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# Time-temperature-aging-depth shift functions for dynamic modulus master curves of asphalt mixtures

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## HIGHLIGHTS

- Dynamic modulus master curve of asphalt mixture is constructed using modified CAM model.
- Glassy modulus is utilized to present the upper asymptote of master curve.
- Rheological index is used to characterize the slope of master curve.
- A long-term aging shift function is a function of aging time and aging temperature.
- A depth shift function is a function of asphalt pavement depth.
- A master curve including aging effect is developed after using the shift functions.

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## ABSTRACT

Oxidative aging is one of the significant environmental effects on asphalt pavement performance. This study aims to characterize the aging viscoelastic property of asphalt mixtures such as dynamic modulus at different aging times and pavement depths, then develops two aging shift functions to account for the effects of long-term aging and non-uniform field aging in the pavement depth. Tensile creep test and direct tension test are conducted on 12 laboratory-mixed-laboratory-compacted (LMLC) asphalt mixtures with three laboratory aging times and 16 field-aged asphalt mixtures with four field aging times, respectively. The dynamic modulus of LMLC mixtures is determined from the tensile creep test and the elastic–viscoelastic correspondence principle is utilized to obtain the dynamic modulus of field-aged asphalt mixtures from the direct tension test. The dynamic modulus master curves of the asphalt mixtures at different aging times and pavement depths are constructed using the modified Christensen-Anderson-Marasteanu (CAM) model. It is shown that both of the rheological index and glassy modulus increase with aging time and the crossover frequency decreases with aging time. The long-term aging shift function is determined as a function of aging time, acceleration factor, activation energy, and aging temperature. The depth shift function is determined as a function of pavement depth. With the aid of the two aging shift functions, it becomes possible to construct a single dynamic modulus master curve after taking into account the effects of temperature, long-term aging, and non-uniform aging with pavement depth below the surface.

## 1. Introduction

It is known that oxidative aging has a considerable influence on the viscoelastic property of asphalt mixtures and asphalt pavement performance. Aging is a chemical reaction between asphalt binders and oxygen, which causes the formations of polar carbonyl area (CA) [1,2]. During the aging process, the asphalt gradually loses volatile fractions, which leads to the hardening and brittleness of the asphalt mixtures. For the asphalt pavements, there are usually two stages of aging: one is called short-term aging, and the other is named long-term aging [3]. The short-term aging occurs during the procedures of mixing, compaction and laying down, thus it is during the pavement construction period. In this stage, the aging effect can be assumed to be identical from the surface to the bottom of

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the asphalt layer since the chemical reaction between oxygen and binders is almost uniform. The long-term aging starts after laying down. The oxygen in the atmosphere first reacts with the asphalt mixtures at the pavement surface and reacts more quickly in the higher pavement temperatures at and near the surface then more slowly at greater depths through the connected air voids, so that less chemical reactions are generated in the deeper layers below the surface. Therefore, the long-term aging in the asphalt surface layer is a non-uniform aging process. The modulus gradient is developed during the long-term aging period, which is an important characteristic of the field-aged asphalt mixtures. As a result, the pavement surface becomes stiffer and more brittle than the deeper layers, and the pavement surface is more prone to fatigue cracking and thermal cracking [4–6]. On the other hand, the long-term aging is mainly affected by aging time and aging temperature [7–11].

Due to the pronounced effects of oxidative aging, there are considerable research efforts on the characterization of the aging behavior. The aged asphalt binder properties are well determined [12]. One approach is to conduct rheological or physical tests on the asphalt binders. The Fourier Transform Infrared Spectroscopy (FTIR) is a popular method to measure the increase of CA [13–15]. It is an efficient tool to analyze the aging process based on the associated chemical components. In addition to this approach, the asphalt binders conditioned at different aging times or aging temperatures are used to measure the shear modulus with the dynamic shear rheometer (DSR). The change of shear modulus is utilized as an indicator of the aging level of asphalt binders [16,17]. The binder viscosity can also be obtained from the DSR, which is further correlated with an empirical relationship to predict the dynamic modulus of asphalt mixtures [18]. Additionally, the Global Aging System (GAS) is a widely-used aging prediction model, which is based on the viscosity gradient obtained from the extracted binders of numerous field cores at different pavement depths in different climate zones of North America [3]. In the mixture level, the mechanics tests such as dynamic modulus test are conducted on the laboratory-mixed-laboratory-compacted (LMLC) asphalt mixtures at different aging times and temperatures [19,20]. However, the standard dynamic modulus test method is not applicable to the field-aged asphalt mixtures due to the complications associated with the field conditions such as the field core dimension. To overcome this obstacle, an indirect tension test (IDT) method is proposed for determining the dynamic modulus of the field cores [21]. The modulus of field cores can also be measured using the asphalt mixture performance tester (AMPT) with small size samples [22]. Nevertheless, these two methods ignore a significant characteristic of the field-aged asphalt mixtures, i.e., non-uniform aging with pavement depth. More importantly, a single dynamic modulus master curve cannot be constructed including the effects of temperature and aging for both of the LMLC and field-aged asphalt mixtures, only the coefficients of the sigmoidal model at different ages are empirically related to the aging time without the aging shift functions. As a result, the effects of long-term aging and non-uniform aging on the dynamic modulus cannot be captured and predicted efficiently.

In order to address the shortcomings of the aforementioned methods, it is preferred to develop a novel method to predict the dynamic modulus master curves of the aged asphalt mixtures, which takes into account the effects of long-term aging and non-uniform aging. In other words, a single dynamic modulus master curve with the effects of temperature, loading time, long-term aging, and non-uniform aging needs to be constructed by applying the time-temperature and time-aging-depth shift functions. In this study, the tensile creep test is conducted on the LMLC mixtures conditioned at different aging times to obtain the corresponding dynamic modulus. In the study prior to this work, a mechanistic-based method is developed to determine the complex modulus gradient of asphalt field cores using the direct tension test [23]. The same test protocol is adopted in this study to obtain the dynamic moduli of field-aged mixtures at different field aging times and pavement depths. The results from the two tests are then used to construct the dynamic modulus master curves to develop and implement the two aging shift functions for the asphalt mixtures.

This paper is organized as follows. The next section first introduces the samples used in this study including the field-aged and laboratory-aged mixtures, and briefly discusses about the two laboratory testing protocols and analysis methods, then presents the dynamic moduli at different aging conditions. The subsequent section shows the construction of dynamic modulus master curves, and the development and application of the long-term aging shift function for the LMLC mixtures. The following section discusses the implementation of the long-term aging shift function and the development of the depth shift function to account for the non-uniform aging effect with pavement depth, and the construction of a final single master curve for the field-aged mixtures. The summary of findings and conclusions are included in the last section.

## 2. Laboratory testing method and results

### 2.1. Material and mix design

The asphalt field cores include one type of hot mix asphalt (HMA) and one type of warm mix asphalt (WMA) treated by a foaming process. They are fabricated with a PG 70–22 asphalt binder and Texas limestone aggregates. The water content is 5% by weight of the binder in the WMA foaming process. The binder content of 5.2%, the nominal maximum aggregate size of 9.5 mm (3/8 inch), and the aggregate gradations are identical for the HMA and WMA. The field cores are taken from one WMA section and one HMA section near Austin, Texas. The mix design and the aggregate gradation are detailed in a technical report [24]. The thicknesses of the field cores range from 38 to 51 mm. A total of 16 field cores (8 HMA and 8 WMA specimens) are collected at the center of two lanes of the HMA section and the WMA section at 1, 8, 14 and 22 months after construction. It is reasonable to assume that the collected cores are not damaged by traffic within the aging periods while they are in the field. A PG 67–22 asphalt binder and Texas limestone aggregates are used for the fabrication of the LMLC mixture specimens. The optimum binder content of 4.5% and the aggregate gradation are determined based on Texas Department of Transportation (TxDOT) Type C gradation and TxDOT specification TEX-204-F, respectively [25]. Two target air void contents of 4% and 7% are used in this study. The loose mixes are first conditioned in the oven for 4 h at 135 °C in accordance with AASHTO R 30 [26], then they are compacted using the Superpave gyratory compactor (SGC) into cylindrical specimens with 150 mm in diameter and 175 mm in height. The cylindrical specimens are cored to 100 mm in diameter and 150 mm in height after cooling down to obtain uniform air void distributions. After coring, the specimens are conditioned in the environmental room for 0 month, 3 months, and 6 months at an aging temperature of 60 °C to simulate the uniform long-term aging. There are two replicates tested for each air void content and aging time. Thus, there are 12 laboratory specimens tested in total. It should be noted that the sources of aggregates and asphalt binders are different for the field and LMLC mixtures, and the comparison and match between the laboratory aging and field aging are beyond the scope of this study.