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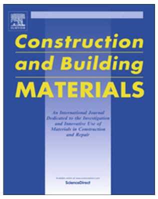

Investigation into crack healing of asphalt mixtures using healing agents

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HIGHLIGHTS

- Cracks in asphalt pavements can be healed effectively using healing agents.
- Crack healing depends on agent type, healing time and aging of mixture.
- Initial healing had the highest contribution to the ultimate healing.
- Multiple fracture-rehealing performance is useful in selection of healing agents.
- Re-healing performance is sensitive to the drying rate of healing agents.

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ABSTRACT

This study investigated the crack healing ability of aged and unaged AC-13 basalt asphalt mixtures using five healing agents. Notched semicircular asphalt mixtures were cracked and healed using the healing agents and the recovered critical load at fracture was adopted as a healing indicator. Crack healing was found to be dependent on the type of healing agent, healing time and aging of mixture. A maximum healing up to 73% was obtained after 8 days of uninterrupted healing. Multiple fracturing-rehealing of the healed mixture didn't significantly affect the healing index (HI) of the successive cycles. The re-healing performance was sensitive to the drying rate of healing agents, and a high drying rate reduced the re-healing performance. The first day of healing had the highest contribution to the ultimate healing potential, and further increase in the healing duration resulted in a steady increase in healing index. The high healing performance indicated that carefully selected healing agents have the potential to heal cracks in asphalt pavements.

1. Introduction

Asphalt mixtures are the most common pavement construction materials worldwide and their basic structures comprise of graded aggregates and fillers bound by an asphalt binder. The aggregates form the structural backbone of the pavement while the asphalt binder acts as an adhesive to maintain the aggregates in their relative positions [1]. Deterioration of the asphalt binder during its service life is inevitable considering that asphalt pavements experience harsh environmental and loading conditions which include: thermal and UV aging, traffic loading and moisture damage [2–5]. Asphalt pavement maintenance has recently attracted a lot of attention especially in China where most expressways have been in service for a long period of time and their performance has deteriorated. Maintenance is either preventive, corrective or a total reconstruction process [6]. The latter is capital intensive whereas preventive and corrective measures are considered the most economical.

Recently, some researchers have developed an innovative technology towards preventive maintenance of asphalt pavements. Radio or microwave electromagnetic radiations were used to induce a heating effect in steel fiber reinforced asphalt pavements. Using this technology, successful healing of cracks in mastic and asphalt mixtures was reported [7–10]. Laboratory cracked mastic and porous asphalt concrete beams could recover almost 80% of their initial fracture strengths [8,11]. Induction heating technology is still in its trial stages, and most asphalt pavements currently are not steel fiber reinforced to guarantee successful implementation of this technology in healing. Most road engineers still rely on sealing technologies for preventive maintenance purposes.

Chip seals, fog seals and micro-surfacing technologies have been practiced since the 1970s. Initially, these technologies focused on treating emerging cracks through 'filling'. This was con-

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sidered a good procedure for minimizing the emergence of new cracks and inhibiting the growth of already formed micro cracks. In cases where macro cracks were formed, crack filling using hot or cold poured crack sealants was a common practice [12]. Crack sealants however often fail due to the weak adhesion with the cracked surfaces. The proposed current research direction is focused on sealants that go beyond mere sealing of cracks to healing and rejuvenation of bitumen in the neighborhood of the cracked surfaces. As a result, microcapsules which rapture under stress and release rejuvenators that diffuse into the micro cracks have been proposed [13,14]. The rejuvenators held in the microcapsules dissolve the bitumen to increase its flow and healing capacity [15].

Rejuvenator seals have been used to improve the viscosity, penetration and ductility of aged asphalt binders in both asphalt road and airfield pavements [16–19]. For instance, Zhu et al. (2017) used bio-binder/plasticizer based rejuvenator materials to improve the workability and rutting resistance of laboratory long-term aged asphalt binders [20]. Component analysis demonstrated that the bio-rejuvenators were effective in restoring the content of the medium and light weight molecular components lost during the aging process. The functional role of the rejuvenators is to increase the aromatic content in the aged mixture and also increase the ratio of small molecules to large molecules. Sun and coworkers found out that a higher small molecule content/large molecular content ratio, higher aromatics content and a higher short-branched chains promotes healing [21]. Use of rejuvenators has also been favored because they are thermally stable and become active during pavement loading to provide self-healing to the pavement [22].

While a lot of research has been done on the rejuvenation effect of aged asphalt binders using rejuvenators, little has been explored on the ability of these agents to heal cracks within the asphalt pavement. Improvement in the adhesive zone is expected to result in asphalt mixtures with improved performance and extended service life [23,24]. The objective of this research was to study the crack healing performance of rejuvenating/healing materials in aged asphalt mixtures. Five crack healing materials were used to heal cracked semicircular asphalt mixture samples. The ability of these healing agents to reheal cracks after multiple fracturing-rehealing was also investigated. Further still, the effect of aging on cracking, healing and rehealing effect was also evaluated.

2. Materials and experimental program

2.1. Materials

AC-13 basalt asphalt mixture that is widely applied for surface course was designed for this study. The number 13 denoted the nominal maximum aggregate size according to Chinese standard JTG E20-2011 [25]. The basic properties of the basalt aggregates were: crushed stone value of 12%, Los Angeles abrasion value of 7.8%, Flakiness and elongation index of 12.5% and specific gravity of 2.961 g/cm^3. Table 1 shows the gradation of the basalt aggregates. Limestone powder with a density of 2.83 g/cm^3 was used as the mineral filler. Its main chemical compounds were 51.8% CaO, 3.49% SiO_2 and 1.29% Al_2O_3. SBS modified asphalt was used as the binder for mixtures and its optimum asphalt content was determined as 4.9% based on the Marshall design method with specimens compacted with 75 blows per face. This binder had a penetration value of 73 dmm, viscosity of 0.645 Pa·s at 135 °C, ductility of 52.1 at 5 °C and softening point of 68 °C.

Table 1
Aggregate gradation used to prepare asphalt mixtures.

Sieve size (mm)	Specification (%)	Designed gradation (%)
16	100	100
13.2	90–100	95.1
9.5	68–85	76.5
4.75	38–68	53.2
2.36	24–50	37.1
1.18	15–38	26.5
0.6	10–28	19.2
0.3	7–20	13.5
0.15	5–15	9.9
0.075	4–8	5.8

Five healing agents were used for this work. Three of the agents; HA-1, HA-2, and HA-3 were commercial pavement maintenance agents, whose ingredients are the subject of a pending Chinese patent [26]. BBE and SBRE were base asphalt emulsion and SBR modified asphalt emulsion respectively. All of the five agents are cationic emulsion with a residue larger than 50%. Table 2 shows the chemical composition of the residue of the five agents by means of thin-layer chromatography [27] and the viscosity of emulsions and their residue at 25 and 60 °C respectively. The chemical composition presented in Table 2 indicates that HA-1, HA-2 and HA-3 are maltene based emulsion with high content of aromatics, which is reported to be of importance for the self-healing of asphalt [20]. Unlike standard asphalt emulsion of BBE and SBRE, the residue of the other three agents are very oily and sticky. BBE and SBRE met the related technical requirements on PC-1 base asphalt emulsion (BBE) and PCR modified asphalt emulsion according to Technical Specification for Construction of Highway Asphalt Pavements (JTG F40-2004) [28].

2.2. Aging procedure

Effects of AC-13 mixture aging on crack healing were considered in this study. Three categories of test samples namely unaged (UA), short term aged (STA) and long term aged (LTA) were prepared. As for STA mixtures, loose mixtures were spread on a metallic pan to a height of 50 mm and then placed in a force draft oven at 135 °C for 4 h. The samples were stirred after every 1 h. This process simulated asphalt aging process in the field from the time of mixing to compaction. LTA samples were prepared by placing STA compacted samples in an oven at 85 °C for 5 days. This procedure simulated about 5 years of field aging [29]. Both aging processes were conducted according to AASHTO R30 [30].

2.3. Sample preparation

A semicircular bending test (SCB) was adopted to evaluate the fracture resistance of the asphalt mixtures before and after the healing process. This test is commonly used to evaluate the healing potential of asphalt mixtures in the laboratory [10,31]. To make SCB test samples, a Superpave gyratory compactor model Troxler-4140, USA was used for compacting samples to an N_{design} of 75 gyrations at a target air void of 4 ± 0.5%. The samples were cored to a diameter of 100 mm and then sliced into discs each with a thickness of 25 mm as specified in AASHTO TP105 [32]. The discs were then cut into two halves. A notch, 10 mm deep and 4 mm thick was cut at the midpoint along the loading direction as shown in Fig. 1.

2.4. Semi circular bending test

A universal testing machine (UTM-25) was used to carry out SCB testing on the fabricated samples. Before testing, all the samples were preconditioned in the temperature chamber at −10 °C for 4 h. This temperature was chosen to avoid any creep deformation and to create a brittle fracture on the samples [10,12,35]. The samples were loaded at the rate of 0.5 mm/min. The load and vertical displacement were recorded automatically by the control system. Once the sample was completely broken, it was preconditioned in ambient room temperature for 2 h in order to allow the temperature of the samples to rise to about 25 °C. This was done to ensure that all the moisture that had condensed on the surface of the sample due to freezing, dried completely. The stiffness of the mixtures was evaluated from the linear region of the load-displacement curve. Fracture energy (E_f) was calculated according to Eq. (1).

$$E_f = \frac{W_f}{A_{lig}} \tag{1}$$

Ligament area (A_{lig}) is the area of the crack face evaluated according to Eq. (2).

$$A_{lig} = (r - a)t \tag{2}$$

where a, r and t are the specimen's crack length, radius and thickness respectively. Work of fracture (w_f) was computed from area under the load-displacement curve according to Eq. (3).

$$W_f = \sum_{i}^{n} \frac{1}{2}(F_{i+1} + F_i)(d_{i+1} - d_i) \tag{3}$$

where d_i is the displacement at the ith position when the loading force is F_i.

2.5. Application of the crack healing agents

A soft brush was used to apply the crack healing agents on the cracked faces. Different spreading rates were adopted for different agents in order to avoid excessive bleeding of the agents due to their differences in viscosity and residue content. After several trial tests on identical samples, a spreading rate of 0.7, 0.6, 0.4, 0.5 and