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Induced heating-healing characterization of activated carbon modified asphalt concrete under microwave radiation

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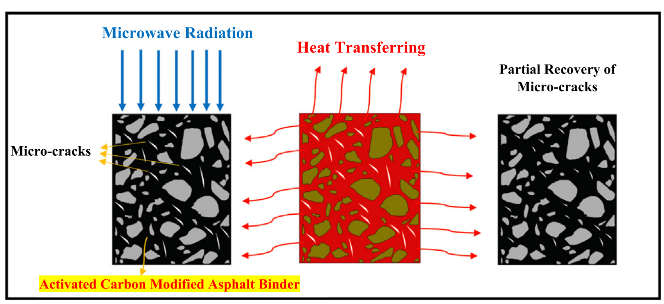
HIGHLIGHTS

- Activated carbon (AC) is proposed as the modifier to increase the electro-magnetic sensitivity.
- Induced heating and healing of the asphalt concrete were studied.
- AC enhances the electro-magnetic absorption of asphalt concrete without degrading the performance.
- AC promotes the induced healing index (HI) of the asphalt concrete.
- The effects of the testing mode, crack length, temperature and damage level on HI were investigated.

GRAPHICAL ABSTRACT

The activated carbon, as a binder-based modifier, is added to the asphalt concrete to enhance electro-magnetic (e.g., microwave) radiation absorption. The supplied microwave power leads to heating the modified asphalt binder inside the asphalt concrete through the eddy current (i.e., electrical) and high speed rotation of the bipolar molecules (i.e., magnetic) mechanisms. Raising the internal temperature causes the asphalt binder to flow through the micro-cracks. The flowing asphalt binder wets the micro-cracks surfaces and partially heals the damages.



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ABSTRACT

This research investigates the crack healing ability of activated carbon (AC) modified asphalt concrete through microwave radiation. As a binder-based conductive additive, AC is expected to increase the electro-magnetic radiation absorption of asphalt binder. To verify this issue, neat and modified binders with different contents of AC were exposed to microwave radiation. It was found that the temperature of AC modified binder increased considerably after microwave heating compared to that of the neat binder. This observation can be regarded as a driving force to use AC in asphalt for the healing purposes. Moreover, statistical analysis of testing results showed that the AC modification did not have any detrimental effect on the asphalt performance. For further evaluation of the healing ability of AC modified asphalt, cycles of breaking and healing were applied to a number of semicircular bending (SCB) and indirect tensile (IDT) testing samples. Notch length, damage level (number of breaking-healing cycle), and aggregate source were found to have significant effects on the induced healing efficiency. The obtained results confirmed that AC is a potentially viable and robust binder-based conductive component for induced heating and healing of asphalt concrete.

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1. Introduction

Asphalt concrete materials are used in various climatic and traffic conditions across the world as a surfacing material, due to its economy, ease of construction, smoothness, and to meet other functional requirements. Being subjected to the different traffic and climatic conditions, asphalt concrete undergoes damage and distresses. The damage in the asphalt concrete often initiates by forming micro-cracks. The cyclic loading applied on the asphalt pavement causes the micro-crack to propagate and form visible cracks. The cracks can adversely affect the serviceability of the pavement and lead to formation of more severe distresses such as frost heave and potholes. The increasing costs of construction, management and maintenance of flexible pavements have motivated researchers to study healing characterizations of asphalt pavements.

Asphalt concrete crack/micro-cracks can be healed through an induced healing process. The induced healing procedure is different from self-healing phenomenon. Induced healing is applied to close the crack/micro-cracks by supplying an external energy; while, self-healing is defined as the ability of a material to heal its crack/micro-crack during the rest times when no external force and energy are applied [1–3]. The induced healing process of the asphalt concrete involves three steps including crack closuring, wetting and then fusion of the crack/micro-crack edges. The wetting of edges facilitates the potential of crack healing as the temperature increases. After getting warm enough to reach Newtonian fluid temperature, binder can flow through and fill in the cracks and micro-cracks. An alternating magnetic and electro-magnetic field can provide the heat needed to make the binder flow. In pavement engineering, this procedure is defined as induced healing technology [4–8]. When effectively applied, induced healing can substantially contribute to the pavement works such as saving the resources, reduction of the traffic disruption caused by road maintenance, decreasing CO_2 emission during the road treatments and improving safety.

To facilitate heating of the asphalt concrete, electrically conductive particles can be added to asphalt concrete. Adding conductive particles to asphalt concrete increases absorption of the electro-magnetic radiation and leads to enhancement of induction heating. Steel wool fiber (SWF) and iron particles are among the most frequent additives used to accelerate the heating process of asphalt concrete [4–7,9,10]. Despite the ease of application and its prevalence, SWF modified asphalt suffers from considerable defects. As an example, heterogeneous distribution of SWF results in higher air voids and causes poor durability of asphalt concrete [7,10,11]. In addition, the iron particles lead to a heterogeneous temperature distribution causing the aging of the asphalt binder around the particles [4]. To overcome these issues, a binder-based additive which is homogenously mixed and placed within the mixture should be implemented. At the same time, this additive should provide the electro-magnetic absorption to accelerate the heating of the asphalt concrete in order to heal the cracks [8].

Carbonaceous materials are among the most frequently used electro-magnetic absorbent additives due to their space charge polarization [12]. Several studies have shown that the addition of activated carbon (AC) to different materials (e.g., soil and wastewater) through dielectric properties effectively developed the ability to absorb electro-magnetic radiation [12–15]. Zhang et al. [14] showed that uneven surface of AC absorbs the microwave energy and leads to a significant rise in temperature. This approach was successfully used to effectively increase the soil temperature [13]. In addition, it has been shown that the high quality coconut shell activated carbon is very susceptible to microwave radiation [15]. AC is a highly porous and amorphous carbon-based material. The low volume pores in the skeleton of AC lead to high surface area adsorption and rapid chemical reactions [16]. Asphalt concrete is susceptible to aging occurred due to heat, oxygen, and ultraviolet (UV) light. It has been demonstrated that an UV absorber can properly improve the aging resistance of bitumen [17]. Also, AC could significantly improve the UV aging resistance of bitumen through absorbing the lightweight fraction of bitumen [18]. Furthermore, adding activated carbon based bio-char to the asphalt concrete resulted in a decrease in its temperature and shear susceptibility [19]. Activated carbon could also act as an adsorptive additive to reduce the volatile organic compound (VOC) emission from asphalt concrete based on its suitable hole and surface structure [20]. Regarding the high temperature behavior of asphalt concrete, researchers in [21] observed that AC could enhance the rutting performance and the load spreading ability of asphalt concrete. That being said, addition of 10% (by weight of binder) AC deteriorated the adhesion between aggregate and binder and led to durability problems [21]. As it can be inferred from the relevant literature, considerable research has been devoted to the rheological and micromechanical properties of AC.

Given its aforementioned features and potentials to close the gap in the efficiency of currently used conductive additives, AC was chosen to be added to the asphalt binder as the binder-based conductive additive. The primary motivation of this modification is to increase the absorption of the electro-magnetic radiation, which facilitates the induced heating and healing of the asphalt concrete exposed to the external supply of electro-magnetic radiations. Therefore, the objective of this research was to investigate the effects of AC on the induced heating and healing of asphalt concrete under the microwave radiation. To this end, the electrical resistivity and temperature rise under microwave radiation were studied. As the microwave radiation needs to penetrate into the asphalt concrete layer to heat and heal the cracks, effects of the sample dimension and thermo-electro-magnetic behavior of asphalt concrete on the heating procedure were investigated. Furthermore, repeated breaking-healing tests were carried out to address the induced healing ability of AC modified asphalt concrete. Moreover, the inherent mechanical characteristics of the AC modified asphalt concrete containing different types of aggregate under various environmental and traffic loadings were discussed. The effects of the damage level, effective healed length and test temperature on asphalt concrete samples under repeated breaking-healing cycles were studied through the indirect tension (IDT) and semi-circular bending (SCB) tests.

2. Material and experiments

2.1. Materials and sample preparation

Performance grade (PG) 58-22 (or 85/100 in penetration grading) asphalt binder was used as the base binder in this study. Table 1 presents the binder specifications. To reach the objectives of this research, activated carbon (AC) was added to the asphalt binder as a conductive component. To prepare AC modified asphalt binder, high shear mixer was employed. Asphalt binder heated to 150 °C was mixed with AC through shear rate of 4000 rpm for 30 min. The properties of activated carbon provided by manufacturer are presented in Table 2.

Siliceous (S) and limestone (L) aggregates were selected in this study in order to investigate the effect of the aggregate type. To fabricate the asphalt concrete specimens, dense graded aggregates (Fig. 1) with a nominal maximum aggregate size (NMAS) of 12.5 mm meeting ASTM D3515-01 were used. Applying Marshall mix design method, binder content of 5% of total mix weight was calculated to yield target air voids content of 4%.

2.2. The electro-magnetic source

Given its ability to directly transfer radiation into material, microwave has captured considerable attention as a capable heating mechanism to overcome limitations of other methods such as electro-magnetic heating. Microwave makes the polar molecules in solution rotate fleetly and then brings obvious heat effects