the most suitable material for filling active cracks because it provides the asphalt with minimum flexibility and low-temperature sensitivity. The combined use of a polymer and rubber provides flexibility to the bitumen and increases its crack-filler performance. The degree of flexibility depends mainly on the grade of the bitumen used, the percentage of rubber, how the rubber is incorporated into the bitumen (mixed or melted), and the percentage of the polymer. The addition of polymer additives to hot-applied thermoplastic crack fillers improves the properties of bitumen and its performance. Combined with its rapid preparation, fast and easy placement (good workability), and short curing time, the utilisation of this mixture in Turkey has been shown to improve adhesion, compatibility with the existing coating layer, flexibility, softening, flow, resistance to aging, adverse weather conditions, and abrasion [25].

In Turkey, the crack filling process consists of crack cutting, crack cleaning, material preparation, material placement, and drying. Crack cutting is performed to create a central, uniform, and rectangular chamber over a given crack while causing minimal damage to the surrounding coating. Cracks are cut using a diamond saw or rotary impact guide. The creation of a shear chamber allows the sealant to penetrate the cracks further. Star-shaped steel teeth form a chamber within the cracks. One of the main reasons for the failure of the crack-filling process is that the filling material does not adequately adhere to the cracked wall. Hence, after the cutting process, the dust created by the router is removed using hot or cold compressed air. Crack cleaning is conducted using hand tools, such as brushing or sweeping, air blasting, hot air blasting, or sand blasting. Spraying compressed air is an effective method for removing particles and dust. For both cleaning and drying the crack, spear-tipped hot compressed air jets are very effective. Sand blasting is performed under dry weather conditions, and air blasting is continued to remove sand from the crack chamber. Sand blasting is a specialised process that requires expensive equipment and materials. Information regarding parameters such as the material heating temperature, placement temperature, long-term heating rules, coating temperature, and humidity conditions is necessary for effective material preparation. Excessive heating can significantly change the properties of a material, whereas a low-heating process can lead to problems, such as improper workability and bonding. In Turkey, the filling material is applied in relatively mild weather in spring or autumn, as it is more difficult to maintain the material temperature during cold and hot weather. Material placement methods in Turkey range from simply filling unprepared cracks to cutting the chamber to a certain size for placing the backfill material. Reservoirs are often associated with sealing operations and simple taping is often used for filling operations, although this is not always the case. Once the filling and sealing processes begin, it is important that all processes move at a steady pace. Drying protects uncured crack-repair materials from rutting under traffic conditions. Drying materials are generally used in pavement sections where traffic is on the material before curing. Lime and sand are widely used as drying materials in Turkey [25].

4. Innovative methods and agents for healing asphalt cracks

Considered a recent milestone, self-healing not only prevents the deterioration of cracks in the asphalt mixture, but also prolongs the service life of the pavement by reducing maintenance and repair work. There are three main methods for the self-healing of asphalt pavements: rejuvenation by healing agents, heating, and other approaches, as shown in Figure 2. In this study, the effectiveness and performance of the first two methods are discussed in detail.

Healing agents are incorporated into pavements through encapsulation with microcapsules, hollow fibres, and microvascular fibres. The rejuvenators are encapsulated, which is the process of covering by a suitable shell or coating. Rejuvenators heal cracks through capsules and fibres (hollow or vascular).

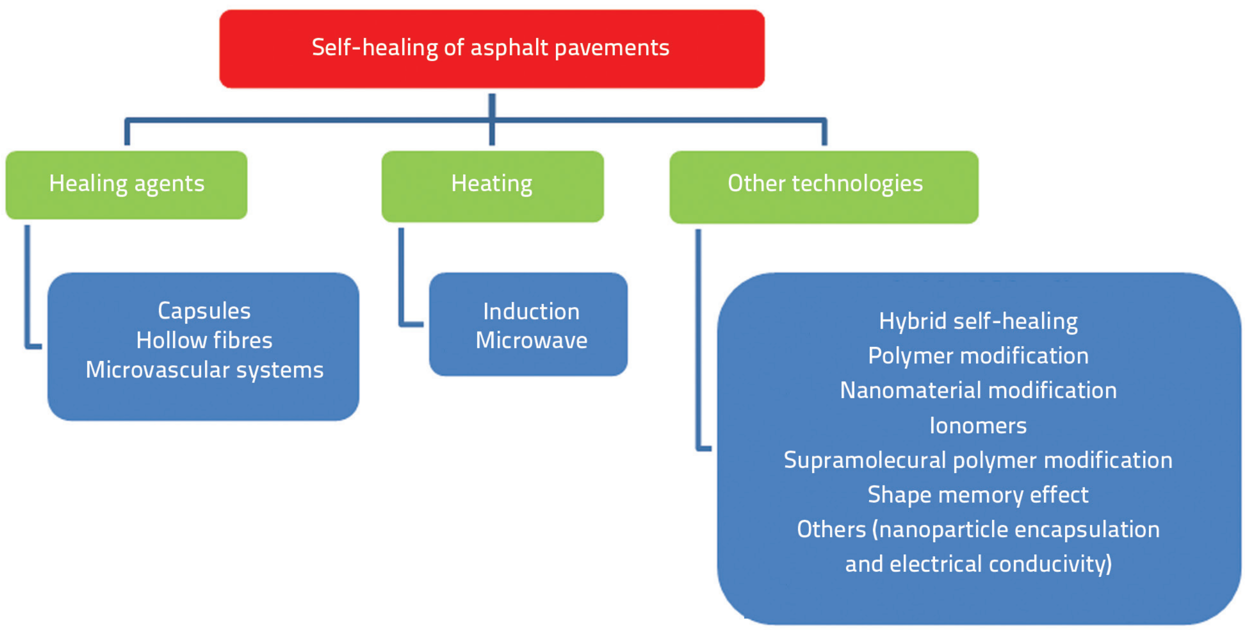

Figure 2. Self-healing methods.

Table 1. Performance of healing agents

Agent	Rejuvenator	Encapsulation	Application (*% by wt. - **time)	Healing efficiency/recovery	Reference
Capsules	Sunflower oil	CAC	0.5 % - 48 h	Fracture energy: 180.2 %	[26]
	Dimethylphenol and SBS	UFR	10 % - 24 h	Impact strength: 95 %	[27]
	Aromatic oil and polar epoxy	UFR	0.3–0.5 % - 4 h	Ductility: 90.37 %	[28]
	R20	CAC	2 % - 4 h	Bending strength: 90.1 %	[29]
	Light oils	MUF	5 % - 48 h	Tensile strength: 83.8 %	[30]
	Waste oil	UFR	4 % - 2 h	Complex modulus: > 80 %	[31]
	Sunflower oil	CAC	0.5 % - 48 h	Fatigue strength: 49.2 %	[32]
	Epoxy resin	UFR	3 % - 3 h	Ductility: 40 %	[33]
	ZS-1	UFR	3 % - 4 h	Ductility: 36.6 %	[34]
	R20	CAC	8 % - 20 h	Peak loads in SCB: 19.3 %	[35]
Hollow fibers	Bio-oil product	Hollow CAF	5 % - 144 h	Bending strength: 100 %	[36]
	21 % saturates and 67 % aromatics	Hollow CAF	5 % - 24 h	Ductility: 82.5 %	[37]
	Rejuvenator	Compartmented CAF	1.3 % - 3 h	Bending strength: 10 %	[38]
Microvasc. fibers	Oily rejuvenator	PVDF hollow fiber	1 No. of fiber - 24 h	Tensile strength: 78 %	[39-41]

** % by wt.: application amount (provided as the percentage of the binder or the mixture weight/volume) and **time: rest period.*
SBS: Styrene-butadiene-styrene, CAC: Calcium alginate capsules, UFR: Urea formaldehyde resin, MUF: Melamine urea formaldehyde, CAF: Calcium alginate fibers, PVDF: Polyvinylidene fluoride and SCB: Semicircular bending.

As a self-healing method applied to asphalt pavement, encapsulation involves the use of microcapsules filled with a healing agent that can repair cracks. Microcapsules are typically made of an agent that can withstand the stress and strain of the pavement and are filled with a liquid healing agent, such as a polymer, epoxy, or asphalt. When asphalt mixtures sustain deterioration, such as cracking or surface wear, the microcapsules rupture and release the healing agent into the damaged areas. The healing agent then fills the cracks or voids, seals the deformed area, and restores the integrity of the pavement. The healing process occurs spontaneously and significantly extends the pavement life. Encapsulation is a promising self-healing technique for asphalt mixtures because it can be easily incorporated into flexible pavements during construction and can help prevent further deformation. Additionally, encapsulation has the potential to reduce the need for costly repairs and maintenance, and can improve the overall durability and resilience of pavements. Some prominent studies revealing the impact of healing agents on the rheology and microstructure of asphalt pavements are summarised in Table 1. In this table, the agent and encapsulation type for self-healing, application amount (provided as a percentage of the binder or the mixture weight/volume), time (rest period), and percentage of healing efficiency/recovery of the application are listed.

As shown in Table 1, healing agents are categorised into three groups: capsules, hollow fibres, and microvascular fibres. Among the capsules, the highest self-healing efficiency was observed for the CAC, followed by UFR and MUF. Although the effectiveness of the fibres in self-healing varies depending on the type of fibre used, CAF is ranked highest, followed by PVDF. Among the liquid-healing agents, the highest self-healing efficiency was observed for the oily rejuvenator, followed by the polymer epoxy-based resin and bio-oil. Overall, it can be concluded that the spore-based capsules and rejuvenators showed the highest self-healing efficiency among all the healing agents.

The fundamental design criteria for capsules are the choice of an appropriate healing agent and encapsulation method. The healing agent should be determined based on its capacity to remedy cracks and repair the deformation of the aged asphalt. The most important variables to consider when choosing the best encapsulation medium are the thermal and mechanical stability to withstand the mixing and compaction efforts, and the capacity to release a healing agent when a crack initiates. A healing effectiveness of up to 38.67 % was achieved with a microcapsule dosage of 0.3 % by weight in the asphalt binder. It should be noted that the ductility of asphalt is adversely affected by increasing the microcapsule dose; hence, the ideal capsule dosage should be restricted to 0.3 to 0.5 % [42].

Table 2. Induction heating's performance for self-healing

Conductive additives	Healing temperature [°C]	Application (* % by wt. - **time)	Healing efficiency/recovery	Reference
Steel wool	112	10 % - 120 s	Fatigue strength: 100 %	[44]
Steel fiber	85	4 % - 164 s	Bending strengt: 83.9 %	[45]
Steel wool	85	4 % - 158 s	Bending strength: 82.5 %	[45]
Steel wool	85	4 % - 250 s	Fracture resistance: 78.8 %	[46]
Steel fib.-ste. slag	90	2 % - 160 s	Peak loads in SCB: 73.37 %	[47]
Steel wool	110	5 % - 600 s	Peak loads in SCB: 72 %	[48]
Steel wool	85	1,27 % - 190 s	Fatigue life extension: 64 %	[49]
Alumin. crumb	110	5 % - 1800 s	Peak loads in SCB: 62 %	[50]
Steel fiber-basalt	90	6 % - 69 s	Peak loads in SCB: 59.08 %	[47]
Steel fiber	87	6 % - 89 s	Fatigue life extension: 56.17 %	[48]
Sting steel wastes	94	5 % - 240 s	Fracture resistance: 47 %	[51]
Graphite nanofib.	105	0,.5 % - 1200 s	Bending strength: 43 %	[52]
Sand blasting ste.	90	4,4 % - 240 s	Fracture resistance: 42 %	[51]
Carbon fiber	104	0,5 % - 1200 s	Bending strength: 41.2 %	[52]
Cast steel partic.	55	6 % - 8 s	Tensile fatigue: 30 %	[53]
Carbon nanotube	108	0,5 % - 1200 s	Bending strength: 5.2 %	[52]

Self-healing by heating is conducted using induction and microwave energy methods. Heating is an effective self-healing method in flexible pavements because it can repair damage quickly and with minimal disruption to traffic flow. Additionally, it can be used to repair small cracks and prevent them from converting into larger and more extensive cracks. However, it is important to note that heating is not a permanent solution and may need to be repeated periodically to maintain pavement integrity.

Asphalt has a limited ability to heal, which is strongly correlated with temperature and rest time. However, it is not always possible to stop the traffic flow to provide a rest period, thereby enabling self-healing at ambient temperature. Thus, the concept of self-healing via induction heating has been proposed. Meijide et al. (2016) stated that induction heating is more effective than infrared heating for healing cracks [43]. However, because asphalt is an electrical insulator, it must be given electrical conductivity to fortify induction heating. Consequently, conductive additives and fibres have been added to asphalt to boost its electrical conductivity. The findings from studies on the induction and microwave methods are presented in Tables 2 and 3.

The studies with the best performance according to the conductive additives, temperature, and application type are listed from top to bottom in Table 2. The table shows that the use of steel wool fibres and conductive fillers such as carbon black and graphite can significantly enhance the self-healing performance of induction-heated asphalt pavements. These materials have high electrical conductivity, which allows for efficient heating and activation of the healing agent. This table also compares the self-healing performance of different types of conductive additives/fibers such as steel, aluminum, graphite, and carbon fibre materials. These results indicate that the use of steel-based conductive materials exhibit the best performance and can improve the self-healing efficiency of induction-heated asphalt pavements. The ideal healing temperature for induction heating process was discovered to be around 85 °C.

Table 3 compares the self-healing performance of the microwave-heated asphalt pavements. Various conductive additives, including different types of steel products, ferrite powder, fly ash, and copper tire steel, have been used in microwave-heated asphalt pavements. The highest self-healing efficiency was observed for steel products, followed by ferrite powder, fly ash, and tire steel-copper. Different frequencies and powers were used for microwave-heated asphalt pavements. Higher frequencies and powers have generally been found to be more effective in healing cracks; however, they can also lead to greater energy consumption and potential damage to pavement. The composition of asphalt mixtures can affect the self-healing performance of microwave-heated asphalt pavements. Asphalt mixtures with higher amounts of mineral fillers and polymers have been found to have better self-healing properties. The moisture content of the pavement can also affect the self-healing performance of microwave-heated asphalt pavements. Pavements with higher moisture content have been consistently found to exhibit lower self-healing performance.

Compared to induction heating, microwave heating does not require the addition of conductive materials, which is considered a significant improvement. In addition, microwave heating of the asphalt was more rapid and consistent. The

Table 3. Microwave heating's performance for self-healing

Conductive additives	Healing temperature [°C]	Application (* % by wt. - **time)	Healing efficiency / recovery	Reference
Steel slag (hot braised)	> 90	60 % - 30 s	Loads in SCB: 96.4 %	[54]
Steel wool	44	2 % - 40 s	Loads in SCB: 95 %	[55]
Steel fiber	80	6 % - 1800 s	Bending strength: 88 %	[56]
Ferrite powder	65,04	20 % - 40 s	Loads in SCB: 83.59 %	[57]
Fly ash	75 - 100	100 % - 80 - 120 s	Loads in SCB: 80 %	[58]
Recycled tire steel-copper slag	70,09	2 % - 20 s	Loads in SCB: 80 %	[59]
Steel slag	50,08	100 % - 40 s	Loads in SCB: 76.82 %	[57]
Steel shavings-copper slag	68,57	4 % - 20 s	Loads in SCB: 60 %	[59]
Steel slag	80	100 % - 1800 s	Bending strength: 57 %	[56]
Steel shavings	71,7	2 % - 40 s	Bending strength: 53.74 %	[60]
Steel slag	45,2	20 % - 80 s	Complex modulus: 39.99 %	[61]
Ferrite powder	55	80 % - 120 s	Fatigue life extension ratio-1.33	[62]

healing effectiveness was further increased by a very small amount of conductive compounds such as steel wool. In general, asphalt microwave healing performs better than induction healing.

Other self-healing technologies include hybrid self-healing [63], polymer modification [64], nanomaterial modification [65], ionomers [66], supramolecular polymer modification [67], shape memory effect [68], and other recommended technologies [69, 70]. As a combination of different self-healing methods (particularly, encapsulation and heating), hybrid self-healing is an effective technique in pavement engineering. Polymer modifications improve the durability and self-healing capacity of asphalt binders. Polymer particles in asphalt mixtures can fill cracks and prevent large-scale deterioration. A nanomaterial modification technique was implemented by adding nanomaterials to an asphalt mixture to enhance its mechanical properties and self-healing performance. Because of their unique chemical structures, ionomers can form strong intermolecular bonds that create self-healing systems for asphalt cracks. Another method is supramolecular polymer modification which involves modifying an asphalt binder with supramolecular polymers that can form reversible bonds. This phenomenon allows asphalt pavements to self-heal by reforming these bonds when subjected to deterioration. The shape memory effect entails the use of specific agents that can recover the original shape after deformation. In asphalt pavements, this technique can be used to repair specific damages by allowing the pavement to "remember" and recover its initial shape. Other recommended technologies include microbially induced calcium carbonate precipitation, rejuvenation, and geosynthetic interlayers. Each of these techniques has its own advantages and limitations, and the best approach is contingent on factors such as the specific type of pavement, nature of the cracks, and available agents for repair and maintenance.

5. Conclusions

Repetitive heavy traffic loads and harsh climatic conditions are the major factors that induce, aggravate, and worsen cracks in asphalt pavements. When the cracks at the onset are left untreated, they inevitably develop into larger deteriorations and even lead to total pavement breakdown. Consequently, governments must allocate a large budget to conduct large-scale maintenance, rehabilitation, and/or reconstruction work at a higher price to maintain the serviceability of asphalt roads. Therefore, preventive maintenance at the right place and at the right time is extremely important for extending the lifespan of pavements. The following conclusions were drawn based on the findings of this review:

- The most common types of cracks in asphalt pavements are transverse, longitudinal, edge, slippage, reflection, block, and fatigue cracking. Among them, fatigue cracking is considered one of the most detrimental deteriorations and is therefore the most challenging matter for highway engineers and associations worldwide.
- In Turkey, cold-applied emulsion derivatives are used to cure passive cracks, while hot-applied thermoplastic materials are used to heal active cracks.
- Self-healing is an effective method for increasing the service life of asphalt pavements and for providing smooth pavements that facilitate traffic safety and comfort. In addition to existing traditional methods, recent developments in self-healing have provided advantages in terms of both crack-healing efficiency and applications. In particular, rejuvenation by a healing agent (hollow fibres and capsules) and heating by induction and microwave irradiation are promising methods.
- Self-healing methods for asphalt pavements can be effective in repairing different types of cracks. Specifically,

capsules can be used to repair small cracks up to 1 mm in width, hollow fibres can repair medium-sized cracks up to several millimetres in width, and microvascular systems can repair cracks of varying widths. Induction and microwave heating are viewed as more favourable methods for repairing larger cracks and other types of asphalt pavement deformations. Hybrid self-healing is suitable for various types of cracks and prevents further deterioration. Polymer modifications and ionomers can potently repair small- to medium-sized cracks and prevent extensive deformation. Supramolecular polymer modification is generally applied to small to medium-sized cracks, whereby the shape memory effect allows the asphalt pavement to recover its original shape after being subjected to deformation. Depending on the specific situation and crack type, other recommended technologies include microbially induced calcium carbonate precipitation, rejuvenators, and geosynthetic interlayers.

- Although several applications and additives in previous studies have undergone considerable laboratory and field testing, many of these technologies are still in the early phases of development and should be tested through more exhaustive research. Future studies are recommended to advance efforts to discover more effective, practical, cost-saving, sustainable, and eco-friendly methods and agents for healing asphalt cracks.

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