Construction and Building Materials 146 (2017) 514–523

Contents lists available at ScienceDirect

Construction and Building Materials

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

Hot mix asphalt time-temperature shifting and fitting techniques: A comparative study

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HIGHLIGHTS

- Sigmoidal model and Prony series can be used to construct creep compliance master curves.
- Comparsions among different shifting and fitting functions were performed.
- The effect of HMA characteristics on Sigmoidal parameters was evaluated.

ARTICLE INFO

Article history:
Received 8 December 2016
Received in revised form 3 March 2017
Accepted 28 March 2017

Keywords:
Master curve
Shifting techniques
Fitting functions
Superposition
Prony series

ABSTRACT

In this study hot mix asphalt (HMA) creep compliance master curves were constructed using different temperature shifting techniques and fitting functions. The study aimed to compare the capability of using five different shifting techniques (numerical, log-linear, William-Landel-Ferry (WLF), Modified Kaelble (MK) and Arrhenius) and two different fitting functions (the Sigmoidal fitting function, and Prony series) to construct creep compliance master curves. To achieve this aim, one hundred and twenty (120) HMA specimens were prepared at three air voids levels (3.4, 4.9 and 6.4%). Half of the prepared HMA specimens were modified using Elvaloy Reactive Elastomeric Terpolymer (Elvaloy® RET at 2% by weight) while the other half remain unmodified. Also, half of the prepared HMA specimens were exposed to short-term aging (STA), while the other half exposed to both short term aging and level 2 long-term aging (LTA2). All the prepared HMA specimens were exposed to a dynamic creep test using a pulse load of 107 kPa at five different testing temperatures (5, 15, 25, 45 and 60 °C). Both graphical and statistical comparisons were made among different shifting techniques and different fitting functions. Generally, The Sigmoidal fitting function was found to be the most accurate fitting function. Comparing with the numerical shifting technique, the best fit between measured and predicted shift factors was found for WLF followed by log-linear, MK and Arrhenius techniques, respectively.

1. Introduction

Time-Temperature Superposition (TTS) is a tool that can be used to identify the HMA characteristics over a range of temperatures and times (frequencies) by shifting data. The data is shifted to an arbitrary reference temperature by a factor which is called time temperature shift factor (a_T). The horizontal shifting is applied over the algorithm of time axis with respect to the reference temperature using different temperature shifting techniques. In order to reduce the divergence between shifted curves and to obtain one single master curve, different fitting functions are used. Different studies have evaluated the material properties depending on the temperature using the horizontal shift factor and proposed different empirical techniques to relate the horizontal shift of curves with respect to temperature. Specifically, using different shifting techniques and different fitting functions helps in prediction of asphalt mixes mechanical viscoelastic characteristics over a wide range of temperature and loading times, which are beneficial in clarifying the overall performance of asphalt pavement and superior prediction of HMA mechanical behavior.

Forough et al. [6], evaluated the effect of using different temperature shifting techniques including (Numerical, Arrhenius, Modified Kaelble (MK), Log-Linear, and Williams-Landel-Ferry (WLF), to construct HMA relaxation modulus master curve. HMA specimens were prepared using different combinations of aggregate gradations, air voids levels, asphalt contents, and aging conditions. The prepared HMA specimens were tested at four different testing temperatures. The results showed that, by applying statistical and

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http://dx.doi.org/10.1016/j.conbuildmat.2017.03.213
0950-0618/

graphical comparisons between the evaluated shifting techniques, the best fit between measured and predicted values was found for the Numerical technique, followed by Arrhenius, WLF, MK, and Log-Linear techniques, respectively.

Chailleux et al. [3] investegated the using of WLF shifting technique to construct a complex modulus master curve for both asphalt binders and mixtures. Three asphalt binders (10/20, 20/30, 50/70 penetration) and one modified binder with 5% SBS were evaluated. Shearing and tension-compression tests were conducted on specimens. The results of this study showed that WLF technique was applicable to generate a master curve.

Pellinen et al. [12] performed a study to model the time-temperature superposition using two shifting techniques; Arrhenius and WLF. The master curves were created using the solver function in Microsoft Excel software. The results of the two evaluated techniques were compared with experimental results for 60 specimens. The results of this study showed that, Arrhenius shifting technique has the highest correlation with R equal to 0.922.

Walubita et al. [16] investigated the capability of using three shifting techniques; Arrhenius, WLF, and optimization technique using the sum of square error (SSE) to create a master curve for HMA relaxation modulus data sets. The results showed that Arrhenius and WLF techniques led to equivalent results and the best fit between measured and predicted data was found for SSE method.

Rowe and Sharrock [14] developed a complex modulus master curve using four different shifting techniques (Arrhenius, WLF, MK and polynomial) to describe the asphalt mixture properties. It was concluded from this study that the most accurate shifting technique to describe the shift factor was the MK technique.

Kim et al. [9] developed a dynamic modulus master curve for asphalt mixtures using two fitting functions (Sigmoidal and generalized logistic functions) and four different shifting techniques (WLF, MK, Arrhenius, and quadratic functions). It was concluded from this study that quadratic shifting function with the generalized logistic fitting function resulted in lower error compared with other methods.

Different temperature shifting techniques were used in this study including;

Numerical Technique a non-functional shifting technique to determine the time-temperature shift factor and the master curve fitting functions coefficients using solver function in Microsoft excel Program.

Arrhenius Equation an equation to determine the shift factor that clearly describes the relationship between temperature and the reaction rate. the shift factor can be described by Arrhenius equation shown in Eq. (1).

$$\text{Log } a_T = \frac{\Delta Ea}{2.303R}\left(\frac{1}{T} - \frac{1}{To}\right) \tag{1}$$

where a_T is the horizontal shift factor for T, ΔEa is the apparent activation energy, R is the universal gas constant which is equal 8.314 J/°K-mol, T is the exiting temperature (°K), and T_o is the reference temperature (°K).

Williams-Landel-Ferry (WLF) Equation based on free volume theory mentioned that for temperatures higher than the glass transition temperature (Tg), the shift factor equation can be written as:

$$\text{Log } a_T = \frac{-C_1.(T - T_o)}{C_2 + T - T_o} \tag{2}$$

where a_T is the horizontal shift factor for Temperature higher than glass transition temperature. T is the exiting temperature, °C, and T_o is the reference temperature, °C, while C_1 and C_2 are empirical constants.

Modified Kaelble (MK) equation it is a modified version of the WLF equation (the absolute value of ($T - T_o$)). The shift factor equation can be written as:

$$\text{Log } a_T = \frac{-C_1.(T - T_o)}{C_2 + |T - T_0|} \tag{3}$$

where a_T, C_1, C_2, T and T_o as defined earlier.

And **Log-Linear Equation**; a function used to determine the value of the shift factor. This technique is useful for HMA tested at temperatures other than higher temperatures. The shift factor equation can be written as Eq. (4):

$$\log a\left(\frac{T}{To}\right) = \beta(\text{T} - \text{To}) \tag{4}$$

where T and T_o are as defined earlier, and β is the slope of the linear relationship between testing temperature (T) and the logarithm of the shift factor log a_T [11].

In order to model asphalt mixes creep compliance (D (t)) master curves, different references proposed different fitting functions (Kim, [8]; [13]).

Different fitting functions were evaluated to determine the HMA viscoelastic characteristics including the Pure Power Law (PPL), Generalized Power Law (GPL), Modified Power Law (MPL), Modified Power Law Series (MPLS), Standard Sigmoid (SS), Generalized Logistic Sigmoid (GLS), and Prony Series (PS) [8]. Generally, the Sigmoidal fitting function is the most popular. PS was considered to be the best fitting function for HMA relaxation modulus master curves.

In this study, two different fitting functions were used to minimize the discrepancy between shifted curves also to obtain a smooth creep compliance master curve.

Sigmoidal Fitting Function was used to fit the creep compliance test data obtained from different testing temperatures. The Sigmoidal fitting function for asphalt mixes creep compliance data sets was identified by Katicha et al. [7], and presented in Eq. (5):

$$y = \delta + \frac{\alpha}{1 + e\beta - \gamma \log Xr} \tag{5}$$

where y stands for the creep compliance D (t). δ, γ, β and α are the Sigmoidal function parameters (fitting parameters) and X_r is the reduced time.

The Prony series has been widely considered in literature to model the material viscoelastic properties. (Kim, [8]; [15]; [5]). Also, it has a physical meaning in the theory of mechanical models, which is, a dashpot for the viscous part and spring for the elastic one (Kim, [8]; [10]. It is also related to the Wiechert (generalized Maxwell) model (Kim, [8]; [4]. The Prony series used to fit the HMA creep compliance data sets can be illustrated by Eq. (6):

$$D(t) = Dg + \sum_{i=1}^{N} Di(1 - e^{-t/\tau i}) \tag{6}$$

Where Dg is a constant referred to the glassy compliance, Di is a constant referred to retardation strengths, and τi is a constant referred to retardation times.

1.1. Objectives

The main objectives of this study were to determine the relative accuracy of different temperature shifting techniques; (numerical, log-linear, WLF, MK, and Arrhenius). And to compare the relative accuracy for two different fitting functions; (Sigmoidal fitting function and Prony series) used to construct creep compliance master curve.