Construction and Building Materials 126 (2016) 434–441

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Dynamic modulus and phase angle of warm-mix versus hot-mix asphalt concrete

A.S.M.A. Rahman *, Rafiqul A. Tarefder

Civil Engineering, The University of New Mexico, 1 University of New Mexico, MSC01-1070, Albuquerque, NM 87131-0001, United States

HIGHLIGHTS

- Foamed WMA shows higher moduli at low temperature, lower moduli at high temperature.
- Significantly higher moduli are observed at moderate temperature for Evotherm 3G WMA.
- Cecabase RT WMA shows significantly lower moduli at higher and moderate temperatures.
- Adverse effects of Cecabase RT WMA can be addressed by using polymer modified binder.
- The model proposed for fitting the phase angle function gives higher degree of accuracy.

ARTICLE INFO

Article history:
Received 10 April 2016
Received in revised form 11 August 2016
Accepted 18 September 2016

Keywords:
Complex modulus
Dynamic modulus
Phase angle
Shift factor
Mastercurves
Warm-mix asphalt

ABSTRACT

Characteristics of dynamic modulus ($|E^*|$) and phase angle (δ) functions of hot-mix asphalt (HMA) are well known from years of laboratory tests and available models in the literature. On the other hand, the $|E^*|$ and δ functions of warm-mix asphalt (WMA) are not well defined yet for reasons like relatively newer use in United States as well as manufactured by using various WMA technologies (e.g. foaming, Evotherm, Cecabase RT, etc.) which use different WMA agents. This study evaluates the effects of different WMA agents on the $|E^*|$ and δ of asphalt concrete (AC). A control HMA and four WMA mixtures were collected from a plant with identical aggregate type and size distribution. The loose AC mixtures were then compacted, cored and sawed to cylindrical specimens for $|E^*|$ and δ testing in the laboratory. Statistical evidence showed that WMA agents significantly affect the $|E^*|$ and δ of AC mixture. The $|E^*|$-values of HMA and WMA are comparable at mid-range frequencies only, indicating that fatigue performances at operational temperature of WMA and its HMA counterpart may be similar. However, high temperature rutting and low temperature cracking may not be similar for WMA and its HMA counterpart.

1. Introduction

Several factors affect the dynamic modulus ($|E^*|$) and phase angle (δ) functions of asphalt concrete (AC), of which, the most significant factors are: temperature, loading rate, aging condition, moisture, and aggregate gradation [1,2]. In addition to these physical or environmental factors, there can be some other attributes such as use of polymer modified binders or different warm-mix asphalt (WMA) agents, which can affect the $|E^*|$ and hence the performance of AC. Asphalt technology, known as WMA, allows for lower AC production temperatures in comparison to HMA. Typically, the mixing and compaction temperatures for hot-mix asphalt (HMA) range between 150 and 180 °C (300–350°F). By using WMA agents, this temperature can be reduced to as low as 100–140 °C (212–280 °F) for WMA [3]. Lower production temperature of WMA has several benefits over HMA. The production of HMA requires higher amount of energy and produces hazardous fumes. On the other hand, use of WMA in highway construction can significantly reduce energy consumption and hazardous gases due to lower temperature involved in production. However, in conjunction with the potential benefits, performance issues of WMA have recently been brought into question.

2. Background

A number of studies have been conducted in the past to understand the performance of WMA mixture. Zelelew et al. [4] found that although there is less aging during production, WMA is more susceptible to permanent deformation compared to HMA and can

* Corresponding author.
E-mail addresses: arahman@unm.edu (A.S.M.A. Rahman), tarefder@unm.edu (Tarefder).

http://dx.doi.org/10.1016/j.conbuildmat.2016.09.068
0950-0618/

possibly be the reason for substandard rutting performance under early age traffic. Diefenderfer and Hearon [5] found similar performance of WMA like in Zelelew et al. [4] in their study, when issues like moisture susceptibility, rutting potential, and fatigue resistance are evaluated. Also studies by Prowell and Hurley [6], Hurley and Prowell [7,8], Prowell et al. [9], Xiao et al. [10], Al-Qadi et al. [11,12], and Tarefder and Pan [13] found equivalent performance of WMA with respect to HMA.

Ali et al. [14] studied WMA prepared using foamed asphalt binders and found lower indirect tensile strength for the foamed WMA in comparison to HMA. Their study also found no significant difference in $|E^*|$ between WMA and HMA. However, their study concluded that use of an appropriate type of aggregate and asphalt binder can address any adverse effect from the foaming technology. Goh et al. [15] found that the addition of Aspha-min as a WMA agent does not affect the value of $|E^*|$ of AC. Hossain and Zaman [16] studied the effect of different doses of wax-based WMA additives and found that the measured and estimated $|E^*|$ of WMA is significantly higher than the control HMA at the medium range of reduced time space. Hamzah et al. [17] investigated the effect of different amounts of Sasobit® WMA agent. In their study, they found that the resilient modulus and indirect tensile strength are highly correlated with Sasobit® contents, aging states, test and mixing temperatures. Their test samples which were mixed and compacted at 150 and 145 °C (302 and 293 °F) incorporating 1.5 and 3% Sasobit® contents, respectively, exhibited higher indirect tensile strength and resilient modulus when compared to control HMA. However, their study was only limited to observe effect of WMA agent on the indirect tensile strength and the resilient modulus of AC. Buss et al. [18] found that significantly lower $|E^*|$ values observed for WMA mixtures with DuraClimeTM and DuraLifeTM agents. Williams [19] found that HMA exhibits stiffer material properties compared to its WMA counterpart.

A comprehensive study was conducted by Ghabchi et al. [20] on evaluating the stiffness as well as low-temperature cracking, rutting, moisture damage and fatigue performance of WMA mixtures with zeolite and chemical based agents. Their investigation found that the WMA agents produce mixtures with lower stiffness, reduced potential of low-temperature cracking, lower fatigue resistance, and a higher rutting potential compared to their HMA counterparts. They came to a general conclusion that performance of a WMA mix widely depends on the technology and the type of other additives (e.g. anti-stripping agent) used. Zelelew et al. [21] investigated plant-produced AC mixtures consisting of the control HMA and four WMA mixtures having technologies named as: Sasobit® and three foaming processes (Advera®, low-emission asphalt, and Gencor). Their study reveals that AC mixture prepared with Sasobit® technology and the control HMA measured higher stiffnesses than those prepared with other WMA technologies.

From the above discussions, it reveals that the performance of WMA might be dependent on the technology used to produce WMA. WMA mixtures prepared with different technologies may provide different performances. Therefore, before a certain WMA is used, it is important to characterize and verify its performance through comprehensive laboratory testing.

3. Objectives and scope

The objectives of this study are to determine the effects of different WMA agents on the overall $|E^*|$ and δ functions of plant produced WMA mixtures typically used by the New Mexico Department of Transportation (NMDOT). The WMA agents considered in this study and brief introductions on these are as follows:

Foaming – The basic idea of asphalt foaming is to inject a small amount of cold water (usually with a mass ratio of 1–5% with respect to the asphalt binder) together with compressed air into hot AC (285–340 °F) in a specially designed chamber. Sudden increase in temperature is experienced by the water and immediately it becomes steam. As soon as the mixture, steam and compressed air are placed in ambient air, the asphalt binder is temporarily expanded into numerous bubbles with increased surface area per unit mass. The purpose is to make it easier for asphalt to disperse into cold granular materials at ambient temperature.

Evotherm 3G – Evotherm 3G® is a water-free WMA technology. Evotherm 3G®, a chemical agent, promotes adhesion at lower temperatures by acting as both a liquid antistrip and a warm mix additive. It can be added at the plant or at the asphalt terminal.

Cecabase RT® – Cecabase RT® is a liquid surfactant into the asphalt binder which allows a temperature drop of the asphalt mixture production and paving processes up to 40 °C (104 °F). The additive Cecabase RT®, an organic agent, also brings better workability and easier compaction of mixes with higher fraction of Reclaimed Asphalt Pavement (RAP).

Cecabase RT® with Polymer Modified Binder – It is believed that any adverse effect of Cecabase RT agent can be address by using Styrene-Butadiene-Styrene (SBS) polymer modified binder in the AC mixture.

4. Materials

Materials used in this study were collected from a paving site at Guadalupe County, New Mexico. The pavement section under construction was one of the Specific Pavement Study Sections (SPS-10) of the Long-Term Pavement Performance (LTPP) monitoring program. There are five sub-sections in this SPS-10 section. The SPIII aggregate blend (19.0 mm Nominal Maximum Aggregate Size (NMAS)) used in LTPP's SPS-10 section is comprised of 33% coarse fraction (3/4 in.), 21% intermediate size (3/8 in.) fraction, 25% crushed fines, 20% RAP, and 1% anti-stripping agent "Versabind". Table 1 presents a brief summary of the materials collected. In order to confirm if the aggregate size distribution of the materials within specified limits of SPIII blend according to AASHTO MP 2 [22], three samples from the aggregate stockpiles were collected and analyzed.

Fig. 1 shows the percentage of material passing verses sieve size plot of the material used in SPS-10 project. The figure also shows the control points (CP) and the maximum density line (MDL) for SPIII blend according to AASHTO MP 2. Observation of Fig. 1 confirms that the aggregate size distribution of the material is within the limits specified by the standard.

Table 1
Summary of HMA and WMA mixes collected from SPS-10 LTPP project.

ID	Mix Type	AC Type	WMA Agent	Polymer Modified?	RAP %	Spec. Binder PG	Used Binder PG	Asphalt Content	Mixing Temp. (°F)
TS-1	SPIII	HMA	N/A	No	20%	76–22	70–28	4.6	322
TS-2	SPIII	WMA	Foaming	No	20%	76–22	70–28	4.6	270
TS-3	SPIII	WMA	Evotherm	No	20%	76–22	70–28	4.6	270
TS-4	SPIII	WMA	Cecabase RT	No	20%	76–22	70–28	4.6	270
TS-5	SPIII	WMA	Cecabase RT	Yes	20%	76–22	70–28+	4.6	270