Construction and Building Materials 53 (2014) 568–583

Contents lists available at ScienceDirect

Construction and Building Materials

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

Investigation of asphalt binder and asphalt mixture low temperature creep properties using semi mechanical and analogical models

Ki Hoon Moon [a,*], Augusto Cannone Falchetto [b,1], Jong Wan Hu [c,d,2]

[a] Samsung C&T Corporation, Material R&D Part, 6th Fl. Daeryung Gangnam Tower, 826-20, Yeoksam 1-Dong, Gangnam-Gu, Seoul 135-935, South Korea
[b] Technical University of Braunschweig, Department of Architecture, Civil Engineering and Environmental Sciences – Pavement Engineering Centre (ISBS), Beethovenstraße 51b, Braunschweig 38106, Germany
[c] University of Inchon, Department of Civil and Environmental Engineering, 12-1 Songdo-dong, Incheon 406-840, South Korea
[d] Incheon Disaster Prevention Research Center, University of Incheon, 12-1 Songdo-dong, Incheon 406-840, Republic of Korea

HIGHLIGHTS

- DIP analysis provides good agreement between generated and original asphalt images.
- Linear relation was observed between $\mathrm{Log}\tau_{binder}$ and $\mathrm{Log}\tau_{mix}$ based on Huet model.
- ENPTE parameter α is a unique value for binder and corresponding mixture.
- An expression for parameter α was developed based on Hirsch and Huet models.
- The new expression for α provides good estimations of the experimental data.

ARTICLE INFO

Article history:
Received 14 September 2013
Received in revised form 8 December 2013
Accepted 9 December 2013
Available online 7 January 2014

Keywords:
Hirsch model
ENPTE transformation
Asphalt
Microstructure
Low temperature creep property

ABSTRACT

The Hirsch model and the ENTPE transformation are commonly used to predict asphalt mixture creep stiffness from asphalt binder creep stiffness data and vice versa, at low temperatures. However, they present accuracy limits and lack of understanding on the physical parameters meaning, respectively. This paper presents an experimental and theoretical investigation to establish a link between the microstructure of mixtures and these parameters. This is accomplished by three-point bending tests on asphalt binders and mixtures, digital image analysis and through a newly derived expression of the α parameter in the ENTPE transformation. The results indicate that reasonable predictions of binder low temperature creep properties can be obtained from the corresponding mixture low temperature creep properties.

1. Introduction

Thermal cracking represents a significant pavement distress in cold climates. As temperature drops below 0 °C, thermal stress starts to increase in the restrained asphalt pavement layer. When the temperature reaches a critical value, called critical cracking temperature, at which thermal stresses exceed the strength of the material, thermal cracking occurs and thermal stresses are relieved. Thermal cracking has serious negative effects on pavement performance, since water can penetrate freely in the pavement structure and accelerate the deterioration process due to freeze–thaw cycles and traffic loading as well as loss in base and subgrade strength.

Currently, many agencies are working on different research projects with the objective of maintaining their pavement networks in acceptable conditions. A number of experimental methods have been developed over the years to characterize asphalt binders' and mixtures' behavior at low temperatures and to select materials with better performance. One fundamental test used to characterize viscoelastic materials is the creep test. In this test, a stress is applied instantaneously to the specimen and it is maintained constant for the entire duration of the test. 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. For asphalt binders, the creep test is performed with the Bending Beam Rheometer (BBR) according to the current AASHTO specification [1]. Recently, it was shown that creep tests can be also performed

---

* Corresponding author. Tel.: +82 2 2145 6507; fax: +82 2 2145 6500.
E-mail addresses: moonx113@umn.edu (K.H. Moon), canno125@umn.edu (A. Cannone Falchetto), jongp24@inchon.ac.kr (J.W. Hu).

[1] Tel.: +49 531 391 62064; fax: +49 531 391 62064.

[2] Tel.: +82 32 835 8463; fax: +82 32 835 0715.

0950-0618/$ - see front matter Crown Copyright © 2013 Published by Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.conbuildmat.2013.12.022

on thin beams made of asphalt mixture using the same BBR equipment that is currently required for asphalt binder tests [2].

2. Problem statement

In past years, micromechanical models were used to analyze asphalt mixture behavior and to explain the relationship between asphalt binder and mixture properties. Asphalt mixtures can be considered composite materials which contain aggregate particles of various sizes and shapes randomly distributed in a matrix of asphalt binder or mastic. Asphalt mixtures have been modeled as two-phase materials consisting of binder (or mastic), and aggregate [3–6] as well as three-phase materials consisting of large aggregate, small aggregate and mastic [7–9]. In most cases, significant differences were observed between the model prediction and the experimental results.

Recently, it was observed that the semi-empirical Hirsch model [10] and a transformation based on mechanically analog models, ENTPE transformation [11,12] could be successfully used to predict asphalt mixture creep stiffness from asphalt binder creep stiffness and vice versa at low temperatures. These models are described in detail in the theoretical background section of this paper.

The semi-empirical model contains parameters related to the composition of the mixture; however, the predictions are not always reasonable. The ENTPE transformation estimates well both mixture and binder properties; however, the meaning of the model parameters is not well understood since they are not defined based on mixture constituents, but rather from fitting both mixture and binder experimental data.

3. Research objective

The main objective of this paper is to derive a mathematical expression which can predict the low temperature creep properties of asphalt binder from the low temperature creep properties of a corresponding asphalt mixture without performing experimental tests on the asphalt binder. This approach is based on two models: the semi-empirical Hirsch model [10] and the analogical model based ENTPE transformation [11,12]. Based on the parameters combinations of the two models, the binder and mixture properties are linked to mixture microstructure by using Digital Image Processing (DIP) techniques. To accomplish this objective, the following research approach was pursued:

1. Use digital scanning to obtain extensive information on the aggregate structure of thin asphalt mixture beams having the same dimensions of BBR mixture specimens used for creep tests [2].
2. Develop a three-phase (aggregate, asphalt mastic and air void) asphalt mixture digital model, and compute aggregate, asphalt mastic and air void volume fractions, through Digital Image Processing (DIP) analysis.
3. Perform three-point bending creep tests on a set of asphalt binders and corresponding mixtures selected to provide combinations of different aggregates and binders.
4. Fit the analogical Huet model [13–14] to the creep compliance data of asphalt binders and corresponding mixtures obtained from BBR testing and determine the model parameters.
5. Develop an equation for calculating the fitting parameter α used in the ENTPE transformation based on the results of DIP analysis and Huet model fit.
6. Provide physical interpretation of the transformation parameters.

4. Theoretical background

4.1. Semi empirical model for asphalt mixture

A semi-empirical model, based on a previous model developed by Hirsch [15] for Portland Cement Concrete (PCC) was proposed by Christensen et al. [10] to estimate the extensional and shear dynamic modulus of asphalt mixtures. The model was generated by combining aggregate, asphalt binder and air void phases in parallel and series as (see Fig. 1):

Based in Fig. 1, the effective modulus of asphalt mixture can be expressed as:

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

where $E_{mixture}$ is the effective modulus of the mixture, E_{agg}, V_{agg} are modulus and volume fraction of aggregate, E_{binder}, V_{binder} are modulus and volume fraction of binder, and P_c is the contact volume as an empirical factor defined as:

$$Pc = \frac{\left(P_0 + \frac{VFA \cdot E_{binder}}{VMA}\right)^{P_1}}{P_2 + \left(\frac{VFA \cdot E_{binder}}{VMA}\right)^{P_1}} \tag{2}$$

where VFA is the voids filled with asphalt binder (%), VMA the voids between mineral aggregate (%), and P_0, P_1, P_2 are the fitting parameters.Eq. (2) can be expressed in terms of stiffness as:

$$S_{mixture} = Pc \cdot [S_{agg}V_{agg} + S_{binder}V_{binder}] + (1 - Pc) \cdot \left[\frac{V_{agg}}{S_{agg}} + \frac{(1 - V_{agg})^2}{S_{binder}V_{binder}}\right]^{-1} \tag{3}$$

Zofka [16] investigated the effectiveness of the Hirsch model [15] to predict the BBR mixture stiffness from the properties of the binder. Based on numerical manipulation the aggregate modulus, E_{agg}, which was equal to 4,200,000 psi (=29 GPa), was changed to a value of 2,750,000 psi (=19 GPa). The same author, in order to improve the prediction of the experimental results, proposed an alternative expression of parameter P_c [16]:

$$P_c = 0.1 \cdot \ln\left(\frac{E_{binder}}{a}\right) + 0.609 \tag{4}$$

where E_{binder} is the relaxation modulus of the binder in GPa, and a is the constant equal to 1 GPa.

It must be noticed that the Hirsch model contains parameters associated to the asphalt mixture constituents; however, the predictions are not always reasonable [12,17].

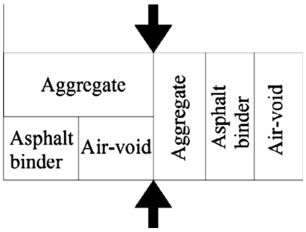

Fig. 1. Semi-empirical model proposed by Christensen et al. [10].