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DOI
10.1016/j.conbuildmat.2025.143054

Publication date
2025

Document Version
Final published version

Published in
Construction and Building Materials

Construction and Building Materials 492 (2025) 143054

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

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ARTICLE INFO

Keywords:
Self-healing asphalt
SMA
Induction heating
Alginate capsules
Conductive capsules

ABSTRACT

The concept of self-healing asphalt has been developed to implement an extrinsic crack repair system, reduce maintenance efforts, and extend the service life of asphalt pavements. Various self-healing asphalt methods have been proposed and demonstrated, however, it is difficult to compare and finalize an optimum self-healing design for an upscaled application. To provide a better understanding of the prospects of each self-healing technology, this study investigates the physical properties and ranks the healing efficiency of each self-healing asphalt technology. Four self-healing systems were investigated, including alginate capsule system, conductive alginate capsule system, induction system, and a hybrid system (alginate capsule & induction). Laboratory tests, including Indirect Tensile test (ITT), Water Sensitivity test (WS), Binder Drainage test (BD), Triaxial test, and Semi-circular Bending test (SCB), were conducted to assess the physical performance of the asphalt mixtures. The healing efficiency of each mix was evaluated with a SCB bending and healing program. The results indicate that the addition of self-healing additives affects the physical properties of the SMA mix. The capsules reduce the mixture strength, stiffness and high-temperature stability, while the steel fibers have the opposite effect. The healing efficiency results show that the capsule healing system and conductive capsule healing system can be repeated twice, while the induction system and hybrid healing system showed a healing index above 60 % in all eight bending-healing cycles, demonstrating a promising and durable healing effect for the SMA mix.

1. Introduction

Asphalt pavement is one of the most popular surfacing materials for roadway traffic [1]. Energy consumptions and pollutants are widely recognized during the mixing, production, transportation, compaction, maintenance and recycling of asphalt concrete [2,3]. In recent decades, with the rapid growing of the worldwide asphalt road network, the maintenance work load keeps increasing every year which results in a significant rise in budget and environmental burdens [4,5]. Building a more resilient and sustainable road infrastructure has attracted more attention, and become one of the key strategies minimize the environmental impact of an asphalt pavement in its life cycle [6–8].

The concept of self-healing asphalt aims to develop a sustainable asphalt pavement maintenance process that allows the crack closure, allowing rapid asphalt pavement damage repair and recovery of its physical and mechanical properties. Extrinsic asphalt self-healing process will allow reduction in the asphalt pavement roads maintenance work [9–13]. To achieve this, various self-healing asphalt techniques were developed, which mainly adopts thermally induced methods, in-situ rejuvenation methods or hybrid methods that combines the advantages of several self-healing asphalt techniques [14–16].

The thermally induced healing methods follow the heating-healing principle, closing cracks in asphalt mixtures by melting the surrounding asphalt with external heating equipment such as electromagnetic

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https://doi.org/10.1016/j.conbuildmat.2025.143054
Received 8 November 2024; Received in revised form 8 April 2025; Accepted 5 August 2025
Available online 11 August 2025

induction and microwave [17–19]. The induction heating method heats up the conductive additives in asphalt mixture via alternating magnetic field, therefore melt the asphalt and effectively heal the crack to recover up to 80 % of its initial strength [20]. The microwave heating method can heat up the asphalt mixture within 30 s and heal the crack at deeper locations. However, the gradient heating effect of induction heating and safety concerns from microwave operation limit their application in in-situ crack repairing [21, 22]. Besides, both heating methods cannot reverse the asphalt aging process, therefore the healed asphalt mixture prone is to cracking in the long-term service life [23].

The in-situ rejuvenation method involves embedding an asphalt rejuvenator (healing agent) within the asphalt mix in a 'capsule' system. The rejuvenator is released when needed to refresh the aged binder and close the cracks [11, 24, 25]. For this purpose, various types of capsules were developed, such as epoxy capsule, alginate capsules, Malamine-Formaldehyde microcapsules, etc. [25–28]. Bio-based alginate capsules attract more and more attention due to its advantage in low price, high-temperature resistance and multiple release potential [29–32]. The in-situ rejuvenation method can rejuvenate the aged binder to recover its visco-elastic performance, however, the capsule healing method usually has limited strength recovery rate and may face obstacles to provide sufficient capsules for upscaling [11, 28].

Recently, the hybrid asphalt healing system was proposed, combining enhanced crack repairing and aged binder rejuvenation, which significantly improved the durability of self-healing asphalt, providing a more promising prospect for further application [23, 33]. It was also reported that some dual healing methods, such as conductive capsules encapsulating ferrite particles and rejuvenator, can stimulate the rejuvenator releasing through microwave heating [34]. Although hybrid healing system showed huge prospect in effective strength recovery and long-term healing, further optimization is needed to balance the involved healing actions and maximize the overall healing effect.

Besides, self-healing asphalt technologies still faces difficulties in upscaling such as mainly about energy efficiency and equipment upgrading, have limited their widespread adoption [35]. For the thermally induced methods, on-site microwave or electromagnetic induction equipment needs to provide sufficient heating speed while considering safety and energy consumption [35]. For the in-situ rejuvenation methods, a stable upscaled capsule production line and reduced costs are needed [36]. As a result, these challenges require industrial upgrades in equipment related to cost reduction, quality control, and safety & environment concerns [11].

This paper presents the laboratory research work from the 'Self-healing Asphalt Pavement Joints' (SHAPJ) project funded by Transport Infrastructure Ireland. The main objective of this work is to design and optimize the self-healing system for SMA-10 mix through laboratory testing and implement the most efficient self-healing design in trial-sectional testing site in a further stage. To this aim, SMA-10 asphalt mixes with various self-healing technologies (induction, rejuvenator encapsulation, and hybrid) were designed first. Then, the asphalt mixture samples were prepared and the physical properties including void content, density, indirect tensile strength, indirect tensile stiffness, water sensitivity, binder drainage and triaxial test were investigated to ensure the workability of the asphalt mix. Subsequently, the healing efficiency of various self-healing asphalt mix was evaluated and ranked through a repeated semi-circular bending and healing test program.

2. Materials and sample preparation

2.1. Alginate capsules and steel fibers

The sodium alginate salt, calcium chloride hexahydrate and magnetite powder are commercially available products. As an environmentally friendly and economically viable alternative, soybean oil is used as the bio-rejuvenator in this study. The information for materials used in the capsule preparation process is presented in Table 1.

Table 1
The information of materials used in the capsule preparation.

Materials	Producer and specification
Alginic acid sodium salt	Sigma-Aldrich, Product No. 180947
Calcium chloride hexahydrate	Sigma-Aldrich, Product No. 442909
Soybean oil	Bleumarine Bretania, Soy Bean Oil
Magnetite powder	Inoxia Ltd., EC 215–169–8 Purity Fe_3O_4 > 98.1 % and SiO_2 < 0.3 %, Density 4.6 g/cm^3

Fig. 2 illustrates the production process of the calcium alginate capsules encapsulating rejuvenator. The calcium alginate capsules were produced from an emulsion of a rejuvenator suspended solution of sodium alginate. To this aim, 6 wt% sodium alginate solution was prepared. Then the sodium alginate and rejuvenator solutions were mixed together to form a capsule solution based on an alginate/rejuvenator ratio of 30/70 which was determined as the optimum ratio for alginate capsules in previous study [37] (Fig. 1a). The mixed solution was stirred for 30 mins at the rate of 100 rpm until a homogeneous and stable phase (Fig. 1b). Afterwards, the capsule solution was pumped through multiple outlets and the beads dropwise into the $CaCl_2$ solution to form wet capsules (Fig. 1c) [38]. Finally, the calcium alginate capsules can be acquired after drying in an oven. The upgraded capsule production setup significantly enhanced manufacturing efficiency, increasing productivity to up to 5 kg of calcium alginate capsules per day. This improvement ensures a sufficient supply of capsules for up-scaled applications, including trial sectional pavement testing. It also allows for continuous and consistent production, maintaining uniform capsule quality.

Following the same principle, the conductive alginate capsules were

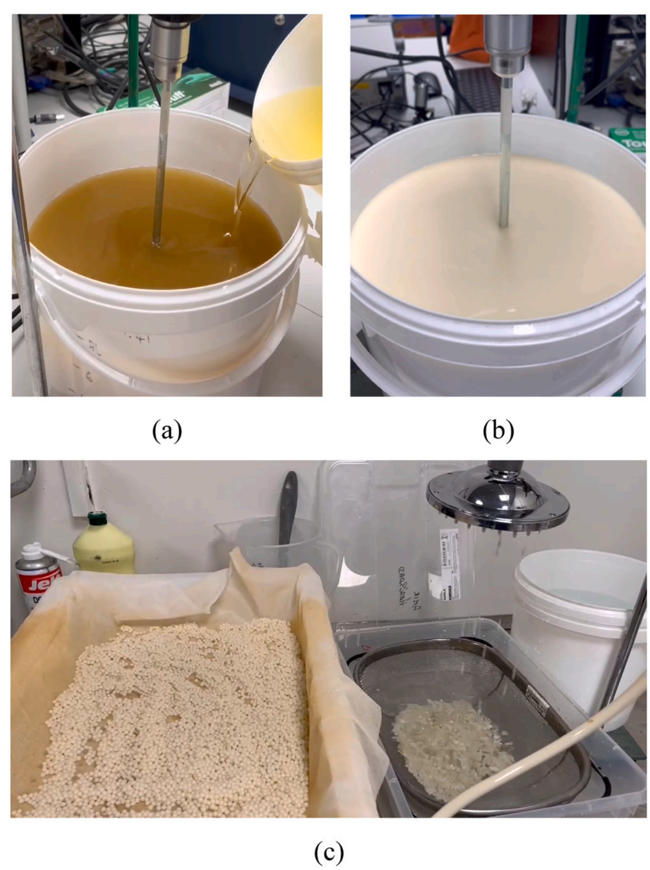

Fig. 1. Up-scaled calcium alginate capsule production setup: (a) sodium alginate mixed with rejuvenator, (b) the homogeneous capsule solution and (c) capsule formation and collection.

prepared, by mixing the conductive particles (iron powder) into the alginate-oil solutions with a ratio of 20:80 [39]. Fig. 2 shows the (a) alginate capsule, (b) conductive capsule and (c) steel fibers which were used to build up the self-healing systems in asphalt. All work was carried out at TUDelft. Alginate capsules had an average diameter of 2.74 mm and conductive alginate capsules had an average diameter of 2.82 mm. The steel fibers had a density of 7.6 g/cm^3, an average length of 1.4 mm, and a diameter of 40 μm.

2.2. Self-healing mix design and sample preparation

The asphalt mix design in this study followed a typical asphalt pavement joint mix design SMA-10 (EN13108–5). Table 2 shows the self-healing system design for SMA-10 mix. Four different self-healing systems were implemented in the asphalt mix: the capsule system (C), the conductive capsule system (CC), the induction system (I), and the capsule-induction (hybrid) system (CI). To determine the optimum self-healing design for SMA-10 mix, four different capsule/conductive capsule contents (0.2 %, 0.4 %, 0.6 %, 0.8 %) and four different steel fiber contents (1 %, 1.5 %, 2 %, 2.5 %) were investigated. While for the hybrid system, the steel fiber content kept at 2.5 % and capsule content ranges from 0.2 % to 0.8 %. These values were referred to the existing research on self-healing asphalt [35, 40].

The aggregates, sand, asphalt, cellulose fibers, and filler were provided by Roadstone, Ireland. Specifically, the aggregate type was limestone (density 2700 kg/m^3), the sand used was crushed river sand (density 2658 kg/m^3), the cellulose fibers were wood cellulose fibers, and the filler was limestone powder. The asphalt content for all the mix was fixed at 5.8 % of the total weight. In general, polymer modified asphalt PMB is used in SMA-10 mix design. However, considering the in-situ rejuvenation function from the capsules, all the self-healing asphalt mix design followed a neat PEN 40/60 asphalt based SMA-10 mix. As such, the PEN based mix and PMB (SBS modified asphalt, PMB 65, EN14023) based mix without any self-healing components were used as reference mix. The self-healing components used in this project, including calcium alginate capsules(C), conductive capsules (CC) and steel fibers (SF) have a diameter around 1–3 mm, so they were added to replace the composition of sand.

The aggregates, filler, cellulose fiber, asphalt and self-healing components were mixed in a drum mixer and then compacted with a gyratory compactor following EN 12697–31. In this study, sufficient amount of asphalt mixture samples was prepared to ensure at least six parallel samples were tested and analyzed, and all the experimental conditions for each group are ensured to be consistent.

3. Test methods

3.1. Void content and bulk density

The void content and bulk density of the asphalt samples was measured and calculated following EN 12697–8 and EN 12697–7, respectively.

Table 2
Self-healing system design for SMA mix.

Self-healing Systems	Sample groups	Calcium alginate capsules (wt%)	Conductive capsules (wt%)	Steel fibers (wt%)
Capsule System (C)	C1	0.2	-	-
	C2	0.4	-	-
	C3	0.6	-	-
	C4	0.8	-	-
Conductive Capsule System (CC)	CC1	-	0.2	-
	CC2	-	0.4	-
	CC3	-	0.6	-
	CC4	-	0.8	-
Induction System (I)	I1	-	-	1
	I2	-	-	1.5
	I3	-	-	2
	I4	-	-	2.5
Capsule-induction (Hybrid) System (CI)	CI1	0.2	-	2.5
	CI2	0.4	-	2.5
	CI3	0.6	-	2.5
	CI4	0.8	-	2.5
Reference mix	PEN-Ref	-	-	-
	PMB-Ref	-	-	-

3.2. Indirect tensile test

The indirect tensile stiffness tests (ITS) were performed following EN 12697–26 [41]. Fig. 3 presents the test setup which shows the test sample, loading frame and the displacement transducer (LVDT). Asphalt samples were tested under 20°C in a temperature chamber and loaded with four different frequencies (1 Hz, 2 Hz, 4 Hz and 8 Hz). The indirect tensile strength tests (ITT) were performed following EN 12697–23 [42]. A UTM was employed for the ITT testing and the tests were carried out at 5°C with a loading speed of 0.85 mm/s.

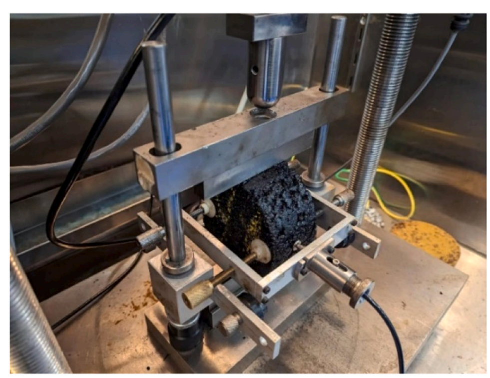

Fig. 3. The indirect tensile test setup.

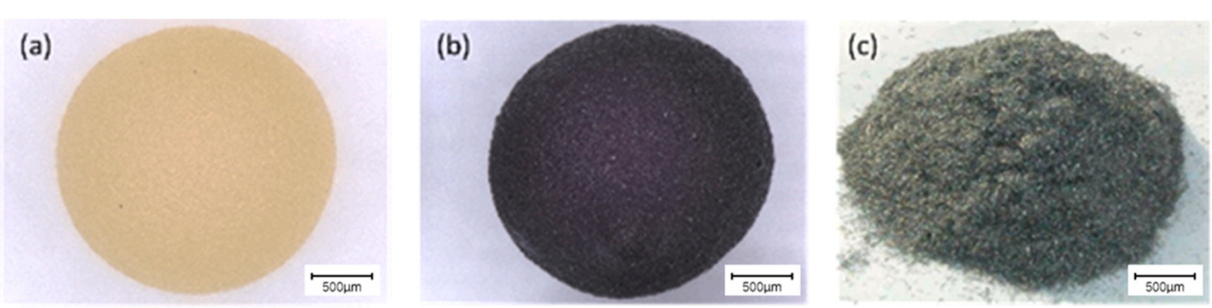

Fig. 2. Microscopy images of the self-healing additives in this project: (a) calcium alginate capsule, (b) conductive capsule and (c) steel fibers.

3.3. Water sensitivity test

The water sensitivity tests were performed following EN 12697–12. The asphalt samples were immersed in water, exposed to vacuum and conditioned in 40°C water for 72 h. The water sensitivity (WS) of the asphalt samples can be acquired by measuring the indirect tensile strength of asphalt samples before and after the water immersion test, following Eq. 1.

$$WS = 100 - \frac{ITS_w}{ITS_d} \times 100\% \tag{1}$$

Where:

ITS_w = Indirect tensile strength of the wet, conditioned specimen (kPa);

ITS_d = Indirect tensile strength of the dry specimen (kPa).

WS = Water sensitivity (%).

3.4. Binder drainage test

Binder drainage property represents the asphalt loss in the transport of the mix from the asphalt plant (production) to the site plays a key role in understanding the rutting resistance and moisture damage susceptibility of asphalt pavement. The binder drainage tests were performed was used to understand whether the proposed self-healing mixtures comply sufficiently to limits for binder content within the mix following EN 12697–18. Fig. 4 shows the glass beakers that were used to contain the asphalt mixture sample (left) and the drained binder on it (right).

3.5. Triaxial test

A Triaxial test was undertaken to help understand the high temperature properties of each asphalt mixture by subjecting them to cyclic compression tests under confinement. The samples in this case were 100 mm +/- 2 mm in height and 100 mm +/- 2 mm in diameter. A taller sample height was decided to mitigate the effects of friction on the test results, and the samples were polished to ensure a flat surface. In each case, the samples were confined in an airtight flexible polymer sleeve with rubber seals at either end and subjected to a cyclic vertical load induced by a force transducer. In this case, 10,000 loading cycles were used at 40 ℃ to determine the creep performance of each mixture by measuring sample deformation. The confinement pressure was set to 50kPa and the loading frequency was 1 Hz. The test setup is depicted in Fig. 5.

Fig. 4. The binder drainage test photos: the asphalt mixture samples weighing on a pan (left) and the beaker used in this project contained asphalt residue after oven curing (right).

3.6. Semi-circular sample preparation

Asphalt cylinder specimens were aged in an oven following the asphalt mixture long-term ageing procedure in AASHTO R30. The samples were first cured under 135°C for 4 h, followed by a curing period of 120 h at the temperature of 85°C, and this simulates 5–10 years of ageing in the field. Fig. 6 shows the SCB test specimen (a and b), the test setup (c) and a sample after testing (d). The SCB specimen has a diameter of 100 mm, a height of 50 mm, a depth of 50 mm and a 10 × 2 mm notch in the middle of the specimen.

3.7. Induction heating procedure

Induction heating test were performed on semi-circular asphalt test specimens with 6 % steel fibers to design and determine the optimum induction heating program for the self-healing SMA-10 mix. Fig. 7 shows the induction heating setup and the thermal camera to record temperature changes during the induction heating process. Aimed to achieve a homogeneous heating-healing effect, the induction heating test were performed on both sides of the SCB specimen in the two steps:

•Step 1. Once the induction heating starts, the alternating current within the coil generates an alternating electromagnetic field, leading to a gradual temperature increase of the SCB specimen from the sample surface to the middle. This step lasted for 90 s.

•Step 2. After one side heating was completed, the SCB specimen was turned over and the induction heating was applied on the other side for 60 s. Finally, the infrared image (Fig. 7b) shows the SCB specimen, with two-sided heating can achieve a uniform distribution of temperature about 85°C.

3.8. Bending and healing program

The crack healing effect is the most reported function of induction heating. The asphalt crack healing with induction heating is usually investigated following a bending and healing program which is based on Three-Point-Bending (3PB) test or Semi-Circular-Bending (SCB) test. The general principle of this program is presented in Fig. 8.

In this program, a bending-healing cycle includes a destructive SCB bending test and a healing action. The healing action was taken based on the built-in self-healing system for each asphalt mix, in which the capsule system and two reference mixes were cured in a temperature chamber at 23°C for 24 h, while conductive capsule system, induction system and the hybrid system were healed with induction heating procedure and then cured in a temperature chamber at 23°C for 24 h.

The healing index can be calculated with Eq. 2. The SCB test is employed as the bending test for the bending and healing program in this project.

$$HI = \frac{C_x}{C_1} \times 100\% \tag{2}$$

Where:

HI is the healing index (%),

C_1 is the initial bending test result;

C_x is the bending test result measured from the x testing cycle.

4. Results and discussions

4.1. Void content and bulk density

Fig. 9 shows the void content of different asphalt mixtures. In general, the addition of self-healing additives, namely calcium alginate capsules, conductive capsules and steel fibers may contribute to a higher void content compared to the PEN_Ref mixture. The void content results for induction healing mixtures are significantly higher, which are all beyond 8 %. While for Capsule System and Conductive Capsule System,

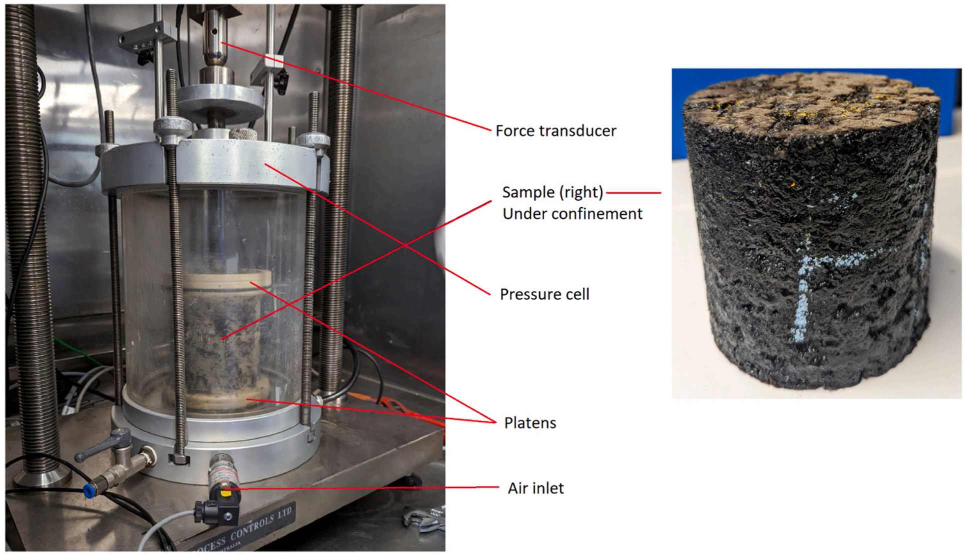

Fig. 5. Triaxial test setup, using cylindrical samples of 100 mm by 100 mm.

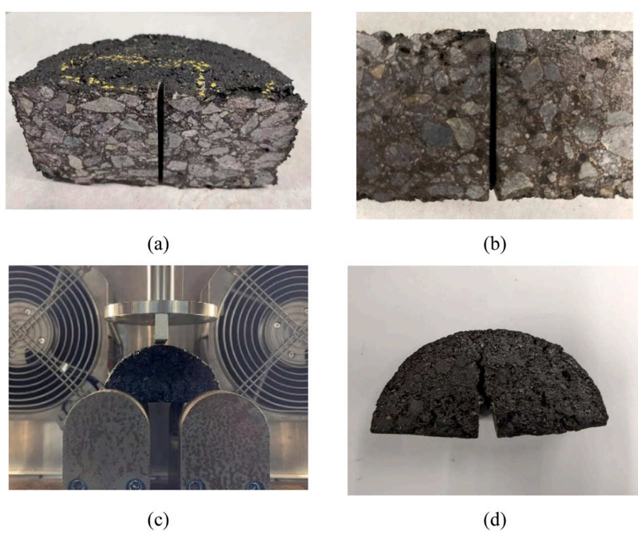

Fig. 6. The SCB test specimen and setup: (a) SCB test specimen (top view), (b) SCB test specimen front view, (c) the SCB test setup and (d) a sample after testing.

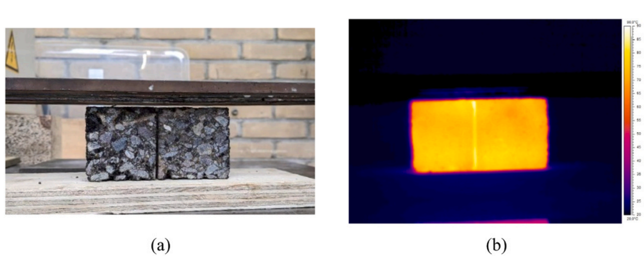

Fig. 7. Induction heating test setup: (a) SCB specimen under induction coil and (b) the SCB specimen after induction heating.

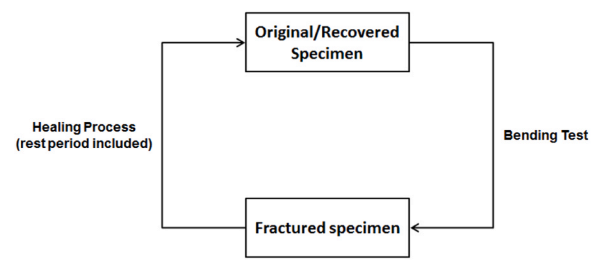

Fig. 8. General principle of bending and healing program used for crack healing efficiency evaluation.

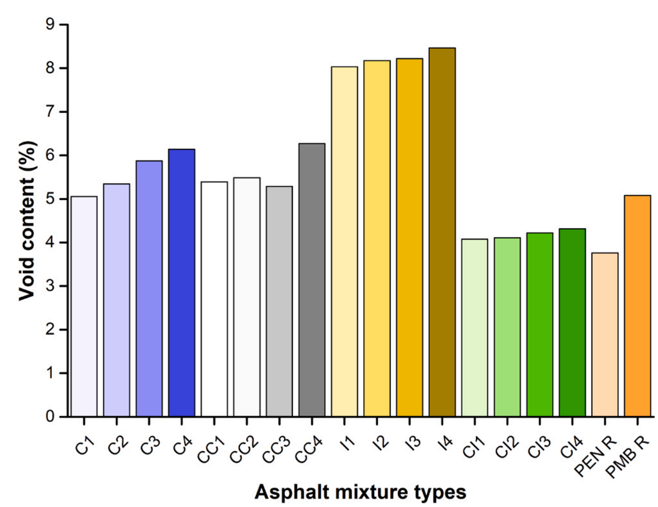

Fig. 9. Void content of the asphalt samples.

the trends are similar, which ranged around 5–6 %, increasing with the number of capsules added. However, the void content for Capsule-induction system is relatively lower, which is close to the PEN reference mix and slightly beyond 4 %. Besides, the void content for the PMB reference mix is 5.1 %.

Fig. 10 shows the bulk density of different asphalt mixture. For the Capsule system and Capsule-Induction system, the bulk density generally decreases as the dosage of alginate capsules increases in the mixture. This reduction can be attributed to the lower density of the capsules compared to the surrounding asphalt matrix, which introduces more air voids and reduces overall compaction efficiency. In contrast, the trends for the Conductive capsule system and Induction system are less distinct. Among all mixtures, the PEN reference mix exhibited the highest average bulk density of 2365.1 kg/m^3 , while the PMB_Ref mix had a

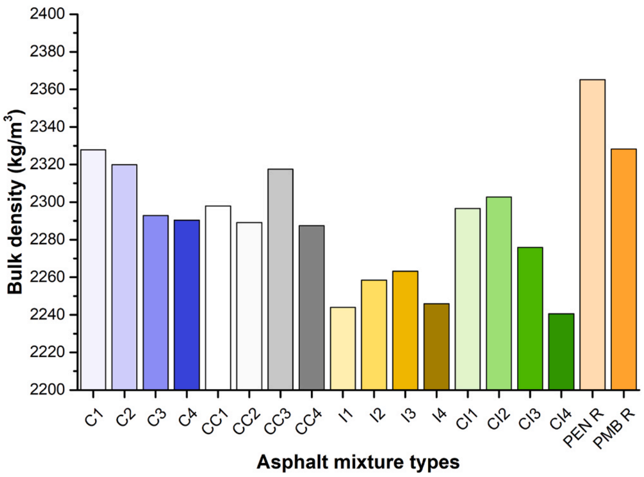

Fig. 10. Bulk density of the asphalt samples.

slightly lower bulk density of 2328.2 kg/m^3 .

4.2. Indirect tensile test

The indirect tensile test aims to investigate the indirect tensile response of the asphalt mixture, including repeatable indirect tensile stiffness test (ITS) and destructive indirect tensile strength test (ITT). The ITS test results for different types of asphalt mixture are presented in Fig. 11. It was found that the addition of self-healing components reduced the stiffness of the cylinder specimens, and this trend become more significant when more capsules or steel fibers were added. This is because the capsules were added to replace the CRF aggregates and reduced the stiffness of the asphalt mixture. It can also be due to the broken capsules during the asphalt production process already released some oil that could soften the binder in asphalt mixture. It also shows that the PEN-Ref always have the highest stiffness modulus, and this value is even higher after lab oven ageing.

Fig. 12 shows the average indirect tensile strength of each mixture. Generally, the indirect tensile strength of asphalt mixture slightly decreases with the dosage of alginate capsules or conductive capsules in the mixture. The PEN-Ref has the highest indirect tensile strength of 3.34 MPa. All other indirect tensile strength results measured from this research range from 2.5 MPa to 3 MPa.

4.3. Water sensitivity

Fig. 13 shows the water sensitivity results of each mixture which presents the resistance of asphalt mixtures to moisture damage. In general, the water sensitivity of asphalt mixture decreases with the addition of alginate capsules or conductive capsules, which was observed in the Capsule System, Conductive Capsule System and Capsule-induction System. This reduction can be attributed to the encapsulated rejuvenator enhances the overall cohesion of the asphalt mix. Conversely, the incorporation of steel fiber contributes to a higher water sensitivity. Among the mixtures tested, the C3 mix has the lowest water sensitivity of 9.77 %, and the PEN reference mix has a water sensitivity of 13.87 %, which shows that traditional asphalt mixtures without encapsulated modifiers are more susceptible to moisture damage. These findings demonstrate the role of capsules in improving asphalt mixture performance under wet conditions.

4.4. Binder drainage

The binder drainage test evaluates the tendency of asphalt binder to drain from the aggregate during storage, transportation and placement, and the results are shown in Fig. 14. It shows that the addition of self-healing components, especially the capsules will result in an increase of drained binders on the beaker. One reason for this could be the softening of the binder. Residual oil on the surface of the capsules could provide rejuvenation and flexibility to the asphalt mastic causing softening. This effect can potentially increase the flow and drainage of the binder through the mixture. This might also be because the capsules which replaced the CRF in the mix reduced the fine particle content, leading to less binder absorption. On the other hand, the use of steel fiber slightly reduces binder drainage of the asphalt mix.

4.5. Triaxial test

Fig. 15 shows the triaxial test results of the asphalt samples, presenting asphalt mixture's resistance to permanent deformation. A higher accumulated strain value indicates greater susceptibility to permanent deformation at elevated temperatures, indicating a lower resistance to rutting. The results indicate that self-healing mix containing steel fibers, namely induction healing mix and hybrid healing mix had a positive impact on rutting resistance, with lower accumulated strains observed than that of the PEN reference mixture. As capsule content increased, however, the accumulated strain increased indicating that higher capsule content would have a detrimental effect on high temperature permanent deformation and rutting properties. This is because the higher void content as a result of capsule inclusion, reducing its density and overall resistance to compaction. It may also because the softening effect of the rejuvenator released from the capsule during the asphalt mixing/compaction process, reducing its stiffness and making it more susceptible to permanent deformation under high temperatures.

4.6. Healing efficiency

The healing efficiency of each asphalt mix was determined using the SCB bending and healing program, which simulates cracking in asphalt pavement and evaluates the ability to recover with the aid of healing systems. Therefore, the healing efficiency result directly reflects the crack healing potential of each built-in healing system [11]. Figs. 16–19 show the healing efficiency results of the asphalt samples. The healing performance of each self-healing system is analysed and discussed individually in the following paragraphs.

Fig. 16 summersises the healing efficiency results of the capsule healing samples. The capsule healing mixes C1 and C2 can recover 8 % of the initial fracture toughness over 2 bending-healing cycles, whereas for C3 and C4, the healing lasts for only 1 cycle. The healing efficiency of all four capsule healing mixes is below that of the PEN reference mix and PMB reference mix. Additionally, the PMB mix exhibits the highest healing efficiency, demonstrating effective healing over 3 bending-healing cycles.

Fig. 17 summersises the healing efficiency results of the conductive capsule healing samples. All conductive capsule healing mixes showed similar healing performance compared to the PEN reference mix, which is slightly better than the capsule healing mix. In the healing process, the magnetite powder is encapsulated in each capsule, randomly distributed in the mix, making the asphalt sample difficult to heat uniformly with induction energy. While the overall healing performance is superior to the capsule healing group, the heating efficiency is very low.

Fig. 18 summersises the healing efficiency results of the induction healing samples. In the induction system, the asphalt sample can be efficiently heated through induction, and the heating speed increases significantly with the incorporation of more steel fibers in the asphalt mixture. The healing performance surpasses that of the capsule system and conductive capsule system, exhibiting higher efficiency and prolonged bending-healing cycles. The induction mix I4 showed the best healing performance that lasts till the 8th bending-healing cycle and the healing efficiency remains 56 %.

Fig. 19 summersises the healing efficiency results of the hybrid healing samples. In the 9 testing cycles, the hybrid healing systems

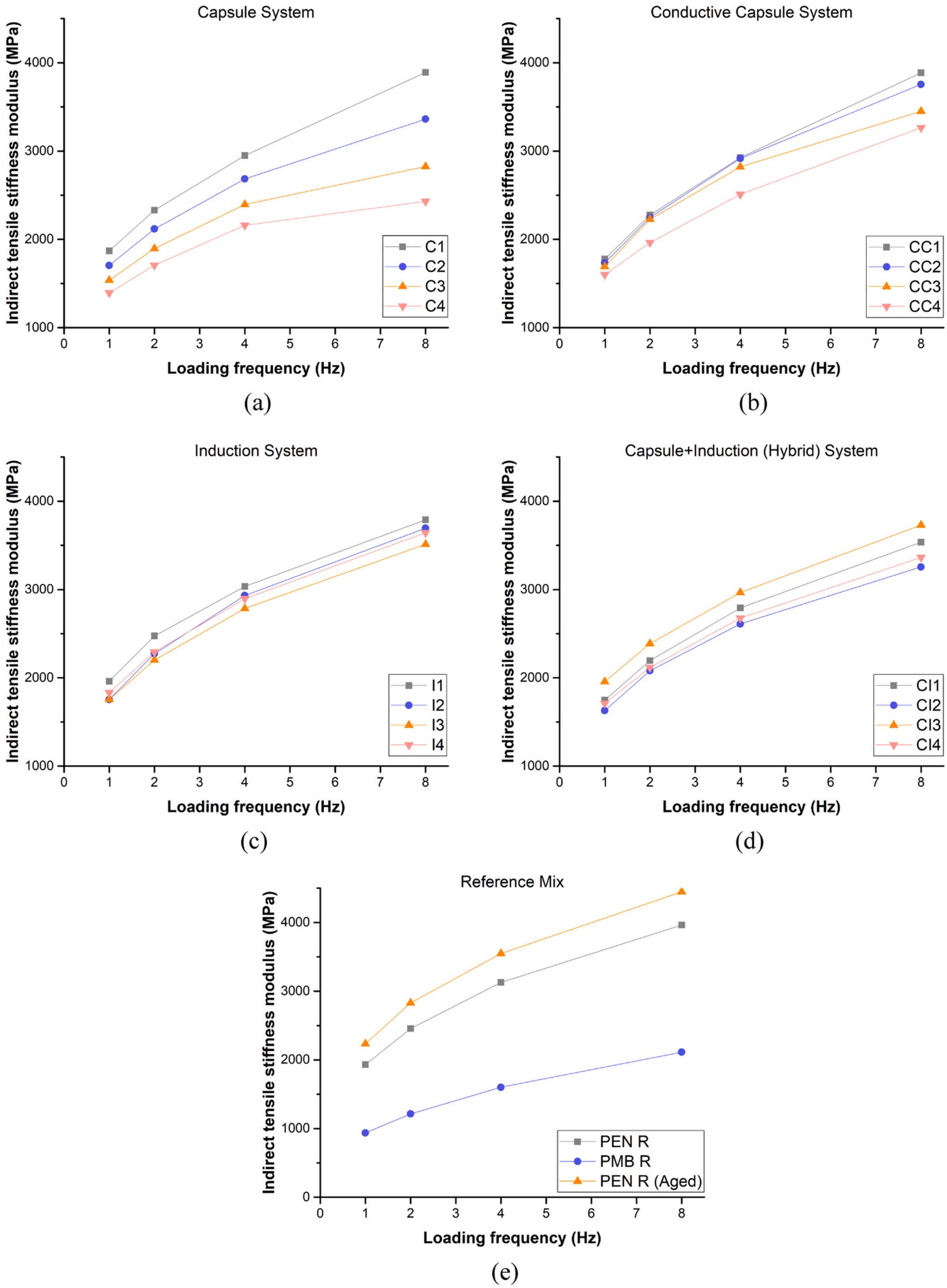

Fig. 11. The indirect tensile stiffness test results: (a) Capsule System, (b) Conductive Capsule System, (c) Induction System, (d) Capsule-induction (Hybrid) System and (e) the reference mix.

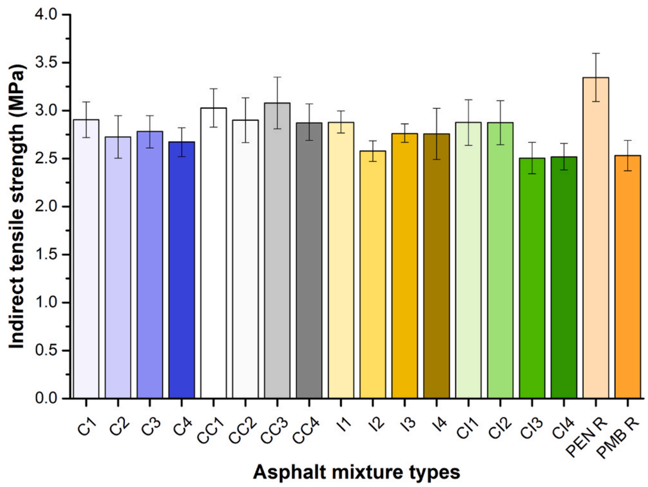

Fig. 12. The indirect tensile strength of the asphalt samples.

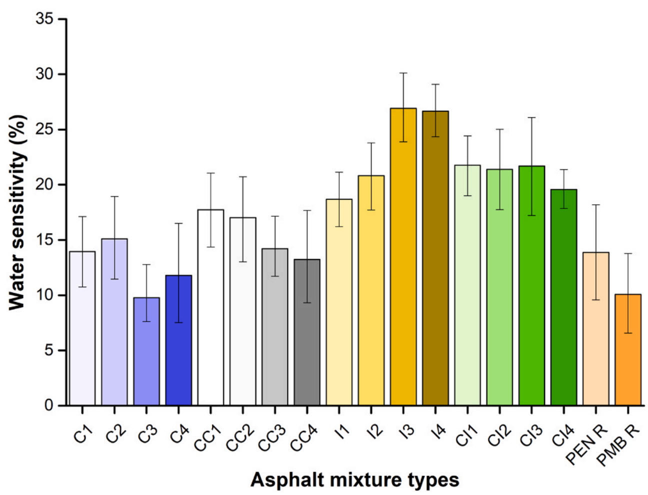

Fig. 13. The water sensitivity of the asphalt samples.

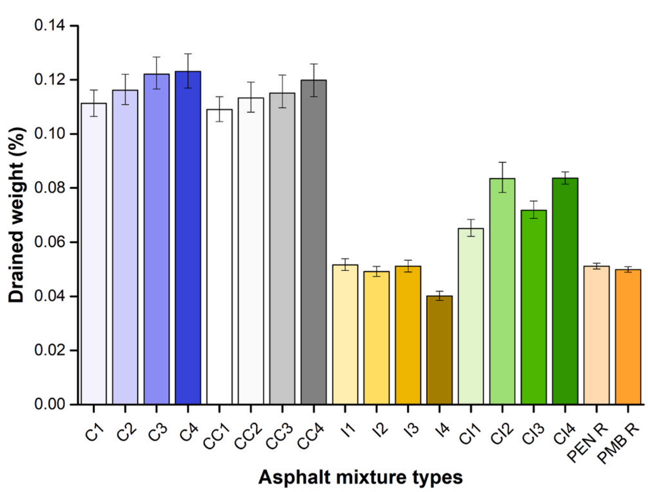

Fig. 14. Binder drainage of the asphalt samples.

showed significantly higher healing efficiency compared to the capsule system, conductive capsule system and both reference mixes. All four CI test groups showed a relatively low healing efficiency of about 40 % in their first healing action, but this efficiency gradually increased and

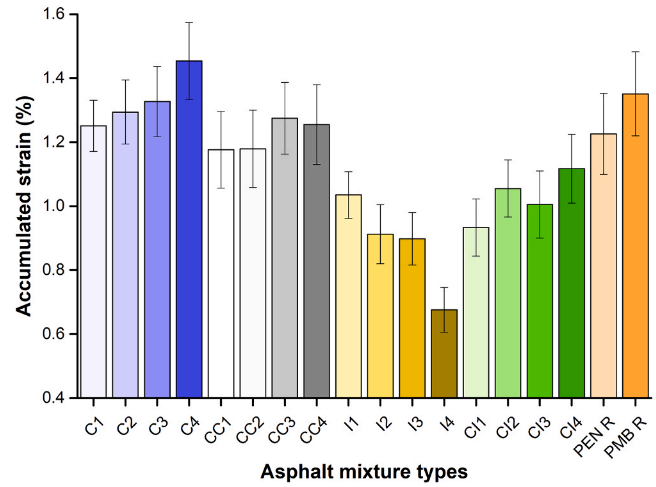

Fig. 15. Triaxial test results of the asphalt samples.

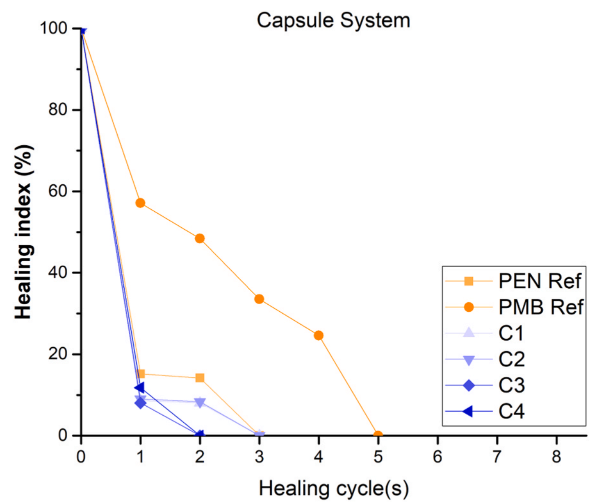

Fig. 16. Healing efficiency results of the capsule healing samples.

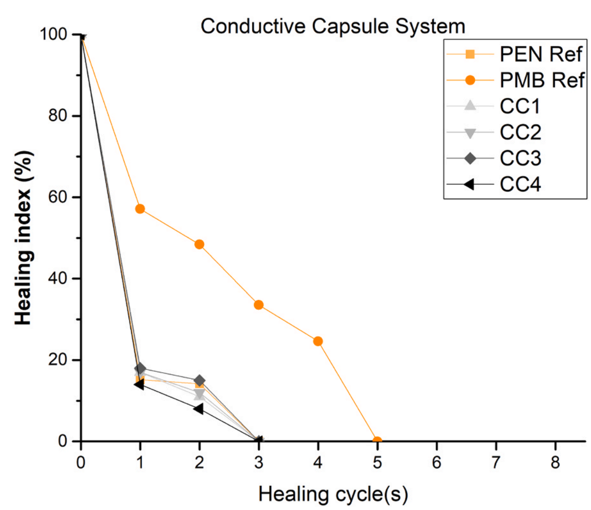

Fig. 17. Healing efficiency results of the conductive capsule healing samples.

remained stable around 60 %. This finding demonstrates that the hybrid system that combines induction heating and capsules can achieve a more durable healing performance in the SMA-10 asphalt pavement joint mix

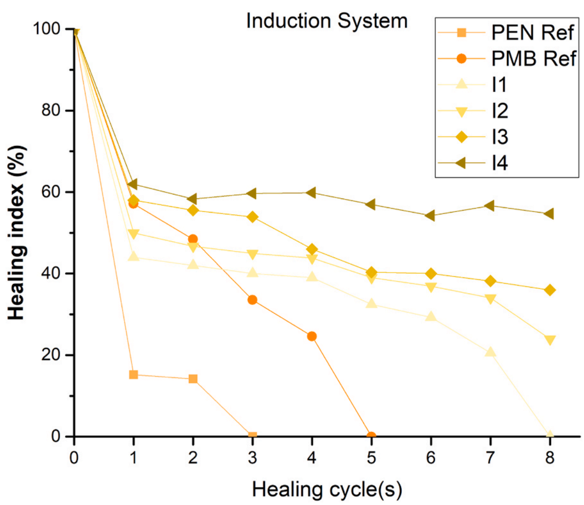

Fig. 18. Healing efficiency results of the induction healing samples.

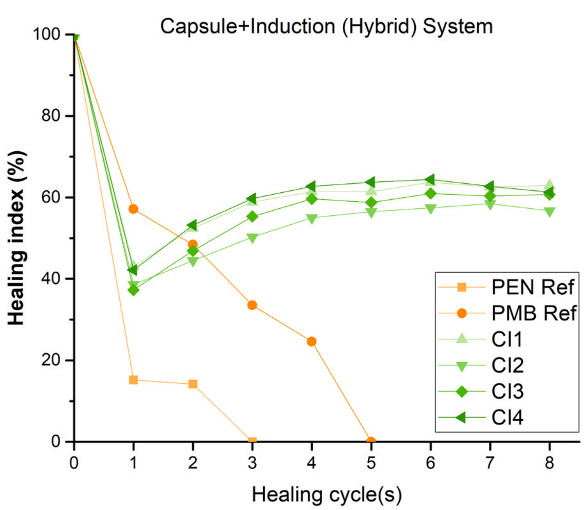

Fig. 19. Healing efficiency results of the hybrid healing samples.

compared to our research experience on self-healing porous asphalt. However, the different amounts of capsules did not have much effect on the healing efficiency results since the four CI mixtures showed similar healing efficiency.

In summary, the induction system and the capsule-induction system exhibited the best healing performance compared to other asphalt mixes investigated in this study. The capsule-induction healing mix CI1 is determined as the optimum mix for high efficiency and durable healing performance. Additionally, the induction mix I4 also demonstrated significant healing during the bending-healing test cycles. Furthermore, the lab work discovered that the PMB reference mix also showed impressive healing, making it an alternative mix with the advantage that does not require additional additives and treatment for healing action. These results underscore the potential of induction-based systems, specifically induction heating and hybrid mix, in extending the service life of an asphalt pavement.

5. Conclusions

In this study, the self-healing systems based on SMA-10 mix were designed, and the asphalt mixture samples were prepared. A series of asphalt mixture tests, including laboratory ageing test, void content/density test, indirect tensile test, indirect tensile stiffness test, water sensitivity test, triaxial test, binder drainage tests and semi-circular bending and healing test, were performed on asphalt mix incorporated with various healing systems. The hybrid self-healing asphalt system outperforms all other healing systems, this is because induction healing is efficiently repairing the damage, closing cracks, and capsules containing asphalt rejuvenator rejuvenates aged asphalt allowing continuous healing. Key conclusions of this lab research are drawn as follows:

- The addition of the self-healing components in the SMA-10 mix, especially the insertion of calcium alginate capsules causes an increase in void content and a decrease in bulk density;
- The ITT and ITS test results indicate that the addition of the self-healing components in the SMA-10 mix, especially the insertion of calcium alginate capsules causes a decrease in both mixture strength and stiffness.
- The WS test results indicate that the addition of encapsulated rejuvenator, such as capsule or conductive capsule, will reduce the water sensitivity of the asphalt mixture. While the use of steel fiber will increase the water sensitivity.
- The binder drainage test results indicate that the addition of the self-healing components in the SMA-10 mix, specially the insertion of capsules causes an increase in drained binder.
- The triaxial test results indicate that the use of steel fiber can enhance the high temperature stability and reduce rutting. However, the inclusion of capsules containing rejuvenator slightly reduces the high-temperature stability. The accumulated strain for all self-healing asphalt mix incorporated with steel fibers is less than 1.2 %, which shows an advantage in resisting permanent deformation.
- The bending and healing test results indicate that the capsule healing system and conductive capsule healing system did not exhibit a promising healing effect in the SMA mix. In contrast, the hybrid healing system, combining induction heating and capsules, demonstrated a significant healing effect that endured for 8 bending-healing cycles, maintaining a stable healing efficiency of over 60 %. There wasn't a substantial difference in healing efficiency when different capsules were added. Furthermore, the induction healing system also displayed durable and efficient healing performance throughout the testing cycles. It is also noticed that the PMB reference mix can achieve effective healing for 4 bending-healing cycles.

CRediT authorship contribution statement

Alan Lynch: Methodology. **Shi Xu:** Investigation, Writing – original draft. **Amir Tabaković:** Writing – review & editing, Conceptualization, Methodology, Supervision. **Ciaran Collier:** Resources, Supervision. **Edward Winterlich:** Funding acquisition, Resources, Project administration. **Erik Schlangen:** Funding acquisition, Supervision, Conceptualization. **Peter Recordon:** Formal analysis, Investigation, Data curation. **Xueyan Liu:** Supervision, Methodology.

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 work reported in this paper.

Acknowledgement

Shi Xu wish to thank the funding from National Natural Science Foundation of China (No. 52108416). The authors greatly acknowledge the financial support from research project 'Self-healing Asphalt Pavement Joints' (SHAPJ) funded by Transport Infrastructure Ireland (TII).

Data availability

Data will be made available on request.

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