A Novel Self-healing system: Towards a Sustainable Porous Asphalt

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A novel self-healing system: Towards a sustainable porous asphalt

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A B S T R A C T

Self-healing asphalt, aimed to produce a sustainable asphalt pavement using green technology, has been studied in the past two decades. Technologies including encapsulated rejuvenator and induction heating have been proposed, demonstrated in the laboratory, and gradually evaluated in field application. This paper looks into the synergy effect of the above two technologies, where induction heating serves as the asphalt damage repair mechanism, requiring just 2 min heating time and encapsulated rejuvenator will replenish (rejuvenate) aged asphalt binder and reinstate bitumen's healing ability. Moreover, the increased temperature from induction heating could in turn accelerate the diffusion process of rejuvenator into aged bitumen. In this paper, the healing efficiency of the combined healing system was tested in comparison with autonomous asphalt healing system, induction healing system and capsule healing system. Porous asphalt concrete with various healing systems were prepared and a laboratory ageing procedure was followed to simulate the condition when healing was needed (after years of serving). X-ray computed tomography was employed to visualize the material composition and distribution inside of each healing systems. The properties of binder extracted from the porous asphalt samples were examined by dynamic shear rheometer. Indirect tensile strength and indirect tensile stiffness modulus tests were employed to characterize the mechanical properties of the porous asphalt samples with various healing systems. Finally, the cracking resistance of these healing systems was investigated by semi-circular bending test, and the healing efficiency was evaluated using a bending and healing programme. The results indicated that the combined healing system, with synergistic effects of aged binder rejuvenation and crack healing, shows a longer life extension prospect over the other healing systems.

1. Introduction

Porous Asphalt Concrete (PAC), with higher than 20% void content, has been applied in more than 90% of the wearing course in the Netherlands (Mo, 2010; Swart, 1997). The porous structure of PAC allows water to drain through efficiently, which brings environmental benefits to filtrate the pollutants away and create a cleaner pavement runoff (Hu et al., 2019; Shirini and Imaninasab, 2016). Besides, PAC significantly reduces the noise pollution caused by vehicles, as such less psychoacoustic annoyance to nearby residents, especially in urban area (Can and Aumond, 2018; Castro et al., 2018).

In the service life of a PAC, the high void content structure makes the vehicle loadings more likely to create stress concertation at the stone-to-stone regions, thus prone to bitumen stripping (Xu et al., 2019a). Moreover, the larger surface area of PAC provides a higher chance to contact the oxygen thus suffering more serious ageing than dense asphalt concrete (Jing, 2019). These negative effects limit the average service life of PAC to around 11–12 years, thus more frequent maintenance and reconstruction than other pavement structure (Molenaar et al., 2010; Zhang et al., 2018).

The PAC performance and life span can be improved and prolonged by using modified asphalt binder, for example, Ethylene-Vinyl-Acetate (EVA), Styrene-Butadiene-Styrene (SBS), rubber and epoxy modified bitumen (Herrington and Alabaster, 2008; Shirini and Imaninasab, 2016; Voskuilen et al., 2004). However, the modified asphalt binder could become a problem in recycling (Copeland, 2011).

As a novel concept, self-healing asphalt aims to produce a sustainable asphalt pavement by using self-healing technology to stimulate and improve the healing capacity of bituminous materials, so that damages can be self-repaired which finally prolongs

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the service life of asphalt pavement. The increased sustainability of asphalt pavement with self-healing technology reduces the maintenance works which not only reduces the need of extra resources (aggregate, bitumen, etc.) but also reduces the emissions of greenhouse gases into the atmosphere (Jahanbakhsh et al., 2019).

The induction heating and encapsulated rejuvenator are two major self-healing technologies developed for asphalt concrete and show significant healing effect in the laboratory and are gradually demonstrated in the field application with time (Ayar et al., 2016; Hager et al., 2010; Sun et al., 2018; Tabaković and Schlangen, 2015; Xu et al., 2018a).

The induction heating method achieves crack healing by heating up asphalt concrete with induction energy (Liu et al., 2011). To start the healing process, the alternating electromagnetic field generated by the upper induction coil induces flowing current inside the asphalt concrete with conductive particles, thus heating up the asphalt concrete, melting the asphalt mastic and finally healing the crack (García et al., 2011b; Norambuena-Contreras and Garcia, 2016). The advantages of induction heating methods include efficient asphalt cracking healing and the healing can be repeated. However, an increased temperature from induction heating could also accelerate the asphalt ageing (Xu et al., 2018b). Moreover, the induction healing effect on aged asphalt concrete is reduced as the stiffer binder requires higher temperature to flow (Gómez-Meijide et al., 2018; Xiao et al., 2019; Xu et al., 2018b; Zhang et al., 2012).

Application of encapsulated rejuvenator in asphalt concrete is another promising method to extend its service life (Xu et al., 2018a). The healing mechanism of the encapsulated rejuvenator lies in the aged binder rejuvenation with the released rejuvenator. This healing system is activated when crack initiates and propagates through the capsule/fibre to trigger the release of rejuvenator, thus the rejuvenator diffuses into the crack surface and softens the aged binder. In this way the crack can be healed with the flow of asphalt mastic (Xiao et al., 2017; Xu et al., 2018c). Till now, variety of encapsulating technics have been developed, for example, Melamine-formaldehyde capsules (Su et al., 2013), epoxy capsules (García et al., 2011a), alginate fibres (Tabaković et al., 2016), alginate capsules (Xu et al., 2017), etc. Alginate, as a bio-material origin from the algae biomass, shows significant environmental and economic advantages in using as a cleaner encapsulation material in self-healing asphalt (Al-Mansoori et al., 2017; Micaelo et al., 2016; Shu et al., 2018; Tabaković et al., 2017; Xu et al., 2019b). The healing effect of the calcium alginate capsules developed by Xu has been demonstrated in asphalt mortar, mastic and porous asphalt concrete (Xu et al., 2018c, 2019a, 2019b). However, the damage healing efficiency of the encapsulated rejuvenator method is very limited and this healing cannot be repeated (Xu et al., 2019a).

Based on the existing findings, the authors noticed that the induction heating and encapsulated rejuvenator are very complementary in healing mechanism (Xu et al., 2018a). Fig. 1 shows that the combination of these two technologies could produce some positive synergistic effects:

I. Increased temperature from induction heating improves the diffusion coefficient of asphalt rejuvenator, thus the healing effect from encapsulated rejuvenator is improved;
II. Rejuvenation with encapsulated rejuvenator softens the aged binder which in turn improves the induction healing effect;
III. Efficient crack healing from induction heating together with aged material rejuvenation from encapsulated rejuvenator result in a more comprehensive and prospective self-healing asphalt.

Hence, the concept of the combined healing system, incorporating the advantages from both induction heating and encapsulated rejuvenator, is expected to achieve an enhanced healing in asphalt concrete.

In PAC, more than 90% of the distress initiates from the micro-crack in asphalt mastic, which means, majority of the damage in PAC can be healed with self-healing technologies.

In this paper, a novel combined asphalt self-healing system is developed, in which the induction heating will heal the asphalt damage, i.e. cracking, and rejuvenation to rejuvenate the aged binder. The process will involve the insertion of both microcapsules encapsulating rejuvenator and steel fibres into the PAC mix. Since the healing effect of asphalt healing systems could be affected by the asphalt ageing (Xu et al., 2018b), a laboratory ageing process was performed to simulate the field ageing effect on PAC, and the ageing effect was evaluated by dynamic shear rheometer (DSR) on the extracted binder from PAC sample. After that, mechanical property and healing efficiency were evaluated and the results were compared with the induction healing system and the capsule healing system. The research methodology of this paper is shown in Fig. 2.

2. Materials and experimental method

2.1. Capsules, steel fibres and porous asphalt mixture design

The materials used to build the self-healing systems in PAC are shown in Fig. 3, including steel fibres and calcium alginate capsules. Aimed to improve the conductivity of PAC to achieve induction healing, the steel fibres were used in induction healing system and combined healing system. The steel fibres with the density of 7.6 g/cm^3, an average length of 1.4 mm, the diameter of 40 μm and the resistivity of 7×10^{-7} Ω cm were provided by Heijmans Infra BV, Rosmalen, Netherlands.

The calcium alginate capsules encapsulating rejuvenator developed by Xu (Xu et al., 2017) were used in the capsule healing system and the combined healing system. Calcium alginate was used as the shell material, and an industrial rejuvenator named R20 provided by Latexfalt B.V., Koudekerk aan den Rijn, Netherlands, was used as the encapsulated healing agent. The manufacture details of these calcium alginate capsules can be found in the previous study (Xu et al., 2018c). The encapsulated rejuvenator in the calcium alginate capsules were designed to release upon cracking in order to achieve localized crack healing on demand.

The PA mix was designed following the Netherlands porous asphalt standard PA 0/11. In total four types of asphalt mix with different healing systems were studied, including capsule healing system, induction healing system, combined healing system and a reference mix without healing system. Table 1 summarises the mix composition of the PA with different healing system. In induction healing system and combined healing system, steel fibres were added as 6% extra volume of bitumen. In capsule healing system and combined healing system, calcium alginate capsules were added to replace 7% the volume of bitumen. A Phoenix Nano CT scanner at a resolution of 20 μm was used to visualize the capsule and/or Fibre distribution in asphalt concrete samples with various healing systems.

2.2. Experimental methods

2.2.1. Slab production and laboratory ageing

The PA mix with different healing systems was mixed and compacted into asphalt slabs (Fig. 4a and b). In total four slabs were manufactured, including capsule healing slab, induction healing slab, combined healing slab and the reference slab. After mixing and compaction, all these slabs were kept in a mould and cured in a

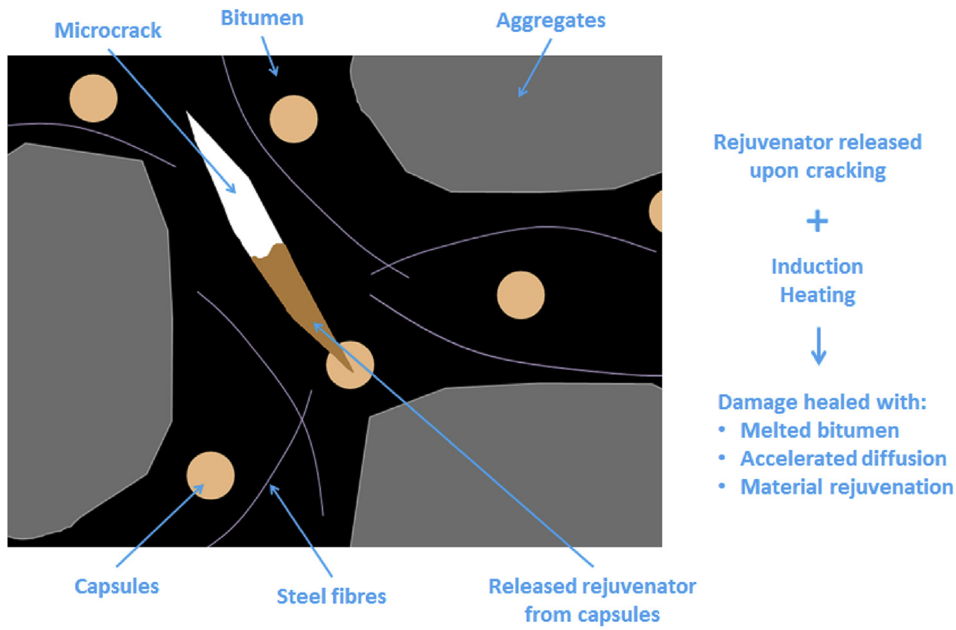


Fig. 1. Crack healing mechanism of the combined healing system.

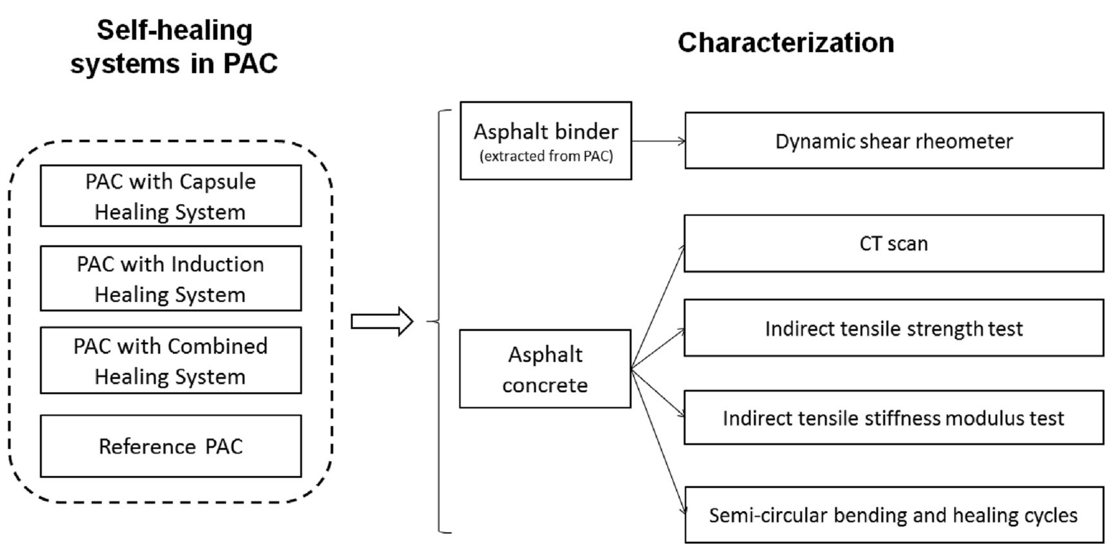


Fig. 2. The research methodology of the evaluation of different healing systems in PAC.

ventilated oven at 135 °C for 4 h and then another 96 h under 85 °C (Fig. 4c), to simulate the ageing effect in the field (Tabaković et al., 2016; Xu et al., 2018b).

2.2.2. Dynamic shear rheometer

Asphalt ageing results in a change of the rheological properties of bitumen by increasing its complex modulus and decreasing its phase angle, and this change can be investigated using dynamic shear rheometer (Behera et al., 2013; Van den Bergh, 2011). A dynamic mechanical analyser made from Anton Paar was used to study the rheological properties of bitumen samples extracted using Dichloromethane (Jing, 2019). In order to evaluate the ageing level of the lab aged PAC, before and after lab ageing, bitumen was extracted from the mixture in reference slab (without healing system).

The frequency sweep tests were performed at the temperature of 0, 10, 20, 30 and 40 °C using a range of frequency sweep from 0.01 Hz to 50 Hz. Finally, the master curves of complex shear modulus (G^*) and phase angle (δ) were generated at the reference temperature of 20 °C based on the Time-Temperature Superposition principle.

2.2.3. CT-scan

A Phoenix Nanotom CT scanner was used to visualize the distribution of capsules and/or fibres in porous asphalt samples with various healing systems. In a CT-scan image slide, the individual phases containing different brightness intensities which refers to its density. As a result, in the CT-scan image of a PA sample, compositions including air voids, capsules, asphalt mastic, aggregates and steel fibres are expected to present in an increased brightness.

With this method, the potential healing mechanism of all healing systems could be indicated, which also help the illustration

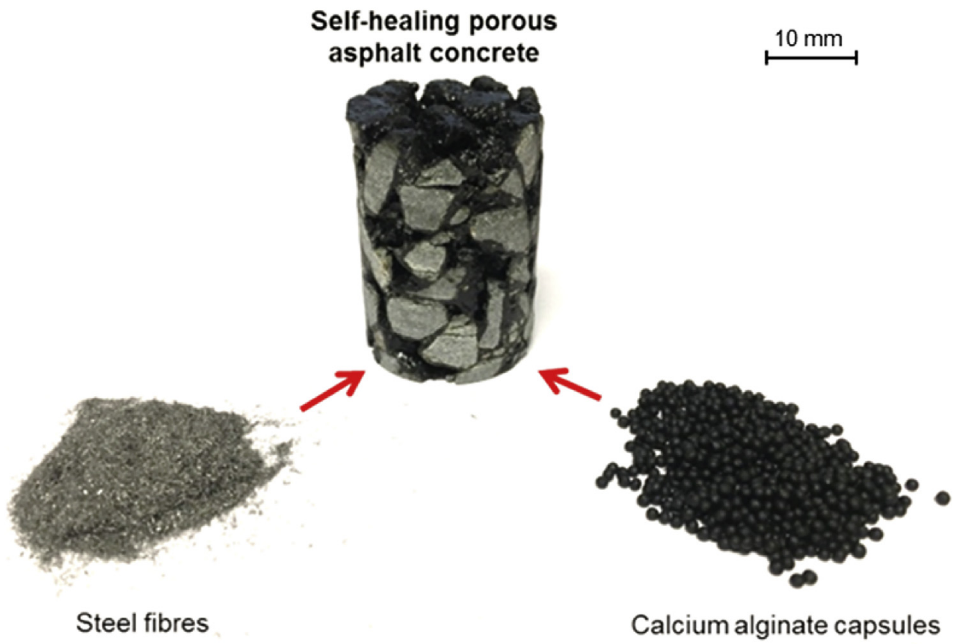


Fig. 3. Steel fibres and calcium alginate capsules used in self-healing porous asphalt concrete.

Table 1
The mix composition of PAC.

Mix Constituent	% Content in Mix			
	Capsule healing system	Induction healing system	Combined healing system	Reference
16 mm	8.14	7.97	8.00	8.14
11.2 mm	63.28	62.00	62.21	63.31
8 mm	8.14	7.97	8.00	8.14
5.6 mm	1.82	1.78	1.79	1.82
2 mm	6.61	6.47	6.49	6.61
500 μm	2.11	2.06	2.07	2.11
180 μm	0.67	0.66	0.66	0.67
125 μm	0.67	0.66	0.66	0.67
63 μm	4.31	4.22	4.23	4.31
Bitumen(70/100)	3.92	4.32	3.85	4.21
Capsules	0.34	–	0.34	–
Steel Fibres	–	1.88	1.70	–

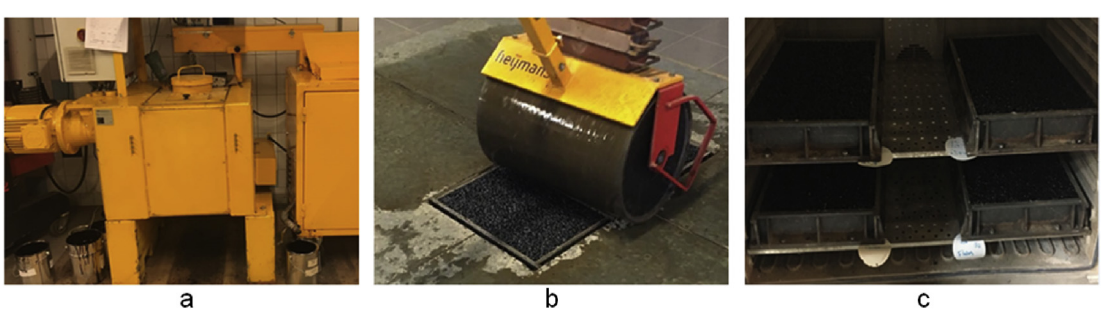


Fig. 4. Preparation PAC slabs: (a) mixing, (b) compaction and (c) ageing.

of the healing efficiency of various healing systems. A resolution of 20 μm was used to fit the lateral dimension of the scanned sample.

2.2.4. Indirect tensile test

The indirect tensile test (ITT) was employed to investigate the mechanical properties of asphalt concrete with different composition. Cylinder samples with a diameter of 100 mm and height of 50 mm drilled from the prepared slabs were tested with both non-destructive indirect tensile stiffness test (2018) and destructive indirect tensile strength test (2017). The indirect tensile stiffness modulus (ITSM) and indirect tensile strength (ITS) could be calculated using the following equations:

$$ITSM = \frac{F(\nu + 0.27)}{Zt}$$

Where

ITSM is the indirect tensile stiffness modulus (MPa);
F is the maximum vertical load (N);
ν is the Poisson's ratio;
Z is the amplitude of the horizontal deformation during the load cycle (mm).
t is the thickness of specimen (mm).

$$ITS = \frac{2P}{\pi DH} \times 1000$$

Where

ITS is the indirect tensile strength (kPa);
P is the peak load (N);
D is the diameter of specimen (mm);
H is the height of specimen (mm).

In this paper, the indirect tensile stiffness modulus tests were performed by a universal testing machine (UTM) at 20 °C at four different frequencies (8 Hz, 4 Hz, 2 Hz and 1 Hz). The Poisson's ratio of 0.22 was assumed for this porous asphalt concrete. The indirect tensile strength tests were performed by UTM at 5 °C with a loading speed of 0.85 mm/s.

2.2.5. Semi-circular bend

A UTM with temperature chamber was employed to perform the SCB tests according to NEN-EN 12697–44:2019 (2019). As shown in Fig. 5, the SCB samples were prepared with a diameter of 100 ± 2 mm, a thickness of 50 ± 1 mm and a radius of 50 ± 1 mm. A notch was placed in the middle of each sample with a length of 10 ± 0.2 mm and a width of 3 ± 0.1 mm. The tests were performed at 0 °C with a loading speed of 5 mm/min.

The maximum stress at failure and the fracture toughness were calculated with the following equations:

$$\sigma_{max} = \frac{F_{max}}{Dt}$$

Where

σ_{max} is the maximum stress at failure (N/mm^2);
F_{max} is the maximum force of specimen (N);
D is the diameter of specimen (mm); t is the thickness of specimen (mm).

$$K_{Ic} = Y_{Ic(0.8)} \sigma_{max} \sqrt{\pi a}$$

$$Y_{Ic(0.8)} = 4.782 - 1.219 \left(\frac{a}{r}\right) + 0.063 e^{\left(7.045\left(\frac{a}{r}\right)\right)}$$

Where

K_{Ic} is the fracture toughness (N/mm$^{1.5}$)
$Y_{Ic(0.8)}$ is the stress intensity factor;
a is the notch depth of specimen (mm);
r is the radius of the specimen (mm).

2.2.6. Healing procedure and evaluation

After a SCB test, a specific healing procedure was performed on the fractured samples according to its build-in healing system:

I. For the systems with steel fibres, including the induction healing system and the combined healing system, induction healing was applied on both sides of the samples to achieve a homogeneous temperature distribution throughout the sample (Xu et al., 2018b) and then followed by a 20 h period conditioned in temperature chamber at 20 °C;

II. For the systems without steel fibres, including the capsule healing system and the reference, the samples were only conditioned in temperature chamber at 20 °C for 20 h.

A SCB bending and healing programme was developed to evaluate the healing efficiency of the samples with various healing systems.

- First, the initial maximum stress at failure was measured by the first SCB test;
- Second, a healing procedure (I or II) was applied depending on the build-in healing system;
- Then, another SCB test was performed to acquire the maximum stress which indicates the regained strength from healing period.
- Afterwards, step 2 to 3 were repeated as a healing cycle. The bending and healing programme stopped until the testing sample reached 7 testing cycles or the peak load is below 200 N.

The healing efficiency of the testing sample was determined using healing index(HI), which was calculated with the maximum stress measured from SCB tests:

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

Where:

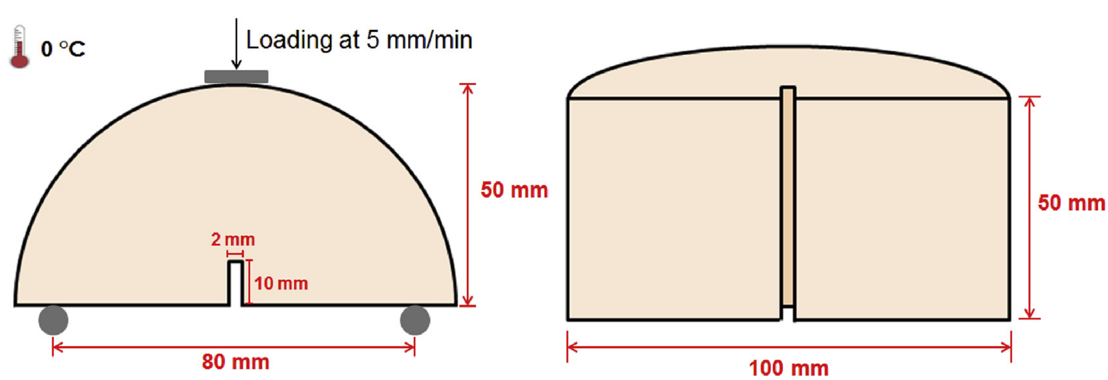


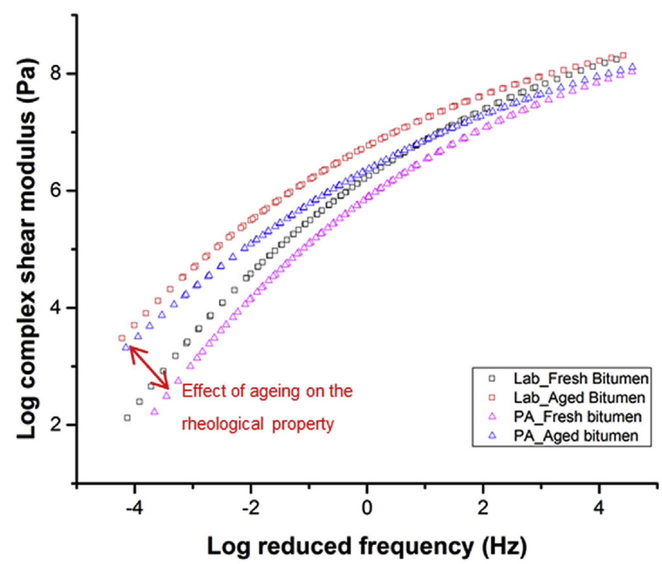
Fig. 5. SCB sample dimensions and testing condition.

HI is the healing index (%),
C_1 is the initial maximum stress at failure;
C_x is the maximum stress measured from the x testing cycles.

3. Results and discussion

3.1. Dynamic shear rheology test

The rheological properties of asphalt binder are related to its ageing level. As such, DSR tests were performed on the asphalt binder samples extracted from the Reference porous asphalt (PA) mixture before and after oven ageing. The master curves of complex modulus and phase angle generated from the frequency sweep results are shown in Fig. 6, in which the standard laboratory Rolling Thin-Film Oven (RTFO) and Pressure Aging Vessel (PAV) aged 70/100 bitumen are plotted as references. Fig. 6a shows that after ageing, the complex modulus of asphalt binder increased significantly and the increasing amplitude is very similar to the differences in reference curves, which indicates that the ageing procedure used in this paper could accelerate the ageing effect of the PA mixture which is similar to the standard RTFO and PAV ageing process. In Fig. 6b, the phase angle results show that the ageing procedure reduces the phase angle of the asphalt binder in PA and the reducing amplitude is similar to the standard RTFO and PAV ageing effect. As a result, all the healing systems studied are evaluated based on an aged asphalt mix whose ageing level simulates 5–10 years field ageing as stated in NEN-EN 14769 (2012).



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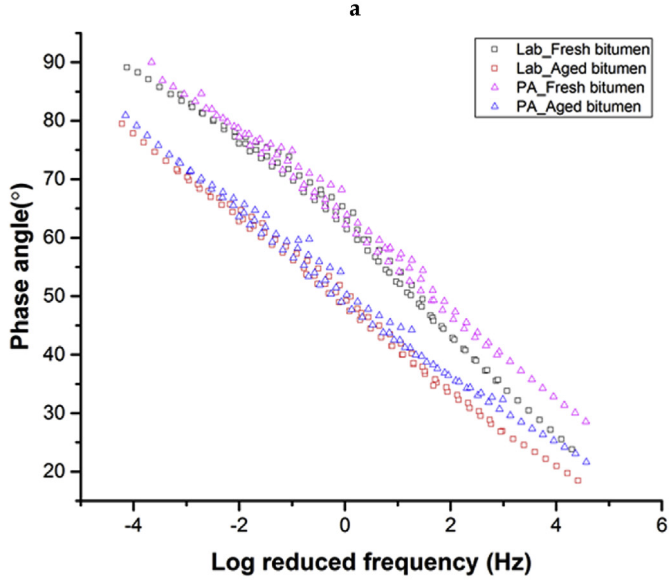

b

Fig. 6. The master curves: (a) complex shear modulus and (b) phase angle.

3.2. CT-scan

Fig. 7 shows the CT-scan image slides of PAC sample with three different healing systems. In the capsule healing system (Fig. 7a), calcium alginate capsules are found in dark spherical phase which are randomly distributed and attached with asphalt mastic. As a result, the releasing of rejuvenator from the capsules can easily reach the aged asphalt binder (prone to cracking) to achieve localized binder rejuvenation and eventually crack healing.

In the induction healing system (Fig. 7b), the steel fibres can be found as bright spots within the asphalt mastic area. This fibre distribution allows the induction heat being generated from the asphalt mastic so that cracks happened in asphalt mastic could be healed. In the combined healing system (Fig. 7c), the presences of both capsules and steel fibres are found and their distributions follow the same principles as the individual healing systems. It is noticed that steel fibres can always be found in the mastic area near the capsules, so that the potential synergistic effects from capsule healing system and induction healing system are expected during the healing action.

3.3. ITT

The indirect tensile stiffness modulus of the cylinder PA samples with different compositions (healing systems) is presented in Fig. 8. Among all four types of asphalt mix, the reference mix shows the lowest stiffness modulus at all loading frequencies, which means the incorporation of a healing system such as calcium alginate capsules and/or steel fibres results in an enhancing effect to make the PA stiffer. These results agree with the conclusions of some existing researches (Quantao, 2012; Xu et al., 2019a). Moreover, PA samples incorporated with the combined healing system have the highest stiffness modulus which means the reinforcing effect from calcium alginate capsules and steel fibres can also be combined. The results also indicate that the reinforcing effect from steel fibres is more significant than the calcium alginate capsules as the samples with induction healing system always have a higher stiffness modulus than the capsule healing system.

As shown in Fig. 9, the indirect tensile strength results show a similar trend as the ITSM results, in which the combined healing system has the highest strength and all healing systems are stronger than the reference mix. However, the improvement of the indirect tensile strength from the capsule healing system, the induction healing system and the combined healing system is 0.22%, 4.78% and 9.68%, respectively. The results indicate that the contribution from the healing systems to the ITS is not that significant compares to ITSM.

3.4. SCB bending and healing test

The SCB tests were employed to simulate the crack propagation in asphalt concrete and the acquired fracture toughness was used to evaluate the fracture resistance of the asphalt concrete samples. Fig. 10 shows the fracture toughness of PA samples with various

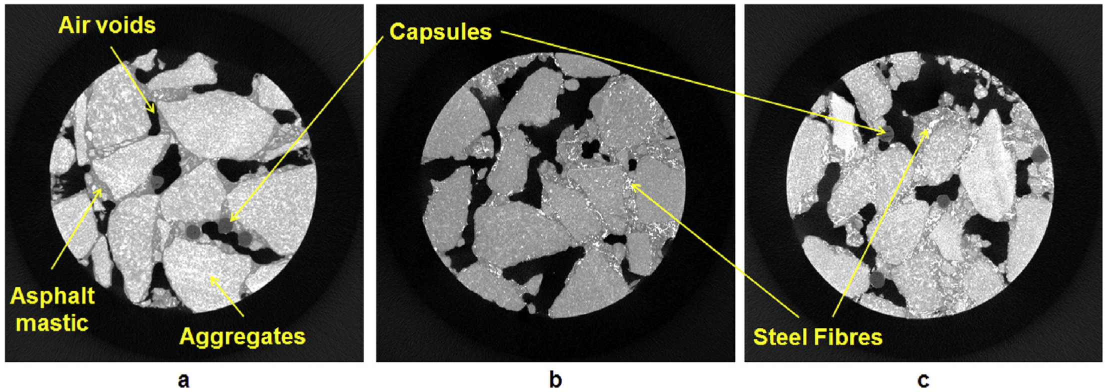

Fig. 7. CT-scan images of porous asphalt concrete with various healing systems: (a) capsule healing system, (b) induction healing system and (c) combined healing system.

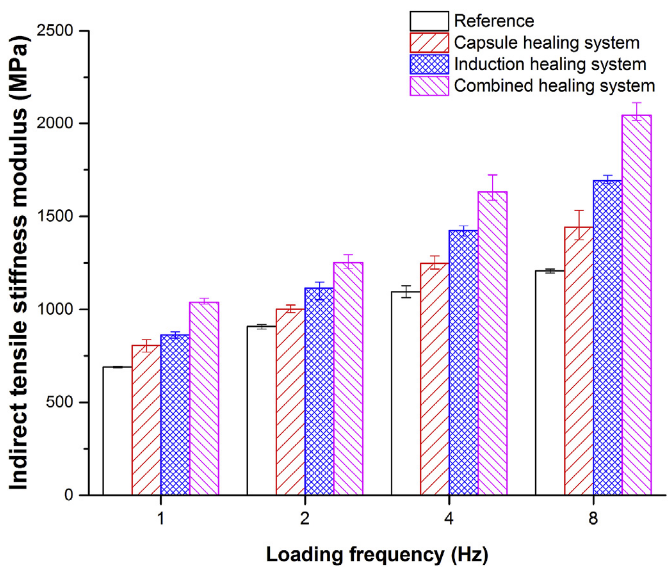

Fig. 8. Indirect tensile stiffness modulus of PA with various healing systems.

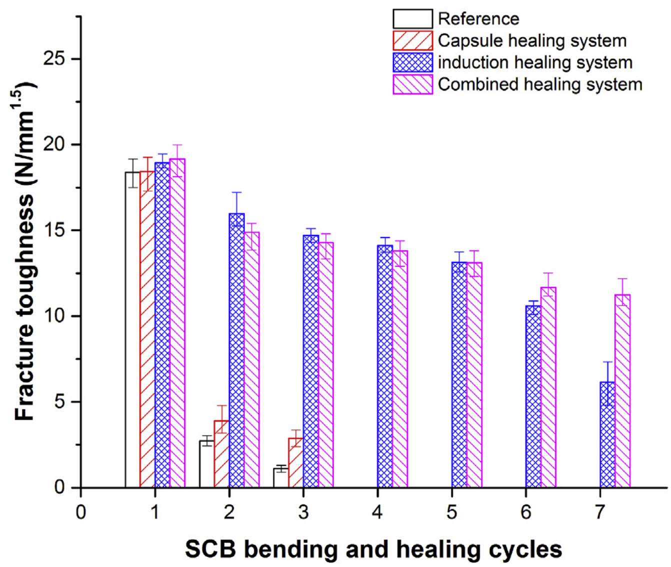

Fig. 10. The fracture toughness of various healing systems.

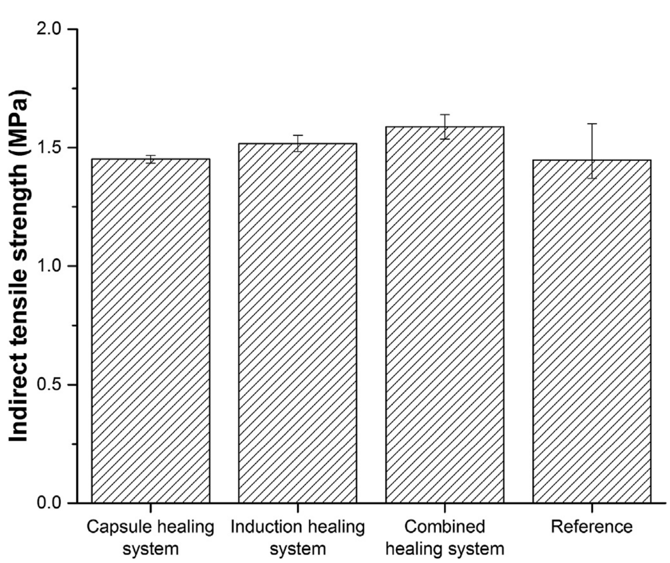

Fig. 9. Indirect tensile strength of PA with various healing systems.

healing systems measured during the SCB bending and healing cycles.

In the first cycle, the induction healing system and the combined healing system showed higher fracture toughness than the capsule healing system and the reference group, which means the addition of steel fibres slightly improves the initial fracture resistance of the PA samples. After the first healing process, the fractured samples with induction healing system and combined healing system were able to regain a fracture toughness around 15 $N/mm^{1.5}$, while the fracture toughness of capsule healing system and the reference group were less than 4 $N/mm^{1.5}$.

The capsule healing system and the reference group could not be healed after the third bending cycle, but the fracture toughness recovery in the capsule healing system was higher than the reference group, due to the healing effect from the rejuvenator released from the capsules. As the bending and healing cycles reached the seventh cycle, the induction healing system and the combined healing system continued to demonstrate an effective healing, and as such test samples are manging to reach a fracture toughness greater than 6 $N/mm^{1.5}$.

Fig. 11 shows the calculated healing index based on the maximum stress at failure. In the first five bending and healing cycles, the induction healing system showed a similar healing index

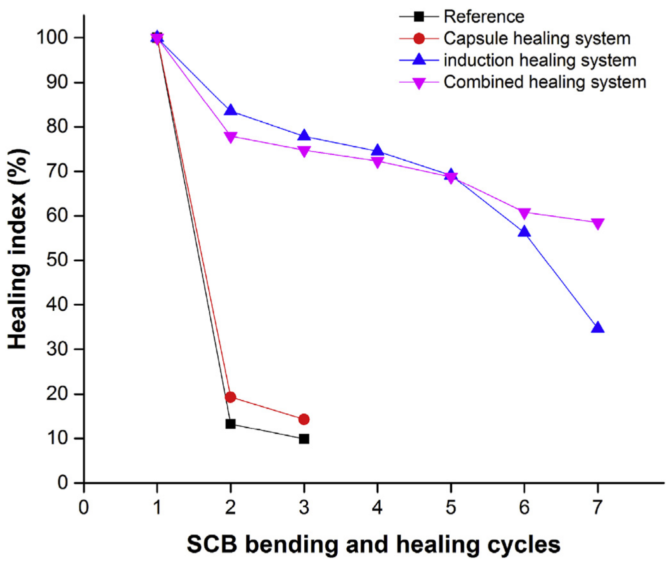

Fig. 11. The healing index of various healing systems.

to the combined healing system. Beyond five cycles, a significant decreasing trend in healing index could be found in the induction healing system, while the combined healing system still continued a stable trend of healing and did not show decrease of the healing index as observed in the induction healing system. Induction heating is a very efficient crack healing method in PAC, however its healing ability is reduced with each healing event, and this reduction is even more significant when performed on aged asphalt (Xu et al., 2018b). At the fifth bending and healing cycle, accumulated permanent deformation on fracture faces made the induction healing less effective. However, the capsules in the combined healing system which release the rejuvenator, wet the fracture surface and soften the aged binder, thus promoting the induction healing effect on fractured samples and finally results in a higher healing index than the induction healing system in the last two cycles.

The SCB bending and healing results indicates that, with more effective and efficient healing in asphalt concrete, the induction healing technology showed a significant advantage over the capsule healing technology. Although the induction healing can be repeated, the healing efficiency is limited due to the asphalt ageing effect which allows an asphalt concrete gradually lose its intrinsic healing capacity, as such a higher temperature is needed from induction heating to heal the crack.

In general, incorporation of combined self-healing system (capsules and induction) into the PAC could achieve both effective crack healing and aged material rejuvenation, thus a more stable and durable healing effect in asphalt concrete.

4. Conclusions

This study proposed the concept of the combined healing system which incorporates both induction healing and capsule healing. The healing effects of various healing systems have been investigated and the advantages of the combined healing system have been demonstrated. The following conclusions can be drawn:

- The CT-scan images show that the capsules and steel fibres can be randomly distributed in the porous asphalt concrete and contacted to asphalt mastic, this distribution allows both healing systems to function.
- The capsule healing system improves the healing capacity of asphalt during the porous asphalt SCB bending and healing cycles, but this healing effect is limited as it lasts only three cycles;
- The combined healing system shows its significant advantage over capsule healing system. Compares to the induction healing system, although their healing efficiency is very similar in the first 5 cycles, the induction healing effect is largely reduced after that and it might because of asphalt ageing.

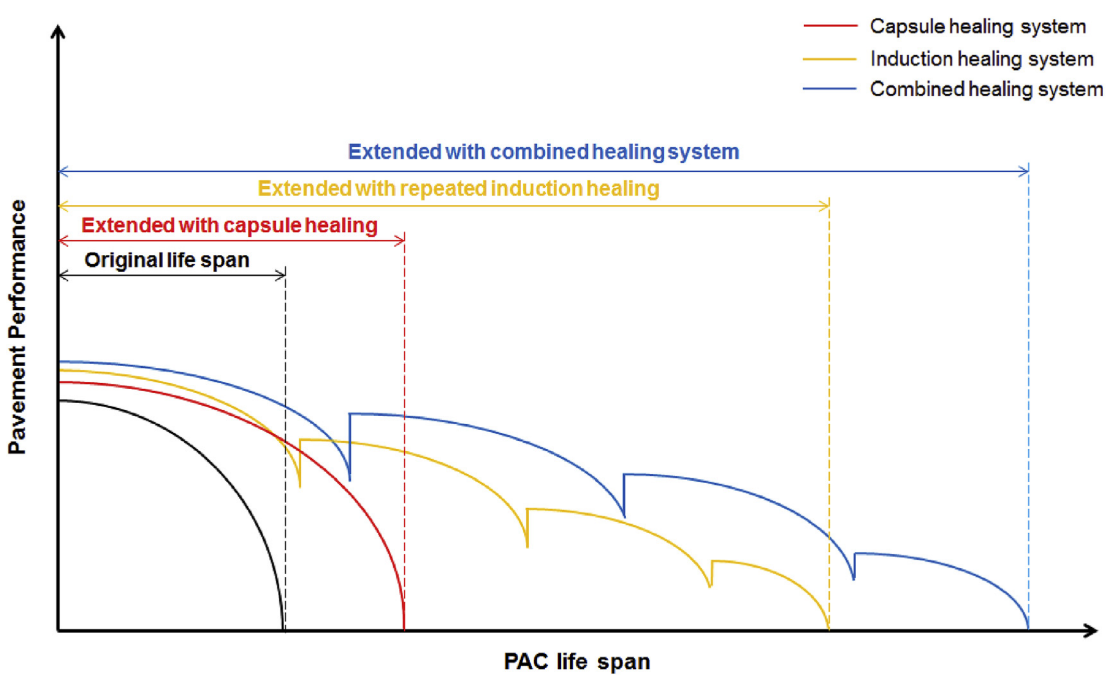

Fig. 12. Life extension prospects in PAC with various healing systems: Capsule healing system, induction healing system and the combined healing system.

- Finally, the combined healing system is able to achieve both effective crack healing and aged binder rejuvenation which contributes to more durable healing in porous asphalt concrete.

5. Recommendations

Based on the research findings presented in this paper, the life-extension prospects of PAC with various healing systems are presented in Fig. 12. Fig. 12 shows that a PAC incorporated with capsule healing system would have an increased life span than the standard PAC, which is because of the improved crack healing effect from aged binder rejuvenation. Compared to the capsule healing system, the induction healing system has a more significant crack healing effect in PAC so that the life span of PAC could be further extended. However, for the combined healing system, the comprehensive healing effect lies in not only the advantages of both encapsulated rejuvenator and induction heating, but also the synergistic effects which promote each individual mechanism, namely accelerated rejuvenator diffusion (with induction heating) and improved induction healing (with asphalt binder rejuvenation). As such, the combined healing system shows the longest PAC life extension prospect among the three healing systems. Following this conclusion, the authors would recommend the multi-healing method which include mechanical property recovery and aged material rejuvenation as a research focus for the future development of self-healing technology in asphalt pavement. Optimization of the combined healing system will be conducted as an extension research of this paper.

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.

CRediT authorship contribution statement

S. Xu: Investigation, Methodology, Data curation, Writing - original draft. **X. Liu:** Supervision, Writing - review & editing. **A. Tabaković:** Supervision, Writing - review & editing. **E. Schlangen:** Conceptualization, Resources, Supervision, Writing - review & editing.

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