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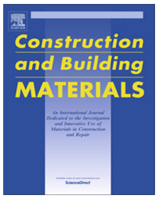

Investigation of the influence of crack width on healing properties of asphalt binders at multi-scale levels

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HIGHLIGHTS

- The healing evolution of asphalt binder is directly monitored under FESEM image analysis.
- The healing rate of asphalt binder is found to be nonlinear based on direct image analysis.
- Temperature and aging have important effect on the healing of asphalt binder under FESEM monitoring.
- Healing is triggered by the diffusion mechanism of asphalt molecules based on MD simulation.
- Crack width directly influences asphalt healing; asphalt heals faster with smaller width.

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ABSTRACT

Crack width, a practical measurement of the damage severity in the field, is conceptually believed to have important influence on the healing properties of asphalt materials. Understanding the relationship between crack widths and healing capacity of asphalt pavement provides practical linkage between the microscopic healing phenomena and the macroscopic pavement performance. The objective of this paper is to characterize the healing behavior of asphalt binders with different crack width at multi-scale levels. A Field Emission Scanning Electron Microscopy (FESEM) was used to directly monitor the effect of crack width on healing at macroscale level. Small scale molecular dynamics (MD) simulation models with different crack widths were built to investigate the micromechanical healing mechanism of asphalt binder and characterize the influence of crack width on healing. The MD modeling was conducted using an open-source code software LAMMPS (Large-scale Atomic/Molecular Massively Parallel Simulator). Healing was found to be triggered by the diffusion mechanism of asphalt molecules. Higher temperature would result in higher diffusivity of molecules and thus higher healing rate. Degree of aging would also have important impact on healing. Both the macroscopic and microscopic investigation indicated that crack width had important influence on the healing of asphalt. For the same crack length asphalt heals faster when the width of crack is smaller.

1. Introduction

The self-healing properties of asphalt materials have been investigated by many researchers. Most studies focused on mechanical experiments to compare the improved engineering properties (dynamic modulus, flexural stiffness, viscosity, etc.) of the damaged materials before and after rest periods [16,17,14]. However, direct observation of the self-healing phenomenon has always been a challenge due to the lack of a well-controlled experimental method and the limitations in image analysis tools.

Crack width, a practical measurement of the damage severity in the field, is conceptually believed to have important influence on the healing of asphalt materials. Understanding the relationship between crack widths and healing capacity of asphalt pavement provides practical linkage between microscopic healing phenomena and the macroscopic pavement performance, therefore offer insights to the characterization of asphaltic materials. However, in current literature the effect of crack width on healing has never been evaluated either from macroscopic level or from microscopic level. Although some attempts have been made to understand the fundamentals of healing behavior and mechanism [2], none of the

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existing research has evaluated the effect of crack size/geometry on healing behavior.

Therefore, the objective of this study is to explore the healing behavior of asphalt binders with different crack sizes at multiscale levels. First, Field Emission Scanning Electron Microscopy (FESEM) is used to visualize the healing phenomenon of asphalt binders and demonstrate visually the effect of crack width on healing. Then, the Molecular Dynamics (MD) procedure, a classical computational simulation method that simulates the physical movements and interactions of atoms and molecules, is applied to preliminarily evaluate the mechanisms of healing behavior with a focus on the effect of crack size/geometry on healing. Qualitative correlation between the macroscopic image analysis and the microscopic MD analysis can thus be determined. The MD simulation provides an opportunity to investigate the effect of crack size on healing by varying the simulation model geometries. This is otherwise impossible to be realized in the real experimental testing.

2. Visualization of healing phenomenon

The direct visualization of the healing phenomenon of asphalt binder was performed with the aid of a scanning electron microscope (SEM) device. A scanning electron microscope (SEM) is a type of electron microscope that produces images of a sample by scanning it with a focused beam of electrons instead of light. The electrons interact with atoms in the sample, producing various signals that contain information about the sample's surface topography and composition. Nonconductive specimens tend to charge when scanned by the electron beam. They are therefore usually coated with an ultrathin coating of electrically conducting material.

Asphalt is nonconductive material requiring coating on the surface in a conventional Scanning Electron Microscopy (SEM) image machine. However, coating may interfere with the surface characteristics of asphalt binder hence influence the healing process in the asphalt materials. A newer version of SEM, FESEM (Fig. 1) uses a lower beam current which reduces the charging of the sample. Need for placing conducting coatings on insulating materials is virtually eliminated on FESEM, making FESEM ideal for testing the surface properties of asphalt materials. Another advantage of FESEM is that sample stub and the chamber can be maintained at target temperatures, making it possible to observe the evolution of healing of a pre-damaged sample at different temperatures.

Fig. 1. Field emission scanning electron microscopy (JSM-7001F FESEM).

2.1. Testing procedure on FESEM

FESEM has a vacuum environment with very low pressure, which could cause asphalt binder bubbling inside of the chamber at ambient or higher temperatures. It could bring damage to the machine and may also disturb the true healing progress at the surface of asphalt materials. Therefore, all the images for this study were only taken under the vacuum mode at −10 °C temperature. During the rest, vacuum pressure was released and the chamber temperature was controlled at the target healing temperature.

Specifically, the steps for FESEM image analysis of asphalt binder included:

1. Prepare an asphalt sample in the silicone mode (8 mm in diameter and 2 mm in thickness) using hot pouring method to ensure a smooth and flat surface.
2. Make a cut crack at the surface of the asphalt sample using a razor blade heated at intermediate temperature. A blade at room temperature could not create a sharp crack and a very hot blade could melt the surface of the sample. The width of the cut crack are changed by adjusting the width of the razor blades to achieve narrow and wide cracks. The depth of the cut crack are manually controlled to maintain the similar crack depth, so that the effect of crack width on healing can be studied exclusively. An example of the cut crack in asphalt sample is shown in Fig. 2(a).
3. Measure and record the exact width of the crack in FESEM length measure mode.
4. Take images in the environmental mode (ESEM mode) at −10 °C temperature.
5. Release the vacuum seal and bring the temperature up to the target healing temperature.
6. Keep the cracked sample within the chamber for designated time period at target healing temperature to allow healing.
7. Repeat steps 4–6 at specific time intervals until three hours healing time at the target temperature is reached.

Table 1 lists the material types and experimental conditions to be evaluated under FESEM image analysis. Specifically, the study evaluated two types of binders, non-polymer modified PG64-28 binder and polymer modified PG70-28 binder. The two different sizes of crack widths (80 μm and160 μm) corresponded to lower and higher damage level respectively. The healing temperature was controlled between 10 and 30 °C, a temperature range that fatigue cracking and healing generally happen in the field.

2.2. Results from FESEM

2.2.1. Healing phenomenon and healing rate with time

Fig. 3 shows the microscopic images of the healing process of the PG64-28 binder for the newly cut sample in Fig. 2(a). The crack width is about 160 μm, and the temperature is at 20 °C. Half an hour later, it is obvious that the depth of the crack became smaller. Approximately one hour later, the edges of the crack became blurry. The image after two hours was very similar to the one at one hour later, indicating the healing process could be gradual and taking hours to happen. The last image was taken several days after the crack was created and one can see that the crack has disappeared and the surface of the crack area became as smooth as the remaining sample surface. As shown in Fig. 2(b), the asphalt sample was completely healed.

From Fig. 3, it is also noticed that the healing rate is not consistent throughout the healing process. Cracks healed faster at the beginning. The depth of the crack became shallower and the edge of the crack became blurry within 30–40 min after the healing started. It took much longer time later to achieve complete crack