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Evaluation of moisture susceptibility of foamed warm asphalt produced by water injection using surface free energy method

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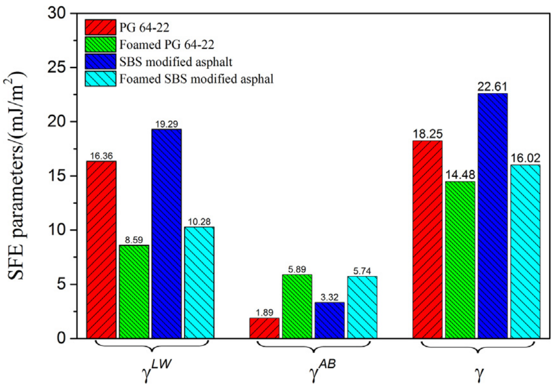
HIGHLIGHTS

- SFE method is used to evaluate the moisture susceptibility of foamed warm asphalt.
- Foamed warm asphalt has lower total SFE, but has higher acid base SFE component.
- Foaming water do not seem to have significant effects on the total SFE of asphalt.
- The wettability and work of adhesion have an improvement after asphalt foamed.
- The effect of foaming water on the work of debonding is negative.

GRAPHICAL ABSTRACT



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ABSTRACT

Foamed warm asphalt are widely used to lower the mixing and paving temperature of asphalt mixtures. However, due to the foaming water addition, moisture damage is one of the main worries. The objective of this paper was evaluate the moisture damage of foamed warm asphalt using surface free energy (SFE) method. Contact angles were measured to estimate the surface free energy components, work of cohesion and adhesion, spreading coefficient and energy ratios (ER_1, ER_2). The results showed that foamed warm asphalt had lower total surface free energy, but had higher acid base SFE component compared unfoamed asphalt. Foaming water did not seem to have significant effects on the total SFE of asphalt. The work of cohesion and ER_1 decreased after foamed, while the work of adhesion, spreading Coefficient (SC) and ER_2 increased after foamed. Analysis base on surface free energy results reflected that the wettability and work of adhesion had an improvement after foamed, while the foaming water weakened the work of debonding.

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1. Introduction

Warm mix asphalt (WMA) is now used widely in many countries around the world, as its production temperature is lower than that required for Hot Mix Asphalt (HMA) [1]. Because less energy needed during construction stages, WMA has less greenhouse gas emission [2]. According to the previous studies, different WMA technologies seek to improve the workability and compact ability of mixtures can be summarized into three categories [3,4]: (1) Foaming techniques, which introduce trace amount of water into the binder and are divided into water based technologies and water containing technologies [5]; (2) Organic or synthetic additives, which provide lower viscosity at temperatures lower than

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the control mixing and paving temperatures; (3) Chemical Additives, which could improve the workability of the mixtures, through a combination of emulsions, surfactants, and polymers [6]. Among these three main methods, foaming WMA produced by water injection have been found to be more practical and convenient as it does not require the additives and only by combining hot asphalt binder with a small amount of water [7]. According to National Asphalt Pavement Association (NAPA)'s report in 2015, foaming technique is used most often in producing WMA, with over 84 percent of the market in USA [8]. Many researchers have proven that the foamed WMA had a similar performance with the control HMA [9–14], however, there are still some concerns on the durability of the foam warm mixture. This is primarily due to the addition of water when foaming, and the water may not be lost all in the construction. Although most researchers have found the moisture will be dissipate and will not highly influence the water stability of foamed WMA [15–21], the moisture damage related failure is still worth attention as a potential risk.

Cohesive failure or adhesive failure at the interface of asphalt-aggregate are the main causes of moisture induced damage [22]. Nowadays, there are some evaluation methods for the water damage of asphalt mixture, such as the Marshall Immersion Test, Freeze-thaw splitting Test [23], Indirect Tensile Strength (TSR) [24], and Hamburg Wheel Tracking (HWT) [25]. However, the correlation between above methods and field observations are not very well, they could not reflect the water damage mechanism as reported [26,27]. From the mechanism, the attenuate of adhesion bond between asphalt and aggregate surfaces is the main cause to moisture damage [28]. The indicators of wettability and adhesion are common used to explain the mechanism of asphalt-aggregate interface [29]. In view of the chemical interactions, most aggregate types have the polar or hydrophilic surfaces, most types of asphalt are regarded as non-polar, and the wettability of asphalt over aggregate is controlled by interface properties of aggregate and asphalt [30]. Therefore, it is important to characterize and evaluate the moisture –induced damage using this interface mechanistic approach.

Surface free energy (SFE) method is an effective way to evaluate and estimate the moisture susceptibility potential of asphalt mixture [26,31], which could directly addresses SFE components: work of adhesion and deboning of bitumen and aggregate [32–35]. Many studies have been carried out the moisture susceptibility evaluation for different asphalt binders with or without additives for different aggregate types using SFE method, and it is proved to be an effective evaluation method [27,34,36–42]. However, fewer researches were found to use SFE approach to research the moisture –induced damage potential of foamed warm asphalt.

Therefore, the aim of this study is to evaluate the moisture induce damage potential of foamed WMA using SFE method. The asphalt binders consisted of foamed and unfoamed PG 64-22 base asphalt, SBS modified asphalt, while the aggregates consisted of limestone and basalt in this study. The indices of SFE components, work of cohesion and adhesion, spreading coefficient and energy ratio were estimated based on the measured contact angles, which could reflect if the moisture susceptibility of foamed warm asphalt changed and weakened.

2. Experimental Setup and methodology

2.1. Fundamentals of surface free energy

As indicated in the literature, nonpolar and acid-base parts are mainly SFE components of asphalt binder and aggregates. According to the Good- Van Oss-Chaudhury (GVOC) theory [43], Cheng et al. [44] determined SFE of liquid and solid, which can be expressed and calculated as following Eq. (1).

$$\gamma_l = \gamma_l^{LW} + \gamma_l^{AB} \tag{1}$$

$$\gamma_s = \gamma_s^{LW} + \gamma_s^{AB} \tag{2}$$

where,

γ_l = surface free energy of liquid; γ_s = surface free energy of solid;

γ_l^{LW} = Lifshitz-Van der waals component of liquid; γ_s^{LW} = Lifshitz-Van der waals component of solid;

γ_l^{AB} = Acid-Base component of liquid; γ_s^{AB} = Acid-Base component of solid.

The surface free energy of liquid–solid interface can be expressed as follows:

$$\gamma_{ls} = \gamma_s + \gamma_l - 2\sqrt{\gamma_s^{LW}\gamma_l^{LW}} - 2\sqrt{\gamma_s^{AB}\gamma_l^{AB}} \tag{3}$$

The relationship between contact angle and SFE can be represent as Young equation, which is as follows:

$$\gamma_l \cos\theta = \gamma_s - \gamma_{sl} \tag{4}$$

The SFE can be calculated by developing Eqs. (3) and (4) into Eq. (5)

$$1 + \cos\theta = 2\sqrt{r_s^{LW}}\left(\frac{\sqrt{r_l^{LW}}}{r_l}\right) + 2\sqrt{r_s^{AB}}\left(\frac{\sqrt{r_l^{AB}}}{r_l}\right) \tag{5}$$

In general, Eq. (5) is written as the following form:

$$\frac{1+\cos\theta}{2}\frac{\gamma_l}{\sqrt{\gamma_l^{LW}}} = \sqrt{\gamma_s^{AB}} \times \sqrt{\frac{\gamma_l^{AB}}{\gamma_l^{LW}}} + \sqrt{\gamma_s^{LW}} \tag{6}$$

Because SFE components of the probe liquids are known, when the contact angles for probe liquids and asphalt are measured. The Lifshitz-Van der waals component and Acid-Base component of asphalt can be calculated by linear analyzing in Eq. (6).

The work of cohesion is considered as the energy which can reversibly separate a column (liquid/solid) of unit area into two new surfaces, and the value can be obtained from the Eq. (7).

$$W_{ll}^c = 2\gamma_l \tag{7}$$

where,

W_{ll}^c = work of cohesion of liquid;

γ_l = surface free energy of liquid, which can be obtained from the Eq. (1).

Associating with Young–Dupre equation and SFE components, the relationship between work of adhesion and contact angle can be built as shown in Eqs. (8)–(11).

$$W_{dry}^a = \gamma_l + \gamma_s - \gamma_{ls} = 2\sqrt{\gamma_l^{LW}\gamma_s^{LW}} + 2\sqrt{\gamma_l^{AB}\gamma_s^{AB}} \tag{8}$$

$$\begin{aligned} W_{wet}^a &= \gamma_{wl} + \gamma_{ws} - \gamma_{ls} \\ &= 2\left(\gamma_{water} + \sqrt{\gamma_l^{LW}\gamma_s^{LW}} + \sqrt{\gamma_l^{AB}\gamma_s^{AB}} - \sqrt{\gamma_l^{LW}\gamma_w^{LW}}\right. \\ &\qquad \left. - \sqrt{\gamma_l^{AB}\gamma_w^{AB}} - \sqrt{\gamma_s^{LW}\gamma_w^{LW}} - \sqrt{\gamma_s^{AB}\gamma_w^{AB}}\right) \end{aligned} \tag{9}$$

$$\gamma_{wl} = \gamma_w + \gamma_l - 2\sqrt{\gamma_w^{LW}\gamma_l^{LW}} - 2\sqrt{\gamma_w^{AB}\gamma_l^{AB}} \tag{10}$$

$$\gamma_{ws} = \gamma_w + \gamma_s - 2\sqrt{\gamma_w^{LW}\gamma_s^{LW}} - 2\sqrt{\gamma_w^{AB}\gamma_s^{AB}} \tag{11}$$

where,

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