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A Novel Micromechanical - Analogical Model for Low Temperature Creep Properties of Asphalt Binder and Mixture

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The ENTPE transformation is commonly used to predict the low temperature properties of asphalt binders from the corresponding mixtures experimental data and vice-versa. Nevertheless, the transformation parameter, α , associated to the ENTPE equation, cannot be directly obtained without relying on both binder and mixture testing. This paper presents a comprehensive investigation to link the ENTPE transformation to the mixture microstructure. This is accomplished by three-point bending tests on asphalt binders and mixtures, digital image processing and statistical evaluation of mixture microstructure, together with a newly proposed micromechanical-analogical model, called MCF (Moon-Cannone Falchetto), used for deriving an explicit expression of α . The values of α obtained from asphalt binder and mixture laboratory measurement are compared to the values predicted by the new formulation. The results indicate that reasonable predictions of low temperature creep stiffness of asphalt binder can be obtained when the new expression of α is used in the ENTPE transformation.

Keywords: Low temperature creep properties, Hirsch model, ENPTE transformation, Asphalt mixture microstructure, MCF model.

1. Introduction

Low temperature cracking of asphalt pavement is a major distress in cold regions. This phenomenon initiates when temperature decreases below 0°C causing an increase in thermal stress within the restrained asphalt mixture layers. When temperature drops below a critical value, called critical cracking temperature, the stress field in the pavement reaches the material strength; hence, thermal cracking occurs and thermal stresses are relieved. Several negative effects are associated to thermal cracking due to water penetrating in the pavement structure, ultimately reducing the pavement service life.

Creep testing represents a simple and convenient option (AASHTO T313-12-UL 2012; AASHTO T322-07-UL 2007) to evaluate the low temperature properties of asphalt material. The creep compliance obtained from the experimental data is used to calculate its inverse, called creep stiffness, which can be related to low-temperature cracking resistance of asphalt pavements. Currently, creep test of asphalt binder is performed in three point bending configuration with the Bending Beam Rheometer (BBR) (AASHTO T313-12-UL 2012). A similar test was successfully proposed to obtain creep stiffness on thin asphalt mixture beams using the same BBR equipment required for asphalt binder tests (Marasteanu et al. 2009).

2. Problem Statement

Asphalt mixture is commonly modeled either as a two- (Papagiannakis et al. 2002) or three-phase material (Li and Metcalf 2005). In the past years, micromechanical models were used to predict asphalt mixture behavior and to determine the relation between asphalt binder and mixture properties; nevertheless, in most cases, significant differences were observed between model predictions and experimental results (Kim and Little 2004).

Recently, the micromechanical Hirsch model (Hirsch 1962; Christensen et al. 2003; Zofka et al. 2007; Velasquez et al. 2010) and the transformation proposed by the research team of the Ecole Nationale des Travaux Publics de l'Etat (ENTPE), which is based on mechanically analog models (Di Benedetto et al. 2004), were successfully used to predict asphalt mixture creep stiffness from asphalt binder creep stiffness and vice-versa at low temperatures (Cannone Falchetto et al. 2011; Moon et al. 2014a).

The Hirsch model is based on the properties of the materials constituents; however, the predictions are not always in agreement with laboratory measurements. On the other hand, the Huet model (1963) and the ENTPE transformation provide good estimates of binder and mixture properties. Nevertheless, the model parameters are obtained by fitting both

mixture and binder experimental data. In addition, the ENTPE transformation parameter α , which directly relates the properties of asphalt binder to the corresponding mixture properties, cannot be obtained a priori from the mixture constituents, but need to be determined on the basis of experimental data (Cannone Falchetto et al. 2011).

3. Objective and Research Approach

The main objective of this research is to implement a micromechanical – analogical model, hereafter called MCF (Moon-Cannone Falchetto) model, to derive a mathematical expression for directly estimating the α parameter of the ENTPE transformation.

Parameter α is currently obtained by simple regression of asphalt binder and asphalt mixture experimental data. However, it is not directly linked to the physical, volumetric and mechanical material properties, although it was observed that mixture design and aging affect its value. The newly proposed formulation of parameter α , will address these limitations by providing an explicit expression of the transformation parameter as function of the properties of the main material phases (aggregate, asphalt mastic and air voids). This can be used to predict the low temperature creep properties of asphalt binder from the low temperature creep properties of a corresponding asphalt mixture without the need of a full experimental testing campaign on asphalt binder.

The proposed research approach is based on the micromechanical Hirsch (1962) model and the analogical Huet (1963) model, together with the ENTPE transformation (Di Benedetto et al. 2004). The binder and mixture properties are linked to the mixture microstructure based on combinations of the models parameters, on Digital Image Processing (DIP) techniques and on the evaluation of the 2-point correlation function together with the auto correlation length (ACL) of the mixture phases. To achieve such a goal, the following research approach was followed:

1. Conduct BBR three-point bending creep tests on a set of asphalt binders and corresponding mixtures selected to provide combinations of different binders and aggregates.
2. Fit the analogical Huet (1963) model to the creep compliance data of asphalt binders and corresponding mixtures to determine the model parameters and the fitting parameter α of the ENTPE transformation.
3. Implement a micromechanical-analogical model, MCF model, to derive an equation for calculating α , based on Hirsch and Huet models, and on volumetric and microstructural properties of the material constituents.

4. Use DIP analysis of asphalt mixture images to obtain a three-phase representation (aggregate, asphalt mastic and air voids) of asphalt mixture.
5. Evaluate the microstructural distribution of asphalt mixture phases through the computation of 2-point correlation function and of the ACL.
6. Use microstructural information as input in the newly proposed formulation of α , and compare the predicted asphalt binder creep stiffness obtained from the ENTPE transformation, using the estimated values of α , to the experimental creep stiffness data.

The diagram in Figure 1 provides a simple schematic of the research approach used in this study.

4. Theoretical Background

4.1 Hirsch Model

A micromechanical model, based on Hirsch (1962) original formulation, was proposed by Christensen et al. (2003) to estimate the extensional and shear dynamic modulus of asphalt mixtures. The effective response is obtained assembling the elements of the mixture in parallel and in series (Figure 2a). The general equation for this semi-empirical model is:

$$E_{mixture} = Pc \cdot [E_{agg} V_{agg} + E_{binder} V_{binder}] + (1 - Pc) \cdot \left[\frac{V_{agg}}{E_{agg}} + \frac{(1 - V_{agg})^2}{E_{binder} V_{binder}} \right]^{-1} \quad [1]$$

where E_{mix} is the effective modulus of the mixture; E_{agg} , V_{agg} are modulus and volume fraction of the aggregate; E_{binder} , V_{binder} are modulus and volume fraction of binder, and Pc is an empirical factor called contact volume.

Zofka (2007) evaluated the use of Hirsch (1962) model to predict the BBR mixture stiffness from the properties of the binder. Although the Hirsch model contains parameters directly linked to the asphalt mixture constituents, the predictions are not always reasonably close to the experimental results (Cannone Falchetto et al. 2011; 2012).

4.2 Analogical Models

The Huet (1963) analogical model is composed of a spring and two parabolic elements combined in series (Figure 2b).

This model was proposed for binders and mixtures; it presents a continuous spectrum and, therefore, it can be schematized by an infinite number of Kelvin-Voigt elements in

series or Maxwell elements in parallel (Huet 1963). The analytical expression of the Huet model for creep compliance is:

$$D(t) = \frac{1}{E_{\infty}} \cdot \left(1 + \delta \cdot \frac{(t/\tau)^k}{\Gamma(k+1)} + \frac{(t/\tau)^h}{\Gamma(h+1)} \right) \quad [2]$$

where $D(t)$ is the creep compliance; E_{∞} is the glassy modulus; h, k are exponents such that $0 < k < h < 1$; δ is a dimensionless constant; t is time; Γ is the gamma function; τ is the characteristic time varying with temperature accounting for the Time Temperature Superposition Principle (TTSP).

An expression of the complex modulus for this model is also available while there is no analytical formula for the relaxation function (Huet 1963):

$$E^*(i\omega\tau) = \frac{E_{\infty}}{1 + \delta(i\omega\tau)^{-k} + (i\omega\tau)^{-h}} \quad [3]$$

where i is the complex number ($i^2 = -1$); $\omega = 2\pi f$; f is the frequency; and E_{∞} is the instantaneous Young's modulus measured at low temperature and at very high frequencies in the glassy state of a material. According to Huet (1963), parameter δ is a dimensionless number close to 2, while exponent k assumes values around 0.3. Exponent h is in the range 0.3-0.8 and depends on the type of bituminous material; for example, aged, oxidized materials present smaller values of h (Moon et al. 2014a).

The Huet model does not provide good predictions of binder and mixture properties at high temperature and/or very low frequencies; however, it is very effective for modeling low temperature creep data (Cannone Falchetto et al. 2011; 2012). A modified Huet model, which addresses the high temperature limitation, was proposed in the recent past (Di Benedetto et al. 2004); this improved model, called 2S2P1D, was obtained by adding to the Huet model a dashpot in series and a spring in parallel (Figure 2c) so that at low frequency it is equivalent to a linear dashpot in parallel with a spring of stiffness E_0 .

4.3 ENTPE Transformation

In previous research efforts, it was observed that, when fitting Huet and 2S2P1D model to low temperature creep compliance and complex modulus data, the parameters of the model components (δ, k, h for the Huet model and β for the 2S2P1D model) have the same values for the selected asphalt binder and corresponding mixtures (Di Benedetto et al. 2004; Cannone Falchetto et al. 2011; 2012). In the same studies, it was also found that glassy modulus and characteristic time are binder and mixture specific; based on this

observation, a simple log-scale relation between characteristic time of binder, τ_{binder} , and characteristic time of mixture, τ_{mix} , at the reference temperature was proposed (Di Benedetto et al. 2004; Cannone Falchetto et al. 2011):

$$\text{Log}\tau_{mix}(T) = \alpha + \text{Log}\tau_{binder}(T) \quad [4]$$

$$\tau_{mix}(T) = 10^{\alpha} \cdot \tau_{binder}(T) \quad [5]$$

where α is a regression coefficient depending on mixture components and binder aging. Based on expressions [4] and [5], Di Benedetto and co-workers (Di Benedetto et al. 2004) derived a transformation expression to obtain the asphalt mixture complex modulus from the asphalt binder experimental data and vice-versa (inverse transformation):

$$E_{mix}^*(\omega, T) = E_{0_mix} + [E_{binder}^*(10^{\alpha} \omega, T) - E_{0_binder}] \cdot \frac{E_{\infty_mix} - E_{0_mix}}{E_{\infty_binder} - E_{0_binder}} \quad [6]$$

$$E_{binder}^*(\omega, T) = E_{0_binder} + [E_{mix}^*(10^{-\alpha} \omega, T) - E_{0_mix}] \cdot \left[\frac{E_{\infty_mix} - E_{0_mix}}{E_{\infty_binder} - E_{0_binder}} \right]^{-1} \quad [7]$$

The above set of equations is known as the ENTPE transformation. Recently, (Cannone Falchetto et al. 2011) it was demonstrated that a similar expression can be obtained based on the Huet model (1963), to relate asphalt binder and asphalt mixture creep stiffness:

$$S_{mix}(t) = S_{binder}(t \cdot 10^{-\alpha}) \cdot \left(\frac{E_{\infty_mix}}{E_{\infty_binder}} \right) = \frac{1}{D_{mix}(t)} \quad [8]$$

$$S_{binder}(t) = S_{mix}(t \cdot 10^{\alpha}) \cdot \left(\frac{E_{\infty_binder}}{E_{\infty_mix}} \right) = \frac{1}{D_{binder}(t)} \quad [9]$$

Equations [8] and [9] represent the time domain formulation of ENTPE transformation for low temperatures and high frequencies. Therefore, if a mathematical expressions for parameter α can be derived, then the low temperature creep compliance (or stiffness) of an asphalt mixture can be predicted from the low temperature creep compliance (or stiffness) of a corresponding binder and vice-versa.

A simple expression of parameter α was proposed by Di Benedetto et al. (2004) using a simple two-phase model of asphalt mixture: aggregate (elastic) and asphalt binder (linear viscoelastic).

$$\alpha = -\frac{1}{h} \cdot \log[K] = -\frac{1}{h} \cdot \log \left[\frac{(s - s \cdot e + e) \cdot E_{aggregate}}{(s - s \cdot e + e) \cdot E_{aggregate} + (1 - s - e - s \cdot e) \cdot E_{\infty_binder}} \right] \quad [10]$$

where h is the a fitting parameter of the 2S2P1D model; s is the equivalent aggregate contact surface; e is the equivalent binder thickness; and $[K]$ is a parameter such that $\tau_{mixture} = 10^\alpha \cdot \tau_{binder} = [K]^{-1/h} \cdot \tau_{binder}$. This model is too simple to explain the physical meaning of α ; however, it provides a reasonable basis for generating a more sophisticated model that can be used to relate α to the microstructural properties of the mixture.

5. Materials and Testing

5.1 Materials and Specimens Preparation

A set of ten different asphalt mixtures (Table 1) was prepared and tested in the asphalt pavement laboratory at the University of Minnesota (U of MN). The aggregate materials consisted of screen sand, lime sand and kram clear stone having Nominal Maximum Aggregate Size (NMAS) = 12.5mm. Two different asphalt binders were used for preparing the asphalt mixtures: a plain PG58-28 binder and a polymer modified (1.1% Elvaloy + 0.3% PPA) PG58-34 binder (AASHTO M320-10-UL 2010). Additional information on the material used can be found elsewhere (Marasteanu et al. 2012). Fifty BBR beams were obtained for each asphalt mixture type from each cylindrical sample through a series of cutting steps (Figure 3a). Red-Green-Blue (RGB) scale images of asphalt mixture slices and beams were acquired for post processing through DIP techniques and microstructural analysis tools (see Section 8).

5.2 Asphalt Binder Creep Test

Three-point bending creep tests were performed on asphalt binder beams using the BBR device (Figure 3b) (AASHTO T313-12-UL 2012). A constant load of 980mN was instantaneously applied to the specimen and the mid-span deflection, $\delta(t)$, was recorded for the entire duration of the test. In this study, the test duration was extended from the standard 240s to 1000s in order to match the procedure used for asphalt mixture creep tests. Creep stiffness, $S(t)$, was calculated as:

$$S(t) = \frac{\sigma}{\varepsilon(t)} = \frac{P \cdot l^3}{4 \cdot b \cdot h^3 \cdot \delta(t)} \quad [11]$$

where σ is the maximum bending stress; $\varepsilon(t)$ is the bending strain; P is the applied constant load; l is the specimen length (102.0±5mm); b is the specimen width (12.7±0.5mm); h is the specimen thickness (6.25±0.5mm); $\delta(t)$ is the deflection at the mid span; and t is time. BBR testing was conducted on two replicates at a single temperature corresponding to low

PG+10°C; specimens were conditioned in ethanol for 1 hour at the target temperature prior to testing.

5.3 Asphalt Mixture Creep Test

Low temperature creep tests were performed with the BBR on thin asphalt mixture beams (Figure 3c) according to the procedure proposed by Marasteanu et al. (2009). Due to the higher mixture stiffness, load was increased to 6000mN and test duration was set to 1000s. The same testing temperature of asphalt binder (low PG+10°C) was used to avoid error associated to time-temperature superposition during analysis and modeling. Similarly to the binder procedure, all mixture specimens were conditioned at the test temperature in ethanol for 1 hour prior to testing; five replicates were tested per each mixture type.

6. Huet Model Fitting of Creep Experimental Data

The Huet (1963) model can be tailored to fit both asphalt binder and mixture creep compliance as (Cannone Falchetto et al. 2011):

$$D_{binder}(t) = \frac{1}{E_{\infty_binder}} \left(1 + \delta \frac{(t/\tau_{binder})^k}{\Gamma(k+1)} + \frac{(t/\tau_{binder})^h}{\Gamma(h+1)} \right) = \frac{1}{S_{binder}(t)} \quad [12]$$

$$D_{mix}(t) = \frac{1}{E_{\infty_mix}} \left(1 + \delta \frac{(t/\tau_{mix})^k}{\Gamma(k+1)} + \frac{(t/\tau_{mix})^h}{\Gamma(h+1)} \right) = \frac{1}{S_{mix}(t)} \quad [13]$$

where parameters, δ , k , h , E_{∞} , and τ , in Equations [12] and [13], can be obtained with a non-linear minimizations process.

Tables 2 provides a summary of the model parameters, while examples of the experimental and fitted creep compliance, $D(t)$, curves for asphalt binder and asphalt mixtures are shown in Figure 4a. Similarly to previous research effort (Di Benedetto et al. 2004; Cannone Falchetto et al. 2011), binders and corresponding mixtures present the same parameters values. Very good agreement was found between measured creep compliance, $D(t)$, and model fitting both for asphalt binders and corresponding mixtures. It was also observed that mixtures having smaller NMA (9.5mm) show lower values of parameters k and h in comparison to mixtures prepared with larger aggregates (12.5mm). This suggests that lower values of exponents, k and h , are associated to stiffer asphalt mixtures (Huet 1963).

The validity of the relationship between the characteristic time of binders, τ_{binder} , and mixtures, τ_{mix} , (Equations [4] and [5]), was then investigated and plots of $\text{Log}\tau_{mix}$ versus

$\text{Log}\tau_{\text{binder}}$ were obtained for both binders (PG58-28 and PG58-34) and corresponding mixture groups (1-5) and (6-10), respectively (Figures 4b).

Figure 4b, visually indicates that the α parameter of the ENTPE transformation has a specific and unique value for each set of mixture prepared with binders PG58-28 and PG58-34, respectively. This is further supported by the very good correlation between the logarithm of binders and mixtures characteristic times that show $R^2=0.985$ and 0.997 , for the two sets of mixtures. Therefore, Equations [4] and [5] can be used for determining parameter α when the values of binder and mixture characteristic times are known. The last column of Table 2 presents the values of the fitting parameter α for all the mixtures used.

In the recent past, it was demonstrated that the ENTPE transformation provides good predictions of asphalt mixture and binder creep stiffness (Cannone Falchetto et al. 2011). Based on the experimental binder and mixture BBR data, on Equations [4], [5], [8] and [9] and on Table 2, the creep stiffness of asphalt mixtures, $S(t)_{\text{mix}}$, was predicted from the creep stiffness of asphalt binders, $S(t)_{\text{binder}}$, and vice-versa (Figure 4c).

The plots of Figure 4c confirm the significant potential of the ENTPE transformation which provides were good predictions. Nevertheless, parameter α was estimated by fitting both asphalt binder and asphalt mixture experimental data, which significantly limit the application of the ENPTE transformation to the prediction of low temperature properties of asphalt binder when, for example, only mixtures can be tested. Therefore, if a mathematical expression can be developed for obtaining parameter α a priori, without entirely relying on testing, then, the low temperature creep properties of asphalt binders can be easily estimated from the low temperature properties of corresponding asphalt mixtures.

7. Modeling of parameter α : MCF model

Parameter α provides the link between binder and mixture properties and, therefore, it must be associated to the contribution of the different material phases: air voids, mastic and aggregate. To build a mathematical expression for parameter α , the following three-step approach was used:

- Assemble a simple 2D micromechanical-analogical model, called MCF (Moon Cannone Falchetto) model, for asphalt mixture consisting of three phases (aggregate, asphalt mastic and air voids) based on Huet and Hirsch models;
- Derive an equation for E^*_{mix} ;

- Obtain a mathematical expression for parameter α by using the MCF model, the identification process and the newly derived equation of E_{mix}^* .

In order to take into account the different mixture phases, while keeping the complexity of the scheme at a reasonable level of complexity, an initial asphalt mixture model composed of an aggregate dominant part (part 1) and asphalt mastic dominant part (part 2) was assembled (Figure 5a). The aggregate dominant part (part 1) consists of coarse aggregates coated with a thin layer of asphalt mastic, and the asphalt mastic dominant part (part 2) accounts for fine aggregates and air voids randomly distributed in the asphalt binder matrix. This two-block scheme is based on the recent findings of one of the authors (Cannone Falchetto et al. 2014a, 2014b) which indicate that at low temperature a significant contribution to the material behavior is given by the mastic phase.

Based on this initial concept, on the Hirsch model structure (Figure 5(b)) and on the Huet (1963) model, a new micromechanical–analogical-based model, MCF model, was implemented (Figure 5(c)). With respect to the aggregate dominant part (part 1), aggregate and asphalt mastic were connected in series and air voids attached in parallel to the entire assembly of spring and parabolic elements (Huet model block), providing a significant contribution to this side of the model. For the asphalt mastic dominant part (part 2), the air voids component was connected in parallel with asphalt mastic and then attached in series with the aggregate spring. Therefore, the model of Figure 5c incorporates information on material phases while it still presents the advantages of the Huet analogical model.

To obtain an expression of parameter α based on mixture microstructure, six parameters were identified for part 1 and part 2 of the model: volume fractions of aggregate, A_1 and A_2 , volume fractions of asphalt mastic, M_1 and M_2 , and volume fractions of air voids, V_1 and V_2 (Figure 5b). Based on the model in Figure 5, the following conditions can be written together with the complex modulus, E_{mix}^* , expression:

$$V_1 + V_2 = V_{tot}, \quad M_1 + M_2 = M_{tot}, \quad A_1 + A_2 = A_{tot} \quad [14]$$

$$V_{tot} + M_{tot} + A_{tot} = 1 \quad [15]$$

$$E_{mix}^* = E_{part1}^* \cdot V_{part1} + E_{part2}^* \cdot V_{part2} \quad [16]$$

$$E_{mix}^* = \frac{A_1 + M_1}{\frac{A_1}{E_{agg}} + \frac{M_1}{E_{mastic}^*}} \cdot [A_1 + M_1 + V_1] + \frac{1}{\frac{A_2}{E_{agg}} + \frac{M_2 + V_2}{E_{mastic}^* \cdot M_2}} \cdot [A_2 + M_2 + V_2] \quad [17]$$

$$\text{Where } V_{part1} = A_1 + V_1 + M_1, \quad V_{part2} = A_2 + V_2 + M_2 \quad [18]$$

Equation [17] can be rearranged based on Equation [3] as:

$$E_{\infty_mix} = \lim_{w\tau \rightarrow \infty} E_{mix}^* (i w \tau_{mix}) = \frac{(A_1 + M_1) \cdot [A_1 + M_1 + V_1]}{\frac{A_1}{E_{agg}} + \frac{M_1}{E_{\infty_mastic}}} + \frac{[A_2 + M_2 + V_2]}{\frac{A_2}{E_{agg}} + \frac{M_2 + V_2}{E_{\infty_mastic} \cdot M_2}} \quad [19]$$

Based on a previous research (Christensen et al. 2003), the relation between asphalt mastic and binder can be written as:

$$E_{mastic}^* = \left(V_f' \cdot E_{agg}^n + V_{binder}' \cdot E_{binder}^{*n} \right)^{1/n} \quad [20]$$

where $V_f' = V_f / V_{mastic}$ is the volume fraction of filler in mastic; $V_{binder}' = V_{binder} / V_{mastic} = 1 - V_f'$ is the volume fraction of binder in the mastic; and n is an exponent with values from -1 to +1 and set as -0.2 according to Christensen et al. (2003). Since for the materials used in this research, V_f' is much smaller than V_{binder}' , Equation [20] was approximated to easily perform the identification process as:

$$E_{mastic}^* = \left(V_f' \cdot E_{agg}^n + V_{binder}' \cdot E_{binder}^{*n} \right)^{1/n} \cong \left(V_{binder}' \cdot E_{binder}^{*n} \right)^{1/n} = [V_{binder}']^{1/n} \cdot E_{binder}^* \quad [21]$$

Hence, for an asphalt mixture Equation [4] can be simply written as:

$$E_{mix}^* (i w \tau_{mix}) = \frac{E_{\infty_mix}}{1 + \delta \cdot (i \cdot w \cdot \tau_{mix})^{-k} + (i \cdot w \cdot \tau_{mix})^{-h}} = \frac{1}{\frac{1}{E_{\infty_mix}} + \frac{y}{E_{\infty_mix}}} \quad [22]$$

$$\text{Where } y = \delta \cdot (i \cdot w \cdot \tau_{mix})^{-k} + (i \cdot w \cdot \tau_{mix})^{-h} \quad [23]$$

By using Equation [4] and expression [21], the complex modulus of asphalt mastic can be written as:

$$E_{mastic}^* (i w \tau_{mastic}) = \frac{[V_{binder}']^{1/n} \cdot E_{\infty_binder}}{1 + \delta \cdot (i w \tau_{binder})^{-k} + (i w \tau_{binder})^{-h}} = \frac{[V_b']^{1/n} \cdot E_{\infty_binder}}{1 + x} \quad [24]$$

$$\text{Where } x = \delta \cdot (i w \tau_{binder})^{-k} + (i w \tau_{binder})^{-h} \quad [25]$$

Using Equations [17], [21] and [24], E_{mix}^* can be expressed as:

$$\begin{aligned} E_{mix}^* &= \frac{(A_1 + M_1) \cdot [A_1 + M_1 + V_1]}{\frac{A_1}{E_{agg}} + \frac{M_1}{[V_{binder}']^{1/n} \cdot E_{\infty_binder}}} + \frac{[A_2 + M_2 + V_2]}{\frac{A_2}{E_{agg}} + \frac{M_2 + V_2}{[V_{binder}']^{1/n} \cdot E_{\infty_binder} \cdot M_2}} = \\ &= \frac{1}{\frac{1}{E_{\infty_mix}} + \frac{y}{E_{\infty_mix}}} \end{aligned} \quad [26]$$

The left hand of Equation [26] can be rewritten as:

$$\begin{aligned}
 E_{mix}^* &= \frac{(A_1 + M_1) \cdot [A_1 + M_1 + V_1]}{\left(\frac{A_1}{E_{agg}} + \frac{M_1}{[V_{binder}]^{1/n} \cdot E_{\infty_binder}} \right) + \frac{M_1}{[V_{binder}]^{1/n} \cdot E_{\infty_binder}} \cdot x} + \\
 &\quad \frac{[A_2 + M_2 + V_2]}{\left(\frac{A_2}{E_{agg}} + \frac{M_2 + V_2}{[V_{binder}]^{1/n} \cdot E_{\infty_binder} \cdot M_2} \right) + \frac{M_2 + V_2}{[V_{binder}]^{1/n} \cdot E_{\infty_binder} \cdot M_2} \cdot x} \quad [27] \\
 &= \frac{\alpha \cdot \beta}{C + D \cdot x} + \frac{\gamma}{E + F \cdot x}
 \end{aligned}$$

The right hand of Equation [27] can be manipulated as:

$$E_{mix}^* = \frac{1}{\frac{1}{E_{\infty_mix}} + \frac{y}{E_{\infty_mix}}} = \frac{1}{H + H \cdot y} \quad [28]$$

Based on Equations [27] and [28], the following approximated identification process can be performed as:

$$\frac{\alpha \cdot \beta}{C + D \cdot x} + \frac{\gamma}{E + F \cdot x} \cong \frac{1}{P + A \cdot x} = \frac{1}{H + H \cdot y} \quad [29]$$

Where parameter A can be expressed as:

$$\begin{aligned}
 A &= \frac{D \cdot F}{\alpha \cdot \beta \cdot F + \gamma \cdot D} = \\
 &= \frac{\frac{M_1}{[V_{binder}]^{1/n} \cdot E_{\infty_binder}} \cdot \frac{M_2 + V_2}{[V_{binder}]^{1/n} \cdot E_{\infty_binder} \cdot M_2}}{\frac{(M_2 + V_2) \cdot (A_1 + M_1) \cdot [A_1 + M_1 + V_1]}{[V_{binder}]^{1/n} \cdot E_{\infty_binder} \cdot M_2} + \frac{M_1 \cdot [A_2 + M_2 + V_2]}{[V_{binder}]^{1/n} \cdot E_{\infty_binder}}} \quad [30]
 \end{aligned}$$

Combining Equations [28] and [30] the following expression can be obtained:

$$\begin{aligned}
 &\frac{\frac{M_1}{[V_{binder}]^{1/n} \cdot E_{\infty_binder}} \cdot \frac{M_2 + V_2}{[V_{binder}]^{1/n} \cdot E_{\infty_binder} \cdot M_2}}{\frac{(M_2 + V_2) \cdot (A_1 + M_1) \cdot [A_1 + M_1 + V_1]}{[V_{binder}]^{1/n} \cdot E_{\infty_binder} \cdot M_2} + \frac{M_1 \cdot [A_2 + M_2 + V_2]}{[V_{binder}]^{1/n} \cdot E_{\infty_binder}}} \cdot x = \frac{1}{E_{\infty_mix}} \cdot y \quad [31] \\
 \Rightarrow A \cdot \left[\delta \cdot (i\omega\tau_{binder})^{-k} + (i\omega\tau_{binder})^{-h} \right] &= \frac{1}{E_{\infty_mix}} \cdot \left[\delta \cdot (i\omega\tau_{mix})^{-k} + (i\omega\tau_{mix})^{-h} \right]
 \end{aligned}$$

and, hence:

$$\begin{aligned}
 i^{-h} \cdot \omega^{-h} \cdot \tau_{binder}^{-h} &= \frac{1}{A \cdot E_{\infty_mix}} \cdot i^{-h} \cdot \omega^{-h} \cdot \tau_{mix}^{-h} \quad [32] \\
 \Rightarrow \tau_{mix} &= \left[A \cdot E_{\infty_mix} \right]^{-1/h} \cdot \tau_{binder}
 \end{aligned}$$

Therefore, based on the MCF model (Figure 5) and on Equations [5] and [32] the following final expression of parameter α is proposed:

$$\alpha = -\frac{1}{h} \cdot \log \left[\frac{M_1 \cdot (M_2 + V_2) \cdot \left(\frac{(A_1 + M_1) \cdot (A_1 + M_1 + V_1)}{E_{agg} + \frac{M_1}{E_{\infty_mastic}}} + \frac{(A_2 + M_2 + V_2)}{E_{agg} + \frac{M_2 \cdot E_{\infty_mastic}}{M_2}} \right)}{E_{\infty_mastic}^2 \cdot M_2 \cdot \left(\frac{(A_1 + M_1) \cdot (A_1 + M_1 + V_1) \cdot (M_2 + V_2)}{M_2 \cdot E_{\infty_mastic}} + \frac{(A_2 + M_2 + V_2) \cdot M_1}{E_{\infty_mastic}} \right)} \right] \quad [33]$$

Equation [33] returns parameter α as function of the volumetric fractions of the asphalt mixture phases as well as of aggregate and mastic moduli. Equation [33], however, does not provide a way to quantify the volumetric fraction of different components for the aggregate dominant part and the mastic dominant part of the MCF model (Figure 5) a priori. In order to obtain the value of parameter α a priori, and to use it in the ENTPE transformation for performing back calculation analysis, A_1 , A_2 , M_1 , M_2 , V_1 and V_2 need to be determined and used as input in Equation [33]. For such a purpose Digital Image Processing (DIP) and 2-point correlation function of the microstructure components represent two analysis tools that can be used for obtaining the contributions of the material phases to the aggregate and mastic dominant parts of the proposed MCF model.

8. Microstructural Analysis

In this section, DIP analysis is first used to identify the three material phases (aggregate, asphalt mastic and air voids) in the asphalt mixture images of the scanned BBR specimen (Figure 2a). Then, 2-point correlation function is numerically estimated and the ACL of the material phases evaluated and used to determine the proportion of each mixture phase which contributes to the aggregate and mastic dominant components of MCF model.

8.1 Digital Image Processing

The phases and the volume fraction of aggregates, asphalt mastic and air voids of BBR asphalt mixture beams were estimated based on DIP analysis of digitalized RGB images having as resolution 720dpi. This resolution limits the possibility of detecting aggregates smaller than 0.075mm, and, therefore, particle smaller than the filler sieve size threshold cannot be identified. The DIP procedure consists of different steps including gray scale

conversion, histogram equalization, contrast enhancement, noise filtering and, most importantly, global thresholding (Zeleeuw et al. 2013, Cannone Falchetto et al. 2013). A detailed explanation on the specific procedure used can be found elsewhere (Moon et al. 2014b). Table 3 presents the mean of the estimated VMA_d , V_{mastic_d} and V_{air_d} of the ten mixtures used in this study, while Figure 6a provides an example of a three-phase asphalt mixture images obtained through DIP analysis.

Good visual correspondence between the material phases in the RGB and three-color scale image (gray for aggregate, green for mastic and red for air voids) is observed. In addition, low coefficient of variation (max CoV = 13%) were found for all the mixtures analyzed. This indicates that each asphalt mixture beam consistently presents similar volume fractions of aggregates, asphalt binder and air voids.

8.2 2-point Correlation Function

The effective mechanical properties and failure characteristics of a heterogeneous material with the same volume fractions can be significantly influenced by the spatial distribution of its constituents (Torquato 2000). Correlation functions provide statistical information on the degree of influence between two different points of a material, located at various distances (Moon et al. 2014b). Among these set of functions, 2- point correlation function presents a simpler formulation compared to other complex statistical tools; in addition, this statistical function is an autocorrelation function for which an auto correlation length (ACL) can be estimated (Berryman 1985, Cannone Falchetto et al. 2013).

The 2-point correlation function, S_2 , calculates the probability that two points, separated by a certain distance, r , are located both in the same phase and can be calculated as (Torquato 2002):

$$S_2^{(i)}(x_1, x_2) = \langle I^{(i)}(x_1) I^{(i)}(x_2) \rangle \quad [34]$$

where $\langle \rangle$ indicates the ensemble averaging and the indicator function $I^{(i)}(x)$ is defined as:

$$I^{(i)}(x) = \begin{cases} 1, & x \in V_i \\ 0, & x \in \bar{V}_i \end{cases} \quad [35]$$

where $V_i \in R^d$ is the volume occupied by the i^{th} phase and $\bar{V}_i \in R^d$ is the volume occupied by the other phase.

When the microstructure of a composite material does not present long range order, the initial value of 2-point correlation function is equal to the specific volumetric fraction, $S_2(r=0)=\phi_i$, and for large r ($r \rightarrow \infty$) it reaches the asymptotic limits of ϕ_i^2 (Berryman 1985).

A recent research effort (Moon et al. 2014b) have demonstrated that 2-point correlation function of a three-phase material such as asphalt mixture can be numerically estimated based on DIP analysis of asphalt mixture BBR beams and on Monte Carlo simulations.

The procedure (Figure 6b) for computing 2-point correlation function consists in dropping vectors of increasing length and random orientation (i.e. angle θ) in the digital image N times, while the number of times that both end points of the vectors are in the phase of interest is recorded. The process is iterated for vectors of lengths varying from 0 to half the size of the image for a number of drops $N > 100,000$ (Cannone Falchetto et al. 2013).

The three-phase images of the different beam specimens were used to compute 2-point correlation functions of aggregates, asphalt mastic and air voids. The values of the 2-point correlation function of each specimen were calculated as the mean of the two larger sides of each beam image. Figure 7 presents the mean 2-point correlation function of aggregate, asphalt mastic and air voids phases for all the asphalt mixture investigated. Small CoV were obtained: for example, in the case of the aggregate phase, a $\text{CoV}_{\max} = 3.8\%$ was observed.

The values of the 2-point correlation function do not fluctuate as the distance, r , increases; this is true for all the mixtures investigated and for all the three phases evaluated. 2-point correlation function starts at approximately ϕ_i and smoothly drops to ϕ_i^2 , as r increases (Berryman 1985). It is very interesting to observe that all the mixture have clear and distinct curves. In addition, the mastic phase presents significantly longer range decay. This clearly suggests a consistently different arrangement of this phase with respect to the other two within the material microstructure. This is also valid for mixtures 5 and 10, where a global shorter decay is observed for all phases.

8.3 Autocorrelation Length and Contribution to the Model Phases

Based on the results of 2-point correlation functions, it was decided to investigate the autocorrelation length (ACL) associated to the correlation function of each mixture in order to determine the contribution of each material phase to the left and right components of the MCF model (Figure 5). ACL measures how quickly a random event decays, or the

distance over which two or three points can be treated as independent for a specific random process (Berryman 1985; Cannone Falchetto et al. 2013; Moon et al. 2014b; Zhang and Sandararajan 2006). For example, Bazant and Pang (2007) associated ACL with the estimation of the dimensions of the Representative Volume Element (RVE) of the material. Based on two recent research efforts (Cannone Falchetto et al. 2013; Moon et al. 2014b), ACL was estimated (for all the material phases) as the distance over which the auto correlation function (ACF) assumes its theoretical value, ϕ_i^2 , in a stable manner within a 5% error (95% confidence interval). Nevertheless, in order to obtain additional information on how the contribution of the phases is allocated in the MCF model, the concept of 2-point correlation function decay was further explored.

The mathematical definition of the autocorrelation function can be given, according to different models, based on simple exponential forms. For example, the penetrable sphere model (Weissberg 1963; Berryman 1985) presents the following expression:

$$S_n^{(i)}(x_1, x_2, x_3, \dots, x_n) = \exp(-\rho V_n) \quad [36]$$

where ρ is the density of spheres and V_n is the union volume of n spheres with radius R and centers at the vertices $x_1, x_2, \dots, x_{n-1}$. A similar expression was proposed by other authors (Zhang and Sandararajan 2005):

$$S_n^{(i)}(r) = \exp(-r/\lambda) \quad [37]$$

where r is the spatial separation and λ is the ACL, which is defined as the distance at which the value of the autocorrelation function decays to $1/e$ of its original value ϕ_i (Zhang and Sandararajan 2005). Expressions [36] and [37] cannot be directly applied to asphalt mixture as demonstrated in recent studies (Cannone Falchetto et al. 2013; Moon et al. 2014b), due the specific heterogeneous characteristics of the material microstructure. In addition, for asphalt mixture this would lead to very short ACL that do not make physical sense, since the 2-point correlation function would still have a value that is significantly higher than its theoretical limit ϕ_i^2 (Figure 7). Nevertheless, such a condition may be used as a criterion for identifying the portion of the global ACL, ACL_G , where the effective interaction within the specific material phases is not significantly affected by the influence of the other phases. This noise effect can be assumed to occur in the initial part of the correlation function curve and, therefore, within the distance, r , over which the 2-point correlation function decay to $S_2^i = \phi_i^2 + (\phi_i - \phi_i^2)/e$. Based on this criterion two different components of the global ACL (ACL_G) can be defined: ACL_d , which corresponds to the

noise zone, and ACL_e , which represents the length of the ACL where it can be assumed that the interaction occurs only within the same material phase. Figure 8a provides a schematic interpretation of the ACL components, while Table 4 presents the estimated values ACL_G , ACL_d and ACL_e .

During the computation of the two parts of the ACL it was observed that the intersection of the tangent to the initial part of the 2-point correlation function curve with the theoretical line $S_2^i = \phi_i^2$ leads to estimate of ACL_d and ACL_e which are very close to those obtained numerically. In addition, the largest ACL value (4.578mm) in Table 4 is smaller than the smallest dimension of the BBR beam (6.25mm). This confirms the results of previous studies (Marasteanu et al. 2009; Cannone Falchetto et al. 2013; Moon et al. 2014a) and provides additional support to the use of BBR beams for asphalt mixture creep tests.

The values of ACL_G , ACL_d and ACL_e can be associated to the effective contribution of the aggregate and mastic dominant parts of the MCF model (Figure 5) and, hence, can be used to determine A_1 , A_2 , M_1 , M_2 , V_1 and V_2 . Based on the performed 2-dimensional DIP analysis and assuming a squared element-area for the i^{th} material phase, having area equal to $(ACL_G^i)^2$, the contribution of the phase i^{th} to the model dominant component can be defined as the portion of the element area equal to $(ACL_e^i)^2$, while the non-dominant component is obtained as $(ACL_G^i)^2 - (ACL_e^i)^2$ (Figure 8b, c, d).

The MCF model is structured into an aggregate dominant part and a mastic dominant part; the air voids component is associated in parallel with the aggregate Huet model block and, hence, it can be assumed that most of the air voids component will contribute to this side of the model. Based on this set of assumptions, the values of the volume fractions A_1 , A_2 , M_1 , M_2 , V_1 and V_2 were computed. Table 5 presents these values as percentage contribution of each material phase to the aggregate and mastic dominant parts of the MCF model, respectively.

Table 5 clearly shows a very minimal contribution of the mastic phase to the aggregate dominant part, while aggregate and air voids enter in the mastic dominant part with higher proportions, although still small. The values of A_1 , A_2 , M_1 , M_2 , V_1 and V_2 are used in the next section to compute parameter α and then to perform the inverse ENTPE transformation (Equation [9]) for predicting the asphalt binder creep stiffness based on asphalt mixture experimental creep data.

9. MCF Model Validation

The values of parameter α can be computed based on Equation [33] and on the inputs of Table 5. The glassy modulus of the mastic phase, E_{∞_mastic} , was obtained based on Equation [21] and on simple DIP gradation analysis, while the aggregate modulus was assumed to be equal to $E_{agg}=27.5\text{GPa}$ for the material used in this study (Cannone Falchetto et al. 2011; Moon et al. 2014). Table 6 presents the values of α previously determined from experimental data fitting (Table 2), the estimated α obtained from the MCF model (Equation [33]), and the values of E_{∞_mastic} .

The values of parameter α calculated with the MCF model are very close to those experimentally determined. The inverse ENTPE transformation (Equation 9) was then performed with the newly derived values of parameter α in order to achieve further validation of the proposed MCF model. Figures 9a and 9b compare the experimental and MCF derived $\log\tau_{mix} - \log\tau_{binder}$ relations for all the mixtures investigated, while Figures 9c and 9d provide the back calculation results of the asphalt binder creep stiffness.

A Very good linear trend of $\log\tau_{mix} - \log\tau_{binder}$ plots can be observed for both mixture groups: 1-5 and 6-10. Nevertheless, parameter α is either underestimated or overestimated for the first and the second group of mixtures, respectively. Reasonable predictions of the experimentally measured creep stiffness of the two asphalt binders, PG58-28 and PG58-34, are obtained using the newly derived expression of α parameter together with the ENTPE transformation. An overestimation of the creep stiffness of the order of 12% is observed for asphalt binder PG58-28 (Figure 9c), while an underestimation as large as 22% was found for asphalt binder PG58-34 (Figure 9d).

It is interesting to observe that the ENTPE transformation is quite sensitive to small variation of the transformation parameter α . Therefore, it is very critical to obtain precise estimation of the ACL and specifically of ACL_G , ACL_d and ACL_e , since these parameters significantly influence the estimation of A_1 , A_2 , M_1 , M_2 , V_1 and V_2 which are required by the MCF model in Equation [33]. Therefore, particular care need to be devoted to potential computational errors associated to the estimation of the correlation function and of the ACL, which, for very steep decay of the correlation function, may require a higher number of integration points and, hence, higher scanning resolution than those used in this study. Figure 7b and Table 5 clearly indicate that the most critical material phase is represented by asphalt mastic, for which a smoother decay is observed together with a minimal contribution to the aggregate dominant part of the MCF model.

10. Summary and Conclusions

In this paper laboratory testing, digital image analysis and material modeling were used to introduce a micromechanical-analogical model to predict the low temperature creep properties of asphalt binder from the corresponding asphalt mixtures experimental results with the aim of significantly reducing the experimental effort required for characterizing the material. The Huet model was first used to fit the creep compliance data of asphalt binders and corresponding mixtures, obtained with BBR tests at low temperatures, and to compute model parameters and the ENTPE fitting parameter α . Then, a micromechanical-analogical model, called MCF (Moon Cannone Falchetto) model, was introduced and used for obtaining an explicit expression of the α parameter, while DIP techniques and numerical estimation of the correlation function of the material microstructural phases were used to estimate α . Finally, the values of α obtained for each mixture were used in the inverse ENTPE transformation to predict the asphalt binder creep stiffness from the corresponding asphalt mixture creep stiffness data and the predictions compared with the experimental measurements.

A number of important conclusions can be drawn from this research:

- The characteristic time of asphalt binder is associated to the characteristic time of asphalt mixture through a linear function in the log-log scale. This means the fitting parameter α can be assumed as a unique parameter which can be used to relate low temperature creep stiffness of asphalt binder to the corresponding standard mixtures through the ENTPE transformation.
- Simple 2D DIP analysis technique and statistical evaluation of the material microstructure can be used to estimate parameter α , based on the explicit expression derived from the newly proposed MCF model.
- The predictions of the asphalt binder creep stiffness obtained by using the values of α , derived from the MCF model, together with the inverse ENTPE transformation are in reasonable agreement with the experimental creep stiffness data.

The results obtained in this research, although at the preliminary stage, are very promising. The MCF model and the expression for parameter α have the potential of significantly reducing the testing required for fully estimating the asphalt binder properties in the asphalt mixture, since parameter α is directly obtained from microstructural properties. It is expected that the findings of this research will significantly improve the design of asphalt mixtures with good thermal cracking resistance. Moreover, MCF model and the newly proposed formulation of α can be potentially used to evaluate the effective

properties of the asphalt binder in recycled mixtures, without relying on chemical extraction, which would result in a complete blending of virgin and recycled binders.

A limited number of asphalt binders and mixtures were investigated in the present study; nevertheless, the coefficients of the proposed mathematical expression of parameter α showed high sensitivity to the volume fraction of the mastic phase. Therefore, additional experimental work, analysis and careful evaluation of the proposed MCF model need to be undertaken to further support and fully validate the results presented in this paper.

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Table 1. Materials

ID #	Binder Type	Air voids %	VMA %	V _{air} %	V _{mastic} %	NMAS, mm
1	Plain PG58-28	7%	15.62	6.09	9.53	9.5
2		7%	17.45	5.98	11.48	12.5
3		4%	14.03	4.32	9.71	9.5
4		4%	15.58	3.84	11.74	12.5
5		4%	15.69	4.85	10.84	12.5
6	Modified PG58-34	7%	15.64	6.18	9.46	9.5
7		7%	17.32	5.86	11.46	12.5
8		4%	14.55	4.97	9.58	9.5
9		4%	15.38	3.65	11.73	12.5
10		4%	15.65	4.8	10.85	12.5

*Air voids: Target air voids for Superpave Mix Design, %

*VMA: Voids in Mineral Aggregate, %

*V_{air}: Volume fraction of air voids, V_{mastic}: Volume fraction of asphalt mastic

*NMAS: Nominal Maximum Aggregate Size, mm

Table 2. Huet parameters of asphalt binders and asphalt mixtures

ID #	Parameters			Binder		Mixtures		ENTPE
	δ	k	h	$E_{\infty \text{ binder}}$	τ_{binder}	$E_{\infty \text{ mix}}$	τ_{mix}	α
1	2.693	0.149	0.593	2914	1.214	30000	1260	3.015
2	3.011	0.187	0.615	3000	1.560	25003	1778	3.056
3	1.551	0.139	0.559	2500	1.015	30000	1163	3.058
4	3.293	0.183	0.628	3000	1.773	25000	1969	3.045
5	2.764	0.141	0.592	2955	1.159	25000	1218	3.022
6	1.986	0.076	0.501	2999	0.734	25000	1034	3.148
7	2.933	0.108	0.556	3000	1.560	25000	2243	3.157
8	1.691	0.091	0.512	2500	1.228	25343	1811	3.168
9	2.525	0.104	0.537	2996	1.215	25000	1723	3.151
10	2.319	0.103	0.526	2979	1.082	25000	1493	3.140

* $E_{\infty \text{ binder}}$: Glassy modulus of asphalt binder (MPa), $E_{\infty \text{ mix}}$: Glassy modulus of asphalt mixture (MPa)

* τ_{binder} : Characteristic time of asphalt binder (MPa), τ_{mix} : Characteristic time of asphalt mixture

* Grey box: Plain binder: PG 58-28, white box: Modified binder: PG 58-34

Table 3. Summary of DIP estimated VMA_d , V_{air_d} and V_{mastic_d} for the ten asphalt mixtures investigated

ID #	Binder type	VMA_d , %		V_{air_d} , %		V_{mastic_d} , %		Δ_{VMA}	Δ_{Vair}	$\Delta_{Vmastic}$
		Mean	CoV	Mean	CoV	Mean	CoV			
1	Plain PG58-28	15.79	4.99	6.26	5.98	9.52	7.44	0.16	0.17	0.01
2		17.25	8.78	6.17	10.50	11.08	9.05	0.21	0.19	0.40
3		13.95	2.27	4.40	5.63	9.55	3.40	0.08	0.08	0.16
4		15.76	4.03	4.26	9.77	11.50	6.24	0.18	0.42	0.24
5		15.83	3.57	4.66	5.37	11.17	6.99	0.15	0.19	0.33
6	Modified PG58-34	15.85	7.38	6.53	9.89	9.32	7.66	0.21	0.35	0.14
7		17.09	8.80	6.04	7.17	11.05	9.75	0.23	0.18	0.41
8		14.77	6.98	5.14	8.94	9.63	7.94	0.22	0.17	0.05
9		15.40	3.62	3.93	13.00	11.47	7.44	0.02	0.28	0.26
10		15.49	5.4	4.41	10.33	11.08	5.39	0.16	0.39	0.23

* $\Delta_{VMA} = |VMA - VMA_d|$, $\Delta_{Vair} = |V_{air} - V_{air_d}|$, $\Delta_{Vmastic} = |V_{mastic} - V_{mastic_d}|$

* V_{air_d} , V_{mastic_d} , and VMA_d are the values obtained from DIP analysis

* V_{air} , V_{mastic} , and VMA are the experimentally measured values (Table 1)

* CoV (Coefficient of Variation) = Standard deviation/Mean (%)

Table 4. Autocorrelation length (ACL) of aggregate, mastic and air voids phases

ID #	Aggregate ACL (mm)			Asphalt mastic ACL (mm)			Air Voids ACL (mm)		
	ACL_G	ACL_d	ACL_e	ACL_G	ACL_d	ACL_e	ACL_G	ACL_d	ACL_e
1	1.218	0.092	1.126	3.948	0.472	3.476	4.578	0.105	4.473
2	1.134	0.098	1.036	3.864	0.396	3.468	4.242	0.105	4.137
3	1.092	0.079	1.013	3.654	0.504	3.150	4.158	0.101	4.057
4	0.798	0.069	0.729	2.814	0.289	2.525	3.024	0.079	2.945
5	0.714	0.054	0.660	0.802	0.091	0.711	0.882	0.022	0.861
6	1.176	0.069	1.107	3.906	0.588	3.318	4.452	0.102	4.350
7	1.008	0.057	0.951	3.696	0.411	3.285	4.032	0.066	3.966
8	0.966	0.083	0.883	3.486	0.481	3.005	3.738	0.102	3.636
9	0.672	0.063	0.609	2.646	0.291	2.355	2.856	0.081	2.775
10	0.726	0.063	0.663	1.050	0.126	0.924	1.344	0.024	1.320

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Table 5. Allocation of the mixtures volume fractions in the MCF model (Figure 5)

ID #	Binder type	Aggregate dominant part (%)			Mastic dominant part (%)		
		A_1/A_{tot}	M_1/M_{tot}	V_1/V_{tot}	A_2/A_{tot}	M_2/M_{tot}	V_2/V_{tot}
1	Plain PG58-28	85.5	1.4	95.5	14.5	98.6	4.5
2		83.5	1.1	95.1	16.5	98.9	4.9
3		86.1	1.9	95.2	13.9	98.1	4.8
4		83.5	1.1	94.8	16.5	98.9	5.2
5		85.5	1.3	95.2	14.5	98.7	4.8
6	Modified PG58-34	88.6	2.3	95.5	11.4	97.7	4.5
7		89.0	1.2	96.8	11.0	98.8	3.2
8		83.6	1.9	94.6	16.4	98.1	5.4
9		82.1	1.2	94.4	17.9	98.8	5.6
10		83.4	1.4	96.5	16.6	98.6	3.5

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Table 6. Estimated values of parameter α from the MCF model

ID #	Binder type	ENTPE α	MCF α	Difference (%)	$E_{\infty, mastic}$ (MPa)
1	Plain PG58-28	3.016	3.020	0.1	3265
2		3.057	2.992	2.1	3441
3		3.059	3.001	1.9	3247
4		3.046	2.901	4.8	3378
5		3.022	3.003	0.6	3364
6	Modified PG58-34	3.149	3.272	3.9	3250
7		3.158	3.288	4.1	3379
8		3.169	3.227	1.8	3211
9		3.152	3.260	3.4	3304
10		3.140	3.222	2.6	3283

Figure 1. Research approach flow chart

Figure 2. (a) Hirsch model (1962), (b) Huet model (1963) and (c) 2S2P1D model (Di Benedetto et al. 2004)

Figure 3. (a) Schematic of asphalt mixture specimens preparation and DIP analysis, and BBR with thin (b) asphalt binder and (c) asphalt mixture specimens

Figure 4. (a) Huet model fitting of creep compliance data of asphalt binders and asphalt mixtures 1, 3, 6, 8; (b) relationship between τ_{binder} , and τ_{mix} , for mixture set 1~5 and 6~10; (c) examples of forward and inverse ENTPE transformation

Figure 5. Asphalt mixture analogical-microstructural model: MCF model

Figure 6. (a) Original and three-phase asphalt mixture beam images of mixture 7; Side 1&2: top; Side 3&4: bottom; Side 5&6: left; Side 7&8: right; (b) schematic of the simplified algorithm for 2-point correlation function

Figure 7. 2-point correlation functions of (a) aggregate, (b) asphalt mastic and (c) air voids mixture phases

Figure 8. (a) Schematic of the ACL components and schematic for the estimation of A_1 , A_2 , M_1 , M_2 , V_1 and V_2 ; the shaded square indicates the dominant contribution of (b) aggregate, (c) mastic and (d) air voids phases.

Figure 9. Experimental and MCF derived $\tau_{\text{binder}} - \tau_{\text{mixture}}$, relation for mixture sets (a) 1, 2, 3, 4, 5 and (b) 6, 7, 8, 9, 10 and ENTPE back calculation of asphalt binder creep stiffness based on the MCF model for mixtures sets (c) 1, 2, 3, 4, 5 and (d) 6, 7, 8, 9, 10

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(b)

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(c)

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