Construction and Building Materials 53 (2014) 74–82

Contents lists available at ScienceDirect

Construction and Building Materials

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

A comparative study of temperature shifting techniques for construction of relaxation modulus master curve of asphalt mixes

Seyed Arash Forough, Fereidoon Moghadas Nejad *, Ali Khodaii

Department of Civil and Environmental Engineering, Highway and Transportation Division, Amirkabir University of Technology, Tehran, Iran

HIGHLIGHTS

- Using Generalized Logistic Sigmoidal Model to construct the relaxation modulus master curves.
- Evaluating effects of mix characteristics, aging, and temperature on the shifting techniques.
- Graphical and statistical comparisons of the shifting techniques.

ARTICLE INFO

Article history:
Received 23 June 2013
Received in revised form 3 November 2013
Accepted 18 November 2013
Available online 15 December 2013

Keywords:
Asphalt mixture
Direct tension test
Tensile relaxation modulus
Master curve
Temperature shift factor
Generalized Logistic Sigmoidal Model

ABSTRACT

Several temperature shifting techniques have been proposed for construction of relaxation modulus master curve of asphalt mixes using the time–temperature superposition principal; however, it is not clear which one works better than the others. Therefore, the main objective of this study was to compare the relative ability of five common temperature shifting techniques, i.e. Numerical, Log-Linear, Williams-Landel-Ferry (WLF), Modified Kaelble, and Arrhenius, to construct the relaxation modulus master curve for dense graded asphalt mixtures. For this purpose, 72 cylindrical asphalt mixture specimens containing crushed stone aggregates with 60/70 penetration asphalt binder were fabricated using two different aggregate gradations, two binder contents, two air void levels, and three aging conditions with three replicates for each experimental combination. Direct tension relaxation modulus tests were conducted on the specimens at four different temperatures using the trapezoidal loading pattern at a low level of strain. The tensile relaxation modulus master curves of all the specimens were constructed using the Generalized Logistic Sigmoidal Model for the five shifting techniques. Finally, both the graphical and statistical comparisons were made among the temperature shift factors resulted by the mentioned techniques, and the best fit between the measured and predicted data was found for the Numerical technique, followed by Arrhenius, Williams-Landel-Ferry (WLF), Modified Kaelble, and Log-Linear methods respectively.

1. Introduction

Asphalt mixtures are thermorheologically simple materials [1]. In other words, it is possible to utilize the time–temperature superposition principal to determine the viscoelastic behavior of asphalt mixes in a wider range of time and temperature than those used for testing [2]. Several temperature shifting techniques have been developed for asphalt mixes according to the time–temperature superposition principal [2]. Among the most important temperature shifting techniques, used for asphalt mixes, are the Numerical, Log-Linear, Williams-Landel-Ferry (WLF), Modified Kaelble, and Arrhenius methods [2–4]. The mentioned techniques are empirical in nature, and usually show different results for the asphalt mixes, having the same mix characteristics, under the same testing conditions.

Almost all the earlier researches on characterizing the viscoelastic behavior of asphalt binders and mixes have been conducted using only one of the mentioned temperature shifting techniques [5–10]. By contrast, comparatively little work has been undertaken for the asphalt binders [11] and no work for the asphalt mixes to compare various shifting techniques and to rank them regarding their relative ability to provide an excellent fitness to the experimental data. Therefore, this research was undertaken to compare and rank the different temperature shifting techniques among various asphalt mixes.

In order to more accurately evaluate and compare the temperature shift factors resulted by the above mentioned techniques, it was first necessary to gather a data base including the tensile

* Corresponding author. Address: Department of Civil and Environmental Engineering, Amirkabir University of Technology, No. 424, Hafez Ave., Tehran 15914, Iran. Tel.: +98 21 64543000.

E-mail addresses: a.forough@aut.ac.ir (S.A. Forough), moghadas@aut.ac.ir (F.M. Nejad), khodaii@aut.ac.ir (A. Khodaii).

0950-0618/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.conbuildmat.2013.11.060

relaxation modulus test results for a variety of asphalt mixtures, having different mix characteristics, at various temperatures and different aging conditions. For this purpose, direct tension relaxation modulus tests were conducted on the dense graded asphalt mixtures, commonly used in binder and wearing courses, at different temperatures and aging conditions, and the tensile relaxation modulus master curves of each mixture were constructed using all the mentioned shifting techniques. Finally, the temperature shift factors determined from each shifting technique were compared using both the graphical and statistical approaches.

2. Temperature shifting techniques

Among the above mentioned temperature shifting techniques, the non-functional Numerical method, having the highest degree of freedom, provides the best fitness to the experimental data; while the other methods, all of which are on the basis of some empirical equations, have lower degrees of freedom. Therefore, they are usually unable to provide an excellent fitness to the experimental data [11].

Numerical technique is a non-functional method in which no equation is used to determine the shift factors [11]. To put it more simply, the temperature shift factors and the master curve model coefficients are simultaneously determined by the method of least square optimization. The optimization process is usually performed using a curve fitting software such as Solver function in Microsoft Excel [12]. Despite the excellent fitness of the predicted to the experimental data by the Numerical technique, the resulted shift factors for a given reference temperature, may not be generalized to the other reference temperatures due to the lack of a functional form and a physical meaning in this technique [11].

Log-Linear technique is one of the most popular temperature shifting methods for asphalt mixes [2], which has been extensively used in the existing literature to construct the relaxation modulus master curves [13]. This technique uses the following Eq. (1) to determine the shift factors:

$$\text{Log}a_T = C(T - T_R) \tag{1}$$

where a_T is the time–temperature shift factor, T is testing temperature, T_R is reference temperature, and C is constant which is determined by analysis of the experimental data.

It is evident from Eq. (1) that the Log-Linear technique has only one degree of freedom; thus, the shift factors obtained by this technique are expected not to be very close to those determined from the non-functional Numerical technique.

Williams-Landel-Ferry (WLF) technique is also one of the shifting methods which is used for both the asphalt binders [13–15] and mixtures [16]. The WLF shift factors are usually determined by Eq. (2):

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

where C_1 and C_2 is the constants which can be obtained through analysis of the experimental data.

It is understood from Eq. (2) that the WLF technique has two degrees of freedom. However, this technique shows better results for the asphalt binders than mixes [2].

Modified Kaelble technique, which is generally used for asphalt mixtures, is the WLF technique with some modifications [17]. The Modified Kaelble shift factors are obtained using Eq. (3):

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

Arrhenius technique is also one of the common temperature shifting methods for asphalt mixes [2]. This technique utilizes the following Eq. (4) for the shift factors:

$$\text{Log}a_T = A\left(\frac{1}{T} - \frac{1}{T_R}\right) \tag{4}$$

where A is Constant obtained by analysis of the experimental data.

3. Experimental program

3.1. Material properties

Two aggregate gradations, having the Maximum Nominal Aggregate Sizes (MNAS) of 25 mm and 19 mm, were used to comply with the gradation specifications of the dense graded binder and wearing courses respectively [18]. The gradations used in this study and the gradation limits are plotted in Figs. 1 and 2. The 60/70 penetration bitumen was also used as asphalt binder for preparation of the specimens.

3.2. Specimen preparation

Five variables, aggregate gradation, binder content, air void level, aging condition, and temperature, were selected to study in the experimental program. Two different aggregate gradations, as shown on Figs. 1 and 2, two binder contents of 5.5% and 6.0%, two air void levels of 4 ± 0.5% and 7 ± 0.5%, and three aging conditions, 0, 4, and 8 days oven aging (equivalent to 1, 7.5, and 18 years field aging [19]), with three replicates were used to make 72 cylindrical asphalt mixture specimens. Tensile relaxation modulus tests, at a constant level of input strain, were conducted on each specimen at four different temperatures, −7, +4, +14, and +21 °C. Therefore, a total of 288 tensile relaxation modulus tests were performed. Prior to the relaxation modulus testing, 24 additional specimens, having two aggregate gradations, two binder contents, and two air void levels, with three replicates, were fabricated and used to conduct the tensile strength tests which were necessary to determine the maximum tensile strain at break for each specimen. A summary of the experimental cases used in this study is shown in Table 1.

Prior to aggregate-bitumen mixing, they were pre-heated at the mixing temperature. The mix was then placed inside an oven at the temperature of 135 °C for 4 h, as defined by the AASHTO PP2 [20], to simulate the short term aging during the time between mixing and placement in the field. Afterwards, 24 asphalt mixture prisms, having the length, width, and height of 450, 150, and 185 mm respectively, were compacted using a shearbox compactor. The asphalt mixture prisms were compacted up to the target air void levels of 4 ± 0.5% or 7 ± 0.5% to represent laboratory mix design or field construction conditions respectively. Then, four cylindrical specimens were cored and sawn to the height and diameter of 150 and 100 mm respectively from each prism. It must be noted that three out of four cylindrical specimens obtained from each asphalt mixture prism were used for the relaxation modulus tests; while the remaining one was utilized for the tensile strength test. In the next step, the actual volumetric properties, bulk specific gravity, air voids in mixture, and voids in mineral aggregates, of each cylindrical specimen were determined, and the specimens that did not meet the target air void levels were discarded. Finally, the compacted specimens were kept inside an oven at a temperature of 85 °C for 0, 4, or 8 days to simulate the 1, 7.5, or 18 years long term field aging [19].

3.3. Tensile strength and relaxation modulus tests

Tensile strength tests were conducted to determine the maximum tensile strain at break, which is needed to select the input strain magnitude for the tensile relaxation modulus tests. It is well known that the tensile strength of asphalt mixes are

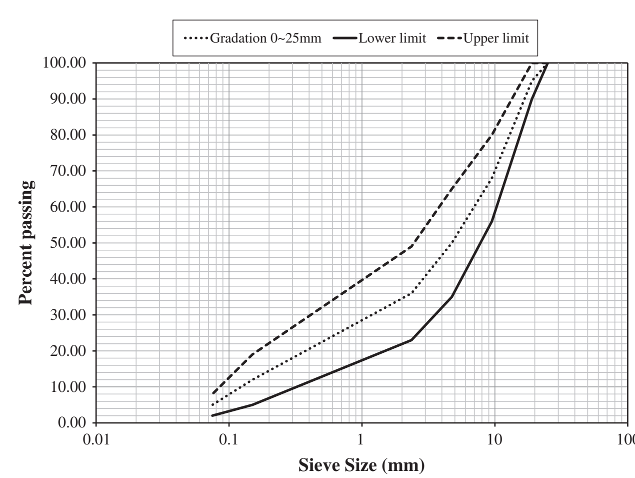

Fig. 1. Aggregate gradation of binder course and the gradation limits.