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Influence of Material Scale and Test Design Parameters on Healing of Asphaltic Materials using healing agents

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ABSTRACT. *An abstract summarizes, in one paragraph (usually), the major aspects of the entire paper in This study investigated the crack healing performance of multiple scales of AC-13 asphalt mixtures treated with two maltene based cationic emulsions and base bitumen emulsion. Crack healing tests on bitumen and mastic subscales were conducted following a tensile fracture-healing-refracture test. Mortar and mixtures healing tests were conducted using a semicircular bending test. The impact of healing time, moisture ingress, aging and variations in healing temperature on crack healing of the treated asphalt materials was investigated. Test results indicated that self-healing of aged asphalt materials is significant at bitumen and mastic subscales and negligible at mortar and mixtures scales. Upscaling from bitumen to mixtures has a serious negative effect on healing. The healing trend of mortar had a strong correlation with healing of mixtures. Therefore, the mortar subscale could accurately screen healing of asphalt mixtures. After long time healing of long-term aged asphalt mixtures treated with HAs, up to 65% of initial peak strength and 55% of fracture energy was recovered. Maltene based cationic emulsions induced better healing than base bitumen emulsion. Asphalt material scale and test design parameters have a significant effect on healing. Therefore, a judicious selection of the appropriate combination of these variables is important in a healing test design.*

Key words: Asphalt materials; Crack healing; Healing agents; Asphalt material scale

1. INTRODUCTION

Asphalt concrete (AC) is a road paving material comprising of about 95% by mass of graded course and fine aggregates and about 5% by mass of bitumen. The graded aggregates and fillers constitute the structural backbone of the paved structure while the bitumen binds them into a coherent unit. AC is considered to be a two-phase material: the mortar phase as the binder (comprised of aggregates smaller than 2.36mm) and the dispersed phase of coarse aggregates [1]. Mortar, which comprises of bitumen, filler and fine aggregates, is considered as the binding phase which coats coarse aggregates instead of bitumen or mastic (comprised of filler and bitumen) [2]. During service life, deterioration of the binder is inevitable considering that asphalt pavements are exposed to harsh environmental conditions and traffic loading. The deterioration is in the form of decreased relaxation and flexibility of bitumen due to aging, moisture damage and fatigue [3]. Consequently, distresses such as pavement cracking, potholes and raveling arise due to the loss of binder cohesion, adhesion and aggregate segregation.

Recent studies have proposed methods that would develop long life or perpetual pavements that would require minimum maintenance. Such innovative methods would increase the pavement lifespan from the current 15-20 years [4, 5] to about 40 to 80 years [6] and hence reduce the maintenance cost significantly. The proposed methods involve an intentional incorporation of encapsulated healing agents [7-10], induction/microwave heating [2, 11-14] of asphalt pavements filled with metallic additives and the spraying of seal and heal agents [15-18] onto the surface of a cracked pavement. These technologies soften the binder around the fractured surface which then flow across the micro-cracks and repair the damaged region. Such approaches are reported to be effective in healing cracks of asphalt pavements [3, 19].

Although infusion of microcapsules/microfibers and induction heating of mixtures infused with conductive fillers is effective in repair of cracked asphalt mixtures, they involve total reconstruction of the aged pavement. Such an approach would be expensive compared to corrective techniques such as the seals technology. In addition, both technologies are inappropriate to heal wide and open macro-cracks because heating or spillage of the rejuvenators can neither close nor fill and seal the gap between the open crack surfaces. Current research direction is dedicated to crack healing agents which restore pavement imperviousness to ingress of water and debris, and also facilitate healing of the crack. These healing agents restore the load bearing and transfer ability of the cracked region, improve the healed regions' capability to resist crack opening and propagation, and facilitate rehealing in case the crack opens in future. Altogether, the pristine level of engineering performance in terms of stiffness, strength, toughness and viscoelasticity of the pavement is restored [20-22].

Generally, crack healing in influenced by several factors such as healing temperature, material aging, duration of time allowed for healing and the moisture state of the crack during crack treatment. It is widely reported that increase in temperature has a positive effect on crack healing [23-26]. In fact, induction /microwave heating approaches are based on this idea. Mixture aging is known to hinder crack healing [17, 27]. Ingress of moisture into a treated crack could interrupt the dipole balance by bonding with the polar groups of bitumen or aggregates or the water-soluble ions and salts linked within the polar sites of bitumen [28]. In terms the evaluation of healing in asphaltic materials, it is well known how the extent of healing is affected by upscaling from bitumen to mixtures. Further, the correlation between healing in the various subscales of asphaltic materials is unknown. Therefore, the objectives of this study was to: (a) investigate the effect of upscaling from bitumen to mixtures on crack healing of asphaltic materials treated with healing agents, (b) establish a correlation between healing at the subscales of asphalt materials with the healing of asphalt mixtures, (c) identify a subscale whose healing is most representative of healing in asphalt mixtures, (d) assess the feasibility of using HAs for crack healing of asphaltic materials.

2. MATERIALS AND EXPERIMENTAL TECHNIQUES

AC-13 basalt asphalt mixtures commonly used in the construction of the surface layer of an asphalt pavement were selected for this study. The gradation of this mixture was determined based on JTG E20-2011 [29]. The passing percentage at sieves of sizes 16, 13.2, 9.5, 4.75, 2.36, 1.18, 0.6, 0.3, 0.15 and 0.075mm were 100%, 95.1%, 76.5%, 53.2%, 37.1%, 26.5%, 19.2%, 13.5%, 9.9% and 5.8% respectively. The crushed stone value, Los Angeles abrasion value, flakiness and elongation index and specific gravity values of basalt aggregates were 12.0%, 7.8%, 8.5% and 2.961g/cm3 respectively. Limestone powder was used as the mineral filler, and it had a density of 2.83 g/cm3 and mineralogical composition of 51.8% CaO, 3.49% SiO_2 and 1.29% Al_2O_3. SBS modified asphalt with a penetration value of 72dmm, ductility of 52cm at 5ºC and softening point of 68.0ºC was used as the binder. The asphalt optimum content was determined as 4.7% based on the Marshall design method with specimens compacted with 75 blows per face. The optimum bitumen content of mortar was determined as 9.2% using the fine fraction in the asphalt mixture while the ratio of bitumen to filler in mastic was 1.2:1. The mastic and mortar subscales were designed to resemble the corresponding subscale in the mixtures.

Unaged (UA), short term aged (STA) and long-time aged (LTA) asphalt materials were used in this study. STA of bitumen was conducted by thin film oven test (TFOT) as specified by ASTM 1754 [30] while LTA aging was carried out by pressure aging vessel (PAV) test as specified by AASHTO R28 [31]. STA and LTA of mortar and mixtures was conducted according to AASHTO R30 [32]. Mortar and mixture testing was carried out using semicircular bending samples (SCB) (Fig -1) prepared according to AASHTO TP 105 [33]. Bitumen and mastic samples were prepared by casting a film on the surface of metallic discs with a diameter of about 18mm. A small drop of molten bitumen or mastic was deposited on the metallic disks and then pressed gently against a paper foil to a uniform thickness of 0.5±0.1mm (bitumen) or 0.75±0.1mm (mastic). This was designated as a one-piece sample. In the same manner, a two-piece sample with a thickness twice that of the one-piece sample was prepared such that it was sandwiched between two metallic disks. The peak strength of the two-piece sample represented the tensile strength of an undamaged binder. Figure 1 shows the one- and two-piece samples of bitumen. Tests on bitumen and mortar were carried out on samples casted on metallic discs (Fig -1) by tensile fracture-healing test method using a standard tensile machine (model ZQ-990A, China).

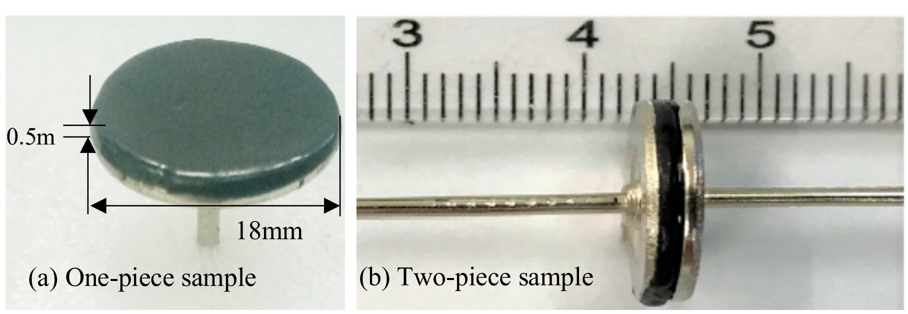


Fig -1: Asphalt samples; one-piece sample (a), two-piece sample (b).

Base bitumen emulsion (BBE) and two maltene based commercial pavement maintenance cationic emulsions (HA-2, and HA-3) were used as healing agents (HAs) in this study. BBE is a standard emulsion used in chip seals, micro-surfacing and flush coats. Maltene based emulsions had high content of aromatics which are considered to be crucial for rejuvenation of aged bitumen. Table 1 shows the chemical composition and viscosity of the emulsified HAs and their residues.

Table -1: Chemical composition and viscosity of the HAs.

Healing agent	Chemical composition (%)				Viscosity	
	Saturates	Aromatics	Resins	Asphaltenes	Residue at 60°C (Pa.s)	Emulsion at 25°C (mPa.s)
HA-2	**18.1**	**48.6**	**22.2**	**11.1**	**140-160**	**50-70**
HA-3	**12.2**	**70.1**	**11.2**	**6.5**	**100-120**	**45-65**
BBE	**14.1**	**29.6**	**43.5**	**12.8**	**210-230**	**150-170**

HAs were applied on the fractured surfaces of mortar and mixtures and one-piece samples of bitumen and mastic at a rate ranging from 0.4 to 0.7 kg/m^2 and 0.2-0.3kg/m^2 using a soft brush. Several trial tests were conducted and these rates was determined to be appropriate for total crack wetting with minimal excessive bleeding of the HAs. The treated samples were then reassembled and any leaking HA was wiped out. They were then stored in a direction normal to the treated faces such that the weight of the upper piece squeezed out any excessive HA and also maintained total overlap of the cracked surfaces. The samples were then healed in air or under water at 25, 35 or 45°C for 1 day. Another set of samples was prepared and healed in air for 1, 2, 4, 8, 15, 30, 60, 90 and 120 days. After the designated healing time, the samples were tested using their respective tests. For each test, 3 replicates were prepared and tested.

Healing was evaluated using peak strength healing index (PI) and fracture energy healing index (EI) defined according to Eqs. 1 and 2 respectively.

$$PI = \frac{F_h}{F_i} \times 100 \quad (1)$$

$$EI = \frac{E_h}{E_i} \times 100 \quad (2)$$

F and E are the peak strength and fracture energy respectively and the subscripts 'i' and 'h' indicate the response parameter tested initially and after the healing process respectively.

3. RESULTS AND DISCUSSIONS

3.1 Influence of material scale and type of healing agent

Figure 2 shows the recovered peak strength and fracture energy of bitumen, mastic, mortar and mixture scales healed at 25°C for 1 day. Bitumen healed without HAs recovered about 75% of its initial strength and 40% of its fracture energy. Cumulative addition of filler, fine aggregates and coarse aggregates decreased the recovered peak strength to 32%, 5.3%, and 0.1% respectively while fracture energy decreased to 22.5%, 5.6% and 0.05% respectively. This implied that additives with high specific surface area had a higher negative effect on healing. In addition, self-healing of mortar and mixtures was negligible. The strength recovered by HA treated bitumen, mastic, mortar and mixtures ranged from 29-47%, 23-44%, 30-45% and 31-37% respectively while the recovery fracture energy ranged from 6-21%, 7-14%, 9-12% and 14-24% respectively for the material scales. This indicated that HAs could induce significant healing in all scales of asphalt materials. Across the material scales, asphalt binder regained the highest peak strength and fracture energy. The healing rate decreased with upscaling from asphalt to mixtures. This could be ascribed to the increase in material stiffness with increase in the rigid particles, which negatively affected diffusion and other healing processes. Presence of the rigid particles also introduce stone-stone and stone-filler interfaces that do not heal under ordinary conditions.

Based on PI, the HAs increased the healing of asphalt mortar by 5- to 8-fold and that of mixtures by 60- to 74-fold. Similarly, the recovery of fracture energy of mortar increased by 1.5- to 2-fold and that of mixtures by 90- to 120-fold for all the HAs. Therefore, HAs induced healing of mixtures which barely healed intrinsically. Amongst the HAs, HA-3 induced the highest healing for all the material scales. It is crucial to note that mixtures are the scale closest to the real asphalt pavements, hence, their healing is a more reliable indicator of healing expected in practical applications. This analysis shows that use of carefully selected healing agents could restore the operational health of aged asphalt materials. Besides the high recovered material response parameters, HAs are also easy to apply. Hence, they have the potential for practical application in asphalt pavement maintenance industry.

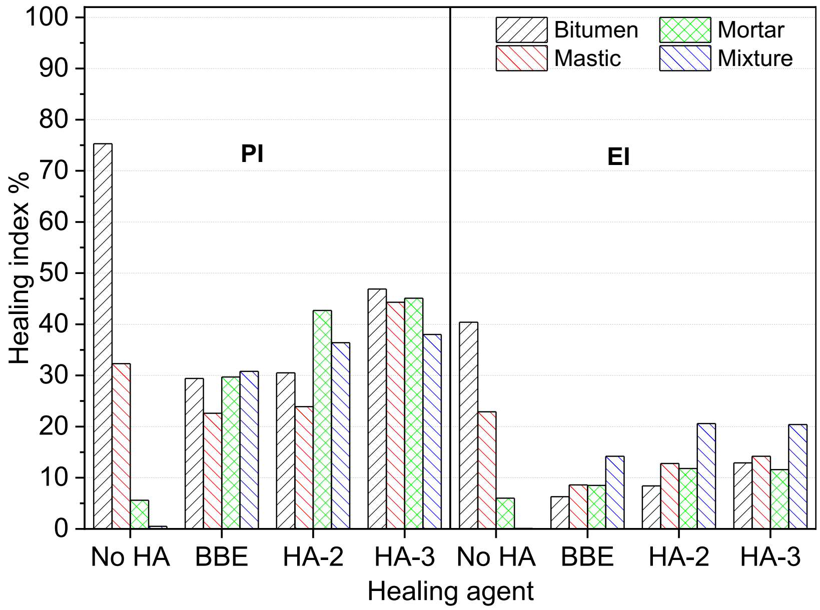


Fig -2: PI and EI of asphaltic materials healed at 25ºC for 1 day.

3.2 Correlation between healing of asphalt binder, mastic and mortar scales with healing at mixture scale.

Asphalt binder, mastic and mortar are usually considered to be the main binding subscales of asphalt mixtures. For this reason, the design of a pavement is based on the fundamental properties of these binding subscales. Therefore, it is imperative to identify a subscale whose properties correlate best with those of mixtures/pavements. Healing values of asphalt binder, mastic and mortar with and without HAs were plotted against the corresponding healing values of mixtures. Figure 3 shows the correlation between the healing performance of mixtures and that of the binding subscales. It is important to note that the data in this figure includes all the healing durations, healing with and without HAs and both PI and EI indexes. It is expected that a more representative subscale would show a performance that mirrors that of mixtures as closely as possible.

Data in Figure 3 was fitted with a linear model and the coefficient of determination values (R^2) for each subscale are indicated alongside the fitting models. The R^2 values of asphalt binder, mastic and mortar subscales were 0.08%, 12.2% and 83.5% respectively. The high R^2 values for the mortar subscale implied that healing in this subscale is closely related to that of mixtures. This hinted that healing of mortar could easily screen healing of mixtures since the healing trend was similar for both scales. On the contrary, healing of asphalt binder was least related to healing of mixtures. As observed earlier, the high healing performance of asphalt binder, both intrinsically and with HAs, did not translate to high healing for higher scales. Therefore, healing evaluation using both asphalt binder and mastic subscales could be deceptive because it doesn’t necessarily translate to the same healing trend for mixtures. Based on these findings, asphalt mortar is the most appropriate subscale to bridge the correlation gap between the binding phases and mixtures/pavement in a multiscale healing performance research.

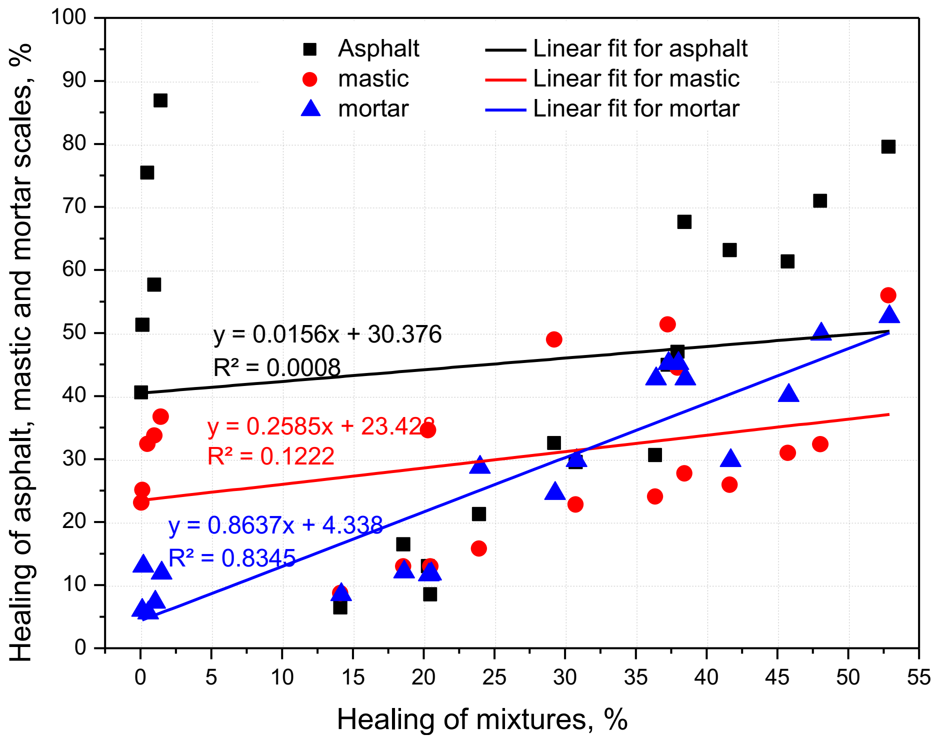


Fig -3: Correlation between healing of mixtures and healing of other material sub-scales.

3.3 Influence of test temperature and moisture state of the crack on healing

The effect of variations in healing temperature and moisture state of a treated crack is shown in Figure 4. A temperature rise from 25 to 45°C increased the recovered peak strength and fracture energy of untreated mixtures from 0.6 to 7.7% and 0.1 to 1.8% respectively. The generally low healing values confirmed that without use of HAs, healing was minimal at this scale. The increase in temperature raised the PI of mixtures treated with BBE, HA-2 and HA-3 by 4, 15 and 19% respectively. For the same rise in temperature, EI increased by 1.7, 7.1 and 8.9% respectively for the HAs. This implied that temperature had an important role in the healing of asphalt mixtures.

The influence of crack wetting was assessed by comparing the PI and EI of identical wet and mixture specimens. The difference between the restored strength of wet and dry samples healed at 25°C ranged from 1.2-11.9% for all the HAs. The corresponding difference in the restored fracture energy ranged from 0.5-6.9%. Therefore, moisture at 25°C had a nominal effect on healing mixtures when the HAs were applied on dry fracture surfaces. After healing the mixtures at 45°C using BBE, HA-2 and HA-3, the difference in PI of dry and wet specimens was 4, 8 and 6% respectively while the corresponding difference in EI was 2, 5 and 3% respectively. Although the negative effect of wetting was higher for mixtures and mortar healed at 45°C than those healed at 25°C, it is clear that all the differences could still be considered nominal. Therefore, when moisture at 25°C to 45°C wets treated cracks asphalt mixtures, the overall effect on healing is marginal.

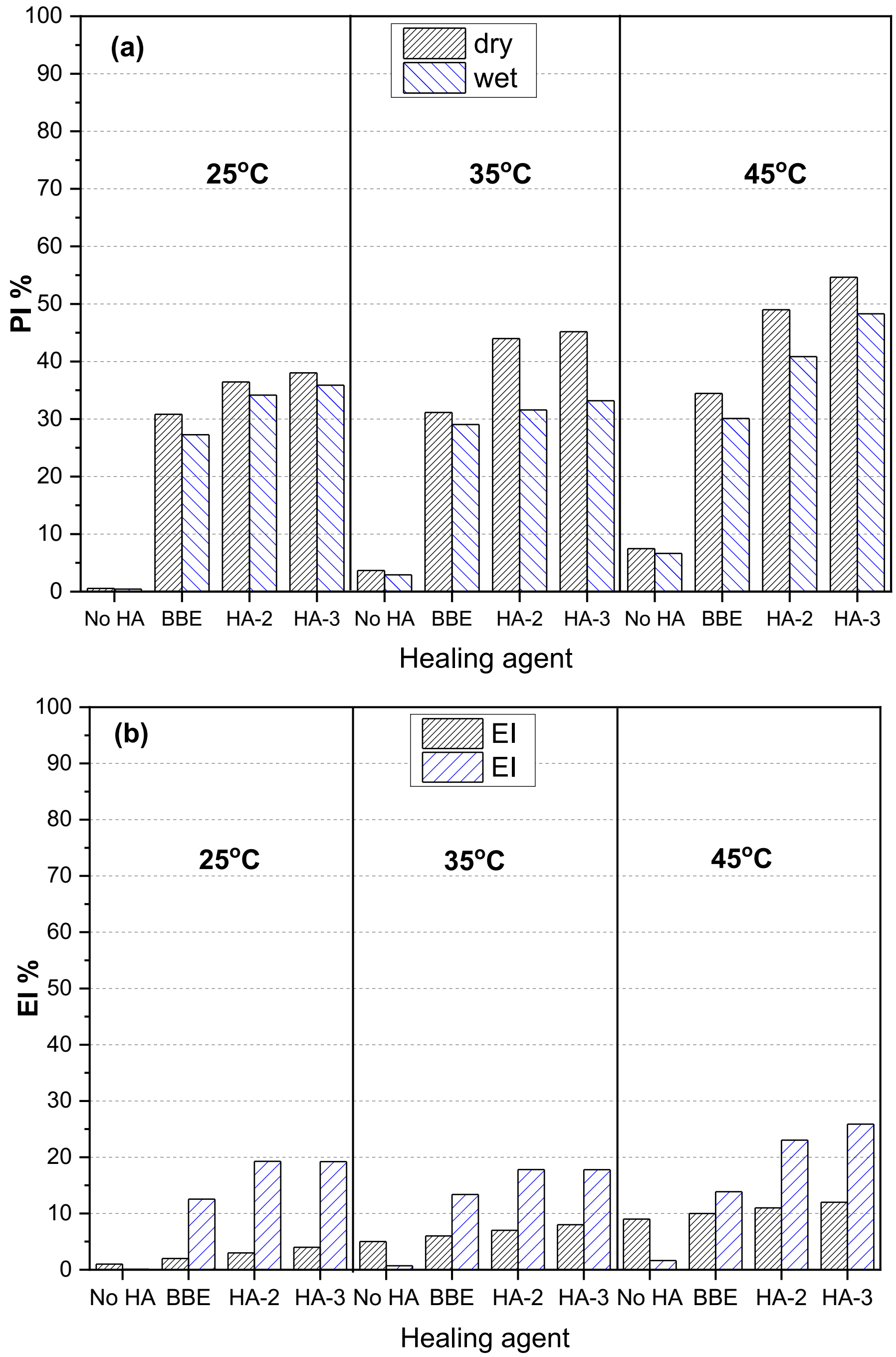
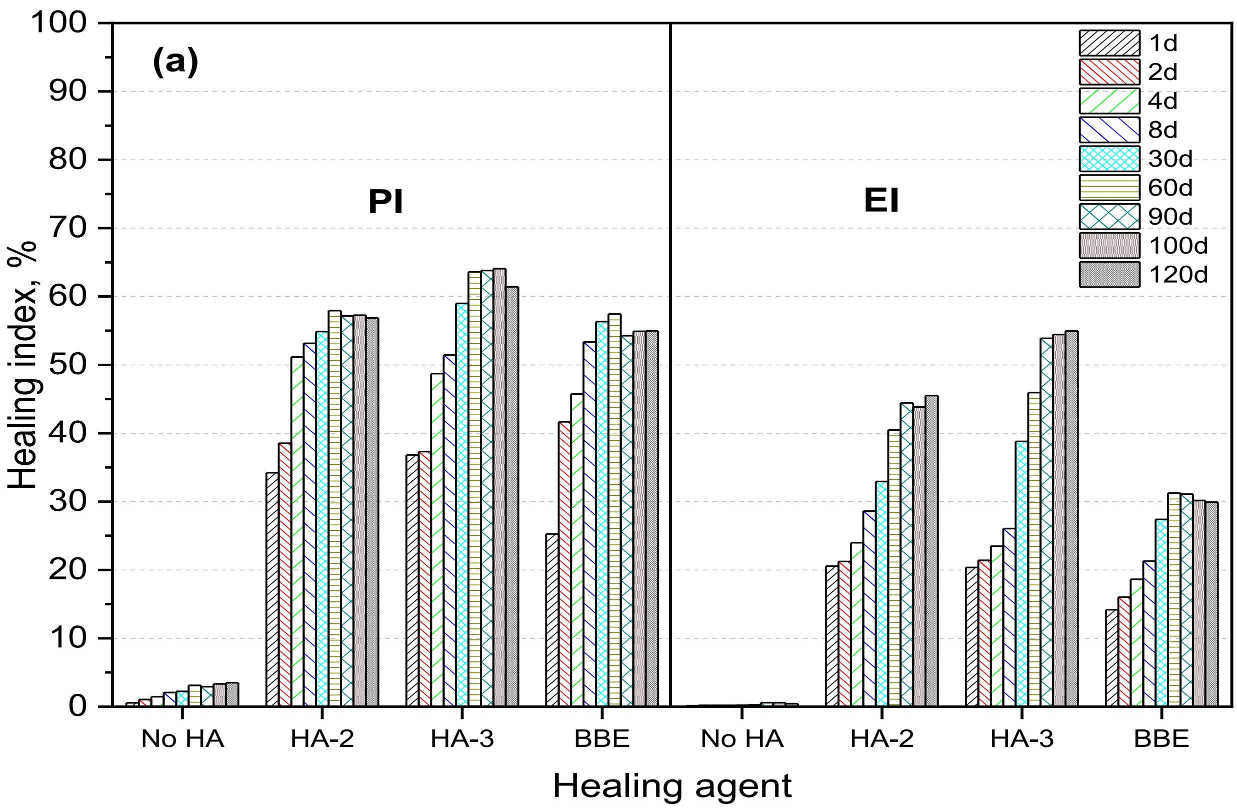


Fig -4: Peak strength (a) and fracture energy (b) recovered by wet and dry asphalt mixtures healed for 1 day at different temperatures.

3.4 Effect of aging and healing duration

The effect of healing time and aging of asphalt mixture samples on crack healing is illustrated in Figure 5 a and b. Figure 5a shows that the peak strength and fracture energy recovered by long time aged (LTA) asphalt mixtures was below 5% regardless of the healing time. When the LTA mixtures were treated with HAs, the recovered properties increased rapidly in the initial 4 days and then attained a near plateau in the successive period. It is expected that in the initial period of healing, there is a high concentration gradient of the light fractions which form the bulk of the HAs. Therefore, the rapid diffusion, capillarity and reptation of the HAs triggered a higher healing rate in this period. With time, the concentration gradient was erased and further healing occurred as the HAs dry and harden to form a rigid solid wedge within the treated open crack. This solid wedge induced a healing effect by improving the stress bearing and transfer ability of the treated crack. The recovered peak strength is higher than the recovered fracture energy. This is because as reported in our previous study, EI indicates a more comprehensive healing effect because fracture energy (sum of dissipated energy and the surface free energy) restored after apparent healing, signifies improved tensile strength, stiffness modulus and resistance to crack initiation and propagation [34]. Samples treated using HA-3 recovered the highest ultimate peak strength and fracture energy. This could be attributed to the high concentration of aromatic fractions in HA-3, which readily rejuvenated aged bitumen in the treated crack surfaces. This effect triggered the repair of secondary bonds that were destroyed during the aging process.

Figure 5b shows the healing data for aged and unaged mixtures after 8 days of healing. Clearly, unaged mixtures restored higher peak strength and fracture energy regardless of the type of HA. Aging affects the viscosity of bitumen by converting the oily components (aromatics) to the more viscous asphaltenes. This directly affects the wettability of bitumen and hence its ability to repair bonds broken during the cracking process. Therefore, the healing ability is highest for unaged mixtures and lowest for LTA mixtures.



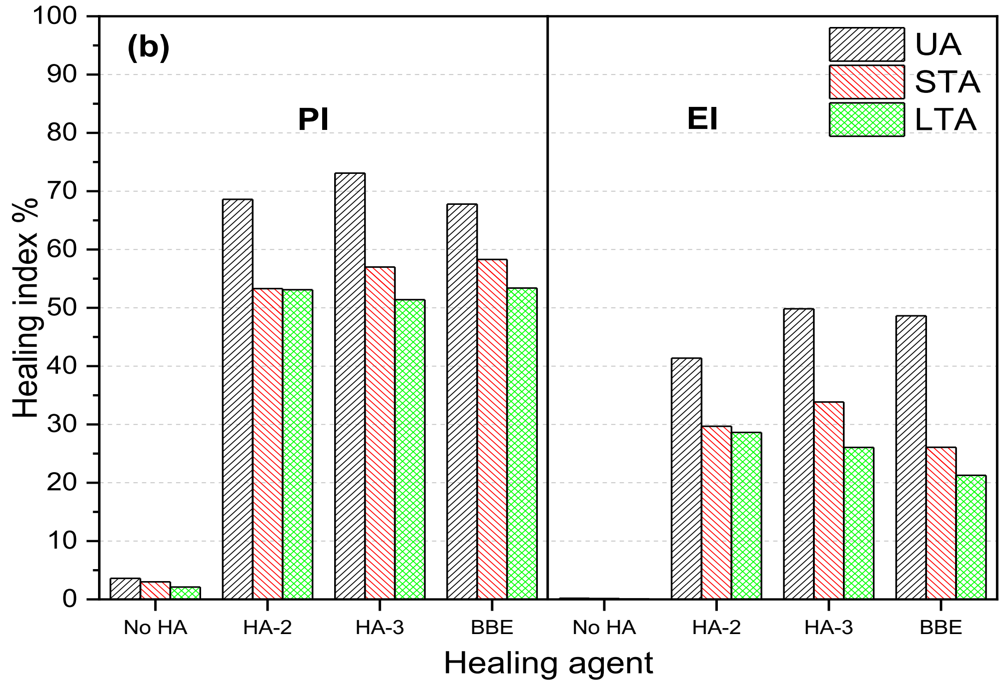


Fig -5: Peak strength and fracture energy restored by HA treated mixtures after different durations of healing (a) and different aging levels (b).

4. CONCLUSIONS

This study investigated the effect of material scale (bitumen, mastic, mortar and mixtures), choice of HA, temperature, moisture state of the crack, aging and healing duration on the healing performance of asphalt materials treated using HAs. Two maltene based HAs and base bitumen emulsion were used to heal fractured samples of the asphaltic materials. Healing was assessed based on the restored peak strength and fracture energy. From the test results and analysis conducted, the following conclusions were drawn:

i). Under normal traffic and ambient conditions, intrinsic self-healing of aged asphalt materials is significant at bitumen and mastic subscales and negligible at mortar and mixtures scales. Therefore, self-healing alone cannot restore the operational and functional performance of asphalt materials.

ii). Upscaling from bitumen to mixtures has a serious negative effect on healing. Cumulative addition of filler, fine aggregates and coarse aggregates decreased the recovered peak strength from 75% to 32%, 5.3%, and 0.1% respectively while fracture energy decreased from 40% to 22.5%, 5.6% and 0.05% respectively. Therefore, additives with high specific surface area had a higher negative effect on self-healing.

iii). Asphalt mortar is the most appropriate subscale to bridge the correlation gap between the binding phases and mixtures/pavements in a multiscale healing performance research. The healing trend of mortar was similar to that of mixtures and the correlation between these two scales was relatively high. Therefore, the mortar subscale could accurately screen healing of asphalt mixtures/pavements.

iv). Macro-cracks of aged asphalt materials could be healed using HAs. After long time healing of LTA asphalt mixtures treated with HAs, up to 65% of initial peak strength and 55% of fracture energy was recovered. Maltene based cationic emulsions induced better healing than base bitumen emulsion. The improved healing of mortar and mixtures subscales using HAs indicated that carefully selected HAs have the potential to heal cracks in asphalt pavements.

v). Asphalt material scale and the selected test design parameters have a significant effect on healing attained by asphalt materials. A judicious selection of the appropriate combination of these variables is crucial in a healing test design.

REFERENCES

[1] Schwartz CW, Gibson N, Schapery RA. Time-Temperature Superposition for Asphalt Concrete at Large Compressive Strains. Transportation Research Record. 2002;1789(1):101-12.
[2] Apostolidis P, Liu X, Scarpas A, Kasbergen C, van de Ven M. Advanced evaluation of asphalt mortar for induction healing purposes. Construction and Building Materials. 2016;126:9-25.
[3] Sun D, Sun G, Zhu X, Guarin A, Li B, Dai Z, et al. A comprehensive review on self-healing of asphalt materials: Mechanism, model, characterization and enhancement. Advances in Colloid and Interface Science. 2018;256:65-93.
[4] Ministry of Transport. JTG D50-2017: Specification for Design of Highway Asphalt Pavement. Beijing, China: China Communications Press; 2017.
[5] Quintus H, Mallela J, Jiang J, Buncher M. Expected Service Life of Hot-Mix Asphalt Pavements in Long-Term Pavement Performance Program. Transportation Research Record: Journal of the Transportation Research Board. 2007;1990:102-10.
[6] Tabaković A, Schlangen E. Self-Healing Technology for Asphalt Pavements. In: Hager MD, Zwaag S, Schubert US, editors. Self-healing Materials. Cham: Springer International Publishing; 2016. p. 285-306.
[7] Al-Mansoori T, Micaelo R, Artamendi I, Norambuena-Contreras J, Garcia A. Microcapsules for self-healing of asphalt mixture without compromising mechanical performance. Construction and Building Materials. 2017;155:1091-100.
[8] Cuvellier A, Torre-Muruzabal A, Van Assche G, De Clerck K, Rahier H. Selection of healing agents for a vascular self-healing application. Polymer Testing. 2017;62:302-10.
[9] Li R, Zhou T, Pei J. Design, preparation and properties of microcapsules containing rejuvenator for asphalt. Construction and Building Materials. 2015;99:143-9.
[10] Shu B, Wu S, Dong L, Wang Q, Liu Q. Microfluidic Synthesis of Ca-Alginate Microcapsules for Self-Healing of Bituminous Binder. Materials. 2018;11(4):630.
[11] Dai Q, Wang Z, Mohd Hasan MR. Investigation of induction healing effects on electrically conductive asphalt mastic and asphalt concrete beams through fracture-healing tests. Construction and Building Materials. 2013;49:729-37.
[12] Franesqui MA, Yepes J, García-González C. Top-down cracking self-healing of asphalt pavements with steel filler from industrial waste applying microwaves. Construction and Building Materials. 2017;149:612-20.
[13] Phan TM, Park D-W, Le THM. Crack healing performance of hot mix asphalt containing steel slag by microwaves heating. Construction and Building Materials. 2018;180:503-11.
[14] Sun Y, Wu S, Liu Q, Zeng W, Chen Z, Ye Q, et al. Self-healing performance of asphalt mixtures through heating fibers or aggregate. Construction and Building Materials. 2017;150:673-80.
[15] Lin J, Hong J, Huang C, Liu J, Wu S. Effectiveness of rejuvenator seal materials on performance of asphalt pavement. Construction and Building Materials. 2014;55:63-8.
[16] Pan C, Tang P, Riara M, Mo L, Li M, Guo M. Effect of Healing Agents on Crack Healing of Asphalt and Asphalt Mortar. Materials. 2018;11(8):1373.
[17] Riara M, Tang P, Mo L, Chen M, Zhang J, Wu S. Experimental assessment of the long-time crack healing in asphalt mixtures using healing agents. Construction and Building Materials. 2018;191:411-22.
[18] Riara M, Tang P, Mo L, Javilla B, Wu S. Investigation into crack healing of asphalt mixtures using healing agents. Construction and Building Materials. 2018;161:45-52.
[19] Ayar P, Moreno-Navarro F, Rubio-Gámez MC. The healing capability of asphalt pavements: a state of the art review. Journal of Cleaner Production. 2016;113:28-40.
[20] Boatemaa L, Kwakernaak C, van der Zwaag S, Sloof WG. Selection of healing agents for autonomous healing of alumina at high temperatures. Journal of the European Ceramic Society. 2016;36(16):4141-5.
[21] Bekas DG, Tsirka K, Baltzis D, Paipetis AS. Self-healing materials: A review of advances in materials, evaluation, characterization and monitoring techniques. Composites Part B: Engineering. 2016;87:92-119.
[22] Scheiner M, Dickens TJ, Okoli O. Progress towards self-healing polymers for composite structural applications. Polymer. 2016;83:260-82.
[23] García Á. Self-healing of open cracks in asphalt mastic. Fuel. 2012;93:264-72.
[24] García A, Norambuena-Contreras J, Bueno M, Partl MN. Single and multiple healing of porous and dense asphalt concrete. Journal of Intelligent Material Systems and Structures. 2015;26(4):425-33.
[25] Tang J, Liu Q, Wu S, Ye Q, Sun Y, Schlangen E. Investigation of the optimal self-healing temperatures and healing time of asphalt binders. Construction and Building Materials. 2016;113:1029-33.

[26] Liu Q, Schlangen E, van de Ven M, van Bochove G, van Montfort J. Evaluation of the induction healing effect of porous asphalt concrete through four point bending fatigue test. Construction and Building Materials. 2012;29:403-9.
[27] Bergh V. The effect of aging on the fatigue and healing properties of asphalt mortars [Ph.D]. Netherlands: Delft University of Technology; 2011.
[28] Riara M, Tang P, Mo L, Hong W, Chen M, Wu S. Evaluation of moisture and temperature effect on crack healing of asphalt mortar and mixtures using healing agents. Construction and Building Materials. 2018;177:388-94.
[29] Ministry of Transport. JTG E20-2011: Standard Test Methods of Bitumen and Bituminous Mixtures for Highway Engineering. Beijing, China: China Communications Press; 2011.
[30] American Society for Testing and Materials. ASTM D 1754: Standard test method for effects of heat and air on asphaltic materials (thin-film oven test). Annual book of ASTM standards. Washington DC, USA: ASTM; 2009.
[31] American Association of State Highway and Transportation Officials. AASHTO R 28: Accelerated Aging of Asphalt Binder Using a Pressurized Aging Vessel (PAV) Washington DC, USA: AASHTO; 2012.
[32] American Association of State Highway and Transportation Officials. AASHTO R30: Standard practice for mixture conditioning of hot-mix asphalt (HMA), Standard specifications for transportation materials and methods of sampling and testing, 30th ed. Washington DC, USA: AASHTO; 2015.
[33] American Association of State Highway and Transportation Officials. AASHTO TP 105: Standard method of test for determining the fracture energy of asphalt mixtures using the Semicircular Bend geometry (SCB). Washington DC, USA: AASHTO; 2013.
[34] Riara M, Tang P, Mo L, Javilla B, Chen M, Wu S. Systematic Evaluation of Fracture-Based Healing Indexes of Asphalt Mixtures. Journal of Materials in Civil Engineering. 2018;30(10):04018264.