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Self-healing Asphalt for Road Pavements

A. Tabaković and E. Schlangen

Abstract This paper presents a unique self-healing system for asphalt pavement which employs compartmented calcium-alginate fibres encapsulating an asphalt binder healing agent (rejuvenator). This system presents a novel method of incorporating rejuvenators into asphalt pavement mixtures. The compartmented fibres are used to distribute the rejuvenator throughout the pavement mixture, thereby overcoming some of the problems associated with alternate asphalt pavement healing methods, i.e., spherical capsules and hollow fibres. The healing system performance, when embedded in Porous Asphalt (PA) mix was tested by employing: (i) Indirect Tensile Stiffness and Strength test (ii) 4 Point Bending Fatigue test. The Semi Circular Bend (SCB) test was adopted to study crack propagation and its closure (healing) in an asphalt mix. The findings demonstrate that compartmented alginate fibres have capacity to survive asphalt mixing and compaction process. The fibres can efficiently repair damage (close the cracks), increase asphalt mix stiffness and strength. However, when the asphalt mix is subjected to fatigue loading the system does not significantly improve healing properties of the asphalt mix. Nevertheless, the findings indicate that, with further enhancement, compartmented calcium alginate fibres may present a promising new approach for the development of self-healing asphalt pavement systems.

Keywords Self-healing · Alginate fibres · Asphalt pavements · Asphalt rejuvenation

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1 Introduction

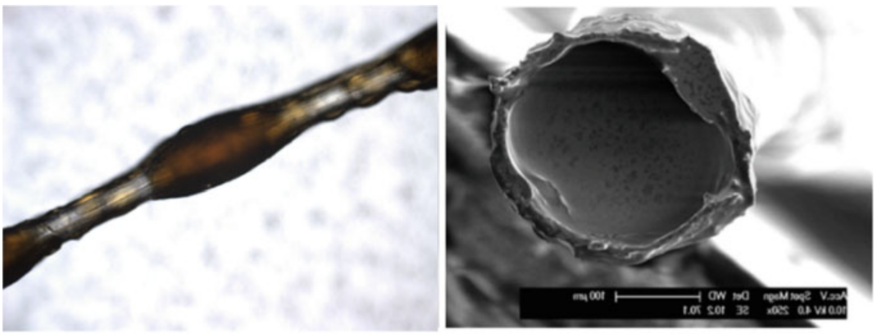
For past decade self-healing technology has been advancing asphalt pavement design (Tabaković and Schlangen 2016, Xu et al. 2018). Self-healing technology offers an alternative method for road maintenance, where the damage is repaired by an internal (implanted) healing system. The objective of self-healing technology is to enable/assist material systems to heal after damage on a local or global scale. It aims to reduce the local or global level of damage and to extend or to renew the functionality and life-time of the damaged part, system or device. To date, researchers have tested three self-healing methods for asphalt pavements as follows (Xu et al. 2018), they are: (i) induction heating, (ii) microwave heating and (iii) rejuvenator encapsulation. The rejuvenator encapsulation approach represents a more favourable method of self-healing as it allows for the rejuvenation of aged binder, i.e., enables it to return it to its original chemical, physical and mechanical properties. Researchers have demonstrated that various types of capsules containing rejuvenator can be produced and that these capsules are sufficiently thermally and mechanically stable to survive the asphalt production process (Xu et al. 2018). However, a difficulty with this approach is that large amounts of microcapsules are needed to make the process effective. The addition of large quantities of microcapsules into the asphalt mix can reduce the quality of the pavement which itself may cause premature pavement failure. Garcia et al. (2016) and Sun et al. (2015) reported that asphalt stiffness was reduced when microcapsules were added. They explained that softening of asphalt binder (viscosity reduction) was caused by the rejuvenator release. However, it is well documented (Gibney 2004) that deformation in the asphalt mix is caused by sand granulates. It is possible that the inclusion of microcapsules, sand like particles, has also contributed to increased asphalt mix deformation, i.e., rutting. Furthermore, the chemical compounds used in the production of microcapsules, such as melamine–formaldehyde (Anderson 1995), in large quantities could pose an environmental threat via leaching.

The encapsulation of rejuvenator in alginate-based compartmented fibres is explored here as a solution to these problems in asphalt mixtures. The study showed that alginate fibres have great potential as self-healing technique for asphalt pavements, i.e. they can be inserted into the asphalt mastic mix (fibres can survive asphalt mixing and compaction process) and can increase asphalt mastic mix strength by 36%. The results demonstrate that optimum rejuvenator content in the alginate fibre is of 70:30 rejuvenator/alginate ratio. The results also show that Porous Asphalt (PA) mix containing 5% of 70:30 rejuvenator/alginate ratio compartmented alginate fibres has higher strength, stiffness and better healing properties in comparison to the control asphalt mix, i.e., mix without fibres. However, 4PB fatigue test showed that self healing system does not significantly improve the healing properties of the asphalt pavement. Nevertheless, the findings indicate that, with further enhancement, compartmented calcium alginate fibres may present a promising new approach for the development of self-healing asphalt pavement systems.

2 Materials and Methods

2.1 *Compartmented Alginate Fibres Production*

The compartmented fibres were spun from an emulsion of rejuvenator suspended in a water solution of sodium alginate. A 6 wt% solution of sodium alginate in de-ionized water was prepared for this purpose. At the same time, a 2.5 wt% poly (ethylene-alt-maleic-anhydride) (PEMA) polymeric surfactant solution was prepared by dissolving the copolymer in water at 70 °C and mixing it for 60 min. After the PEMA has been dissolved in the water, it was allowed to cool to room temperature (20 ± 2 °C) and was combined with the rejuvenator, forming a healing agent solution, in PEMA/rejuvenator 1/1.5 proportion. Sodium alginate and PEMA/rejuvenator solutions were then combined in accordance with Tabaković et al. (2017a) with a 70/30 rejuvenator/alginate proportion, found to be optimal for the compartmented alginate fibres. Figure 1 illustrates compartmented alginate fibre encapsulating bitumen rejuvenator. All of the solutions were mixed at 200 rpm for 60 s. It is important to note that the stirring rate and stirring time can be used to control the size of the rejuvenator droplets in the solution and thus the size of the rejuvenator compartments (Prajer et al. 2015; Tabaković et al. 2016). The emulsions were spun with a plunger-based lab scale wet spinning line in a conventional wet spinning process (Mookhoek et al. 2012) to form the rejuvenator-filled compartmented fibres. More details on the fibre preparation and spinning process can be found elsewhere (Mookhoek et al. 2012). All chemicals used in the process were purchased from Sigma Aldrich, The Netherlands, except for the rejuvenator, Modesel R20, which was provided by Latexfalt B.V., Hoogewaard 183, 2396 AP Koudekerk aan den Rijn, The Netherlands.



a) b)

Fig. 1 Compartmented Alginate fibre, (a) compartmented alginate fibre encapsulating rejuvenator (Tabaković et al. 2016), (b) ESEM image of fibre cross section (Tabaković et al. 2017a)

2.2 *Porous Asphalt Mastic Mix Design and Mixing Procedure*

In an effort to evaluate the efficiency of the rejuvenator encapsulated in compartmented calcium alginate fibres, a Porous Asphalt (PA) mix was designed. The grading envelope Rationalisatie en Automatisering Grond-, Water-en Wegenbouw (RAW) 2005 was used to produce a PA asphalt mix typical of those used for road design (Liu 2012). The limestone used originated from a quarry in Norway, the filler material was hydrated lime (Wigro 60 K), and pen 70/100 of bitumen was used. Figure 2 illustrates the mix grading curve and illustrates how the mix compares well with the grading envelope. Table 1 summarises mix constituents and shows their proportions in the mix with and without fibres. The fibres are added in amount of 5% and 10%

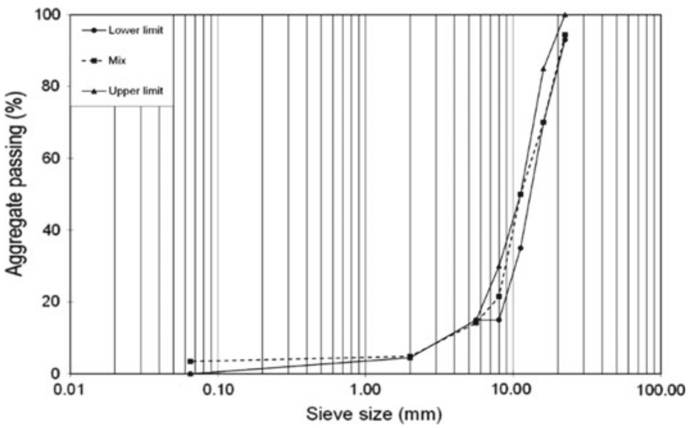


Fig. 2 Porous asphalt mix grading, grading envelope RAW 2005 (Liu 2012)

Table 1 Porous Asphalt mix design (percentage of constituent content is given by weight)

Mix constituent	Constituent size (mm)	Content in mix (%)		
		Without fibre	5% fibres	10% fibres
Gravel	22.4	20.1	20.1	20.1
	16.0	25.6	25.6	25.6
	11.2	34.8	34.8	34.8
	8.0	7.4	7.4	7.4
	6.0	6.7	6.7	6.7
Sand	2.0	0.5	0.5	0.5
Filler	<0.063	0.5	0.5	0.5
Bitumen	–	4.5	4.3	4.1
Fibre	–	0	0.23	0.45

of total bitumen content in the mix, which in total mix volume it represents 0.23% and 0.45% respectively. The aggregate mix constituent content was not changed with insertion of the fibres in the mix.

The porous asphalt mixing is described elsewhere (Tabaković et al. 2017a). In order to account for the asphalt ageing, an aging programme was developed. The ageing protocol was adopted from Kliewer et al. (1995), as follows: Long term; 15 years field ageing 4 h at 135 °C followed by 4 days at 85 °C in a forced air draft oven. Following the asphalt aging procedure, the mix was preheated to the standard asphalt mixing/compaction temperature of 160 °C and the fibres were gradually added to the mix to avoid conglomeration of the fibres within the mix. After the fibres were included in the mix, the test specimens were prepared. The air void content in the mix design was 20%, with a target density of 2.05,124 kg/cm^3 for the control mix and 2.05088 kg/cm^3 for the mix containing the fibres.

The cylindrical test specimens were compacted in accordance with IS EN 12697-31:2007 using a SERVOPAC gyratory compactor and beam test specimens were machined form an asphalt slab which was produced by using a shear box compactor in dimensions: 450 × 50 × 50 mm.

2.3 *Porous Asphalt (PA) Mix Optimisation*

The non-destructive Indirect Tensile Stiffness Modulus (ITSM) test is conducted, in accordance with EN 12697-26: 2012 and the Indirect Tensile Strength (ITS) test, in accordance with EN 12697-23: 2003 were employed in order to investigate effect of the fibres on mechanical properties of the asphalt mix and evaluate the healing efficiency of the compartmented fibres encapsulating the rejuvenator.

<u>Healing programme is as follows</u>:

(1) Three mixtures: control mix (0% fibre) and two mixtures containing 5% and 10% fibres.
(2) Tests: ITSM and ITS.
(3) Test temperature: 20 °C.
(4) Healing temperature: 20 °C.
(5) Healing time: 20 h and 40 h after initial test.

<u>Testing protocol was as follows</u>:

(1) Test samples pre-conditioning at testing temperature (20 °C).
(2) ITSM test diameter I followed by diameter II.
(3) Test specimen relaxation 2 h, followed by 1st ITS test.
(4) Positioning test specimen into healing ring and healing for 2 h.
(5) ITSM repeat–post ITS test.
(6) Positioning test specimen into healing ring and healing for additional 18 h.
(7) ITSM test-pre 2nd ITS test.
(8) 2nd ITS test.

(9) Positioning test specimen into healing ring and healing for additional 20 h.
(10) ITSM test-pre 3rd ITS test.
(11) 3rd ITS test.

2.4 SCB Test—Crack Propagation and Healing

For the SCB test, a modified NCHRP09-46 procedure was adopted. The load was applied at the centre line, above the 'V' notch, at a loading rate of 0.1 mm/s and at a temperature of 20 ± 2 °C. The support span 'S' = 80 mm, included 80% of the test specimen diameter, leaving 10 mm on each side. Figure 3 shows a schematic diagram and an actual view of the SCB test-setup. Several modifications to the test were made in the specimen geometry. The diameter of the specimen was reduced from 150 mm to 100 mm and the thickness from 50 mm to 20 mm, whereas the notch shape was changed from a straight line to the V-notch shape. These changes were employed in order to achieve full depth crack propagation throughout the depth of the test specimen, with the onset at the tip of the notch. Test samples were loaded until the crack has propagated to 25 mm or when the samples started to deform considerably. The crack propagation was measured in order to calculate the crack propagation speed. The crack propagation velocity was measured manually, by observing the crack propagation during the test, from the tip of the crack (0 mm) to the max (25 mm). For this procedure, a measuring scale was painted along the centerline of the specimen. The progression of the crack propagation was measured against the load and crosshead displacement. A special testing programme was designed, including:

- two mixtures: control mix and mix containing fibres (5%),
- test temperature of 20 ± 3 °C,
- healing temperature of 20 ± 3 °C,
- healing time of 20 and 40 h after the initial test.

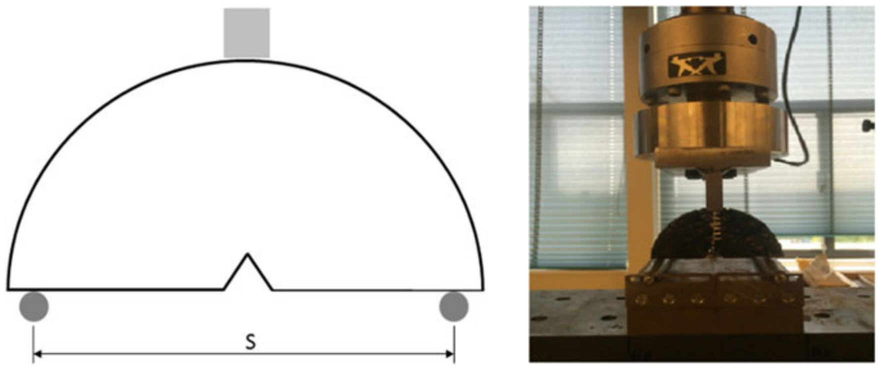


Fig. 3 Left: schematic of a SCB test specimen; right: the SCB test system set up

2.5 Four Point Bend (4PB) Test—PA Mix Fatigue Loading Performance

The Four Point Bend (4PB) Fatigue test was employed as a third test in order to evaluate of asphalt mix healing and asphalt healing system efficiency. The 4PB Fatigue test system is considered the most reliable means of evaluating asphalt pavement performance (Hartman and Gilchrist 2004). The authors believe that the healing system for an asphalt pavement is only effective for micro cracks, because large cracks, even if closed, will still deform the test specimen, thus rendering it useless and challenging the results. Hartman and Gilchrist (2004) found that microcracks result in the creation of large cracks, leading to full pavement failure. Thus, a focus of the self healing system should be the prevention of large cracks and a test system able to insert fatigue loading, simulating repetitive wheel loading, with a deflection strain control allowing small deformations and small crack formation in the test specimen is most suitable for studying the asphalt mix healing and asphalt healing system efficiency. The 4PB Fatigue test system set up is described elsewhere (Tabaković et al. 2017b). Same testing programme as for SCB test was used, except that only one healing stage was performed, 20 h after the initial test.

3 Results

3.1 Porous Asphalt Mix Fibre Content Optimisation

Figure 4a, b show the effect of fibres on the stiffness, strength and their healing (strength and stiffness recovery) abilities. The results from the test support authors statement in their previous publication (Tabaković et al. 2016) “fibres increase the asphalt mix strength and stiffness”. However, the results from this study show that higher fibre content does not necessarily improve asphalt mix healing properties. From the test results is clear that mixtures with lower amount of fibres (5%) and higher rejuvenator/alginate ratio (70:30) have best ability to recover its original stiffness and strength. The asphalt mixtures with higher fibre content (10%) had lower stiffness and strength recovery, between 10% and 20%. This could be simply due to the fact that fibres once broken cannot be repaired and thus the strength is not recovered. Therefore, samples with higher fibre content experience higher stiffness and strength loss. However, the test sample (asphalt mix) recovery efficiency might have depended on the test sample damage. During the test it was observed that some samples were damaged more than others perhaps this played a role in asphalt mix strength recovery. Therefore, further studies are needed in order to optimise asphalt mix design containing the compartmented alginate fibres encapsulating the bitumen

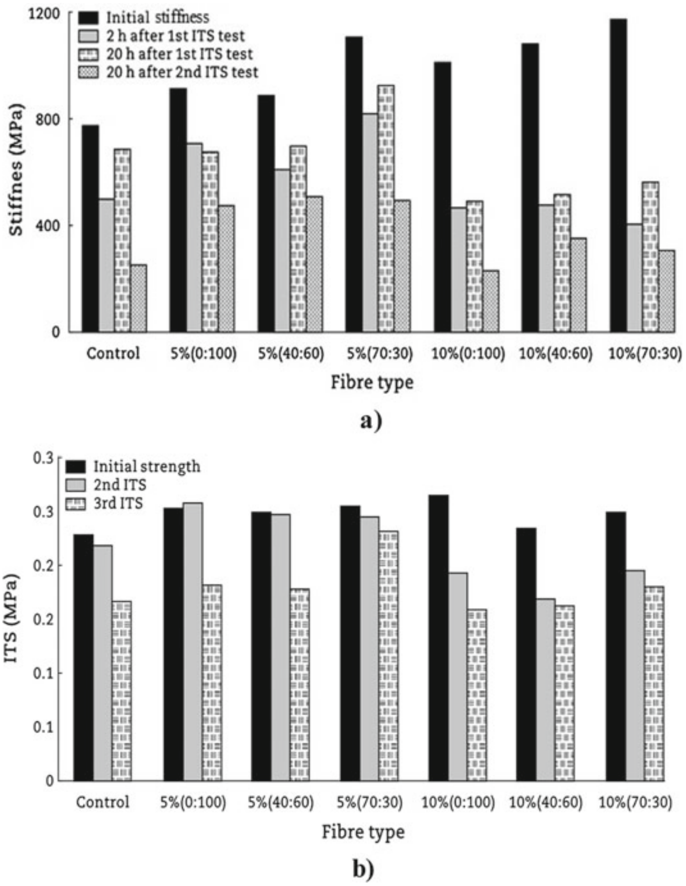


Fig. 4 Effect of fibres on: **a** asphalt mix stiffness and **b** on asphalt mix strength

rejuvenator. Nevertheless, these results confirm that compartmented fibres encapsulating the bitumen rejuvenator is viable self-healing technology for asphalt mix crack/damage repair.

3.2 SCB Test—Crack Speed

The SCB test was specifically employed in order to study crack propagation and its closure (healing) in an asphalt mix. Figure 5 illustrates successful crack closure (healing) in an asphalt test specimen containing 5% compartmented alginate fibres encapsulating the rejuvenator after 20 h of healing.

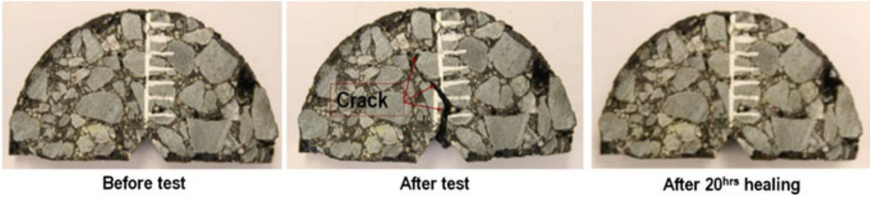


Fig. 5 SCB test specimen crack closure/healing

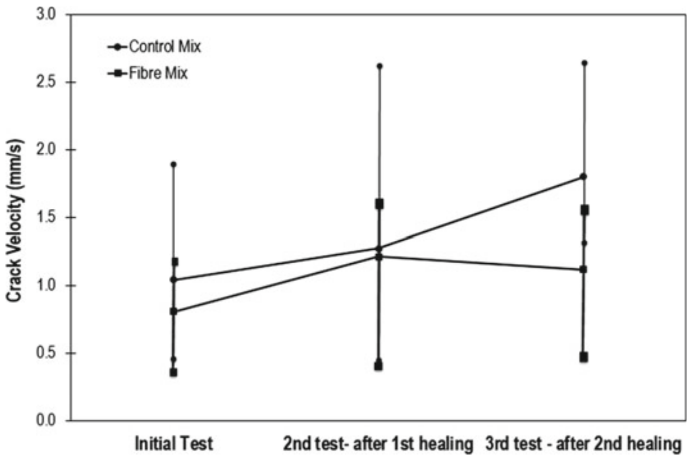
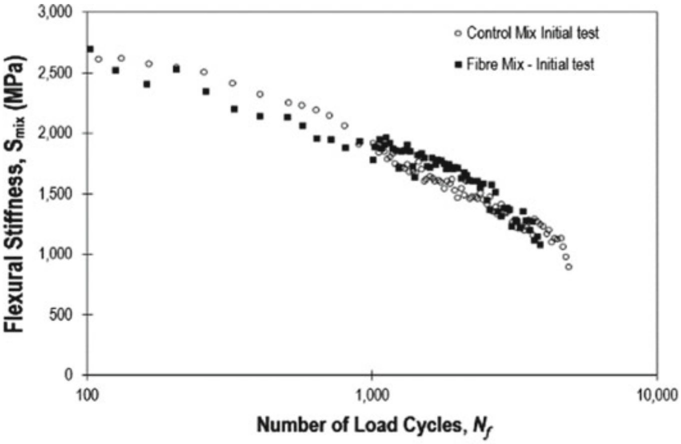


Fig. 6 Crack speed

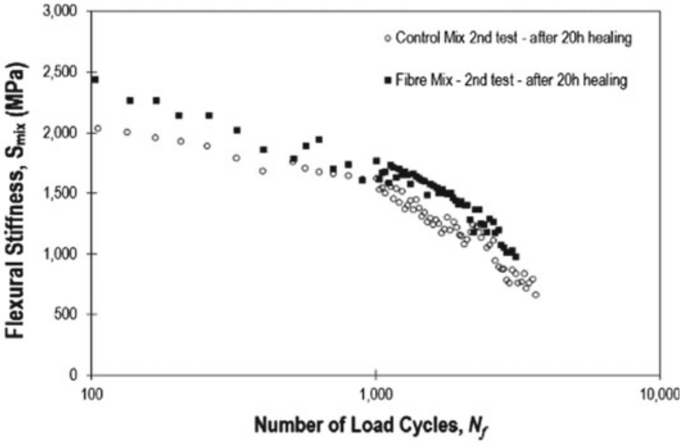
Figure 6 shows the crack propagation speed within the test sample at the initial test and after two healing stages. It is clear from the graph that the fibre mix experiences slower crack propagation. This could be due to the softened binder and reduced fracture energy available for crack propagation. This result illustrates the benefits of the compartmented fibre encapsulating a rejuvenator mix in terms of crack propagation, where the rejuvenation (softening) of aged binder can reduce the brittleness of the aged binder, thereby reducing the energy available for crack propagation.

3.3 4PB Test-Healing Efficiency

Figure 7 shows the healing efficiency of the PA control mix and fibre mix flexural stiffness (S_{mix}). The results show a very close initial test performance (Fig. 7a). However, Fig. 7b shows a higher stiffness recovery for the PA fibre mix after 20 h healing at 20 °C. These results demonstrate the potential benefits of the PA mix containing compartmented alginate fibres encapsulating the rejuvenator.



a)



b)

Fig. 7 4PBT results—healing efficiency of the fibre asphalt mix vs. control asphalt mix, **a** initial test results; **b** test results after 20 h healing at 20 °C

4 Conclusion

This study presents a unique concept self-healing system for asphalt pavement, where compartmented alginate fibres encapsulating rejuvenator (asphalt binder healing material) are employed to locally distribute the rejuvenator and to overcome the problems associated with spherical capsules and hollow fibres. The work presents proof of concept of the encapsulation process which involved embedding the fibres into the asphalt PA mixture and the survival rate of fibres in the asphalt mixture. The test results demonstrated that fibres have suitable thermal and mechanical strength to survive the asphalt mixing and compaction process. Furthermore, fibre optimisation process showed that PA mix containing 5% of 70:30 rejuvenator/alginate ratio compartmented alginate fibres has higher strength, stiffness and better healing properties in comparison to the control asphalt mix, i.e. mix without fibres. SCB test demonstrated that system has capacity to close (heal) crack and also to reduce crack propagation speed after the healing period. However, 4PB fatigue test showed that self-healing system does not significantly improve the healing properties of the asphalt pavement. Nevertheless, the findings indicate that, with further enhancement, compartmented calcium alginate fibres may present a promising new approach for the development of self-healing asphalt pavement systems.

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