Construction and Building Materials 83 (2015) 70–76

Contents lists available at ScienceDirect

Construction and Building Materials

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

Analysis of different indices for high- and low-temperature properties of asphalt binder

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HIGHLIGHTS

- Different high-temperature evaluation indices were compared.
- Different low-temperature evaluation indices were compared.
- R_J that can evaluate both high- and low-temperature of asphalt was established.

ARTICLE INFO

Article history:
Received 5 October 2014
Received in revised form 6 February 2015
Accepted 10 February 2015
Available online 13 March 2015

Keywords:
Asphalt binder
Evaluation index
High-temperature performance
Low-temperature performance

ABSTRACT

The high- and low-temperature performance of asphalt binders have an important effect on the rutting and cracking resistance of asphalt pavements, thus these are two of the most important performance of asphalt binders. Nowadays, there are many indices to evaluate the high- or low-temperature performance of asphalt binders respectively. But there is still no unified option about which index is better.

As a kind of typical viscoelastic materials, both of the high-temperature performance and the low-temperature performance of asphalt binders are related to viscoelastic characteristics of asphalt binders, but they are opposite to each other. That is, a binder needs to have more elastic part for high-temperature performance but more viscous part for low-temperature performance. So the ratio of viscous part to elastic part is important to high- and low-temperature performance of asphalt binders. Based on that thought, a new index based on viscoelastic characteristics, referred to as R_J, is developed in this study. Different high- and low-temperature evaluation indices including R_J were analyzed by comparing the performance ranking evaluated by them with the ranking of the corresponding mixtures. The correlation between performance of binders evaluated by different indices and the performance of the corresponding mixtures were also analyzed. Based on the results, zero shear-rate viscosity and non-recoverable stiffness is found to be suitable for evaluating the high-temperature performance of asphalt binders, stiffness at 60 s from BBR is found to be suitable for evaluating the low-temperature performance of asphalt binders. The established evaluation index, R_J, is found to be suitable for evaluating both performances of asphalt binders.

1. Introduction

Rutting and cracking are two of the main distresses found in asphalt pavements. The ability of asphalt binder to resist rutting and cracking damage can have a profound effect on the service performance of an asphalt pavement. Thus, the high- and low-temperature performance of asphalt binders and corresponding evaluation indices have been two active research topics for a number of years, and some valuable results have been obtained.

The high-temperature evaluation indices of asphalt binders employ the softening point, viscosity, $G^*/\sin\delta$, etc. The softening point is commonly used in China for the high-temperature evaluation of asphalt binders [1]. The higher the softening point value, the better the high-temperature performance of the asphalt binder. Also, several countries, including the United States and Australia, have a viscosity grading standard. Asphalt binders with high viscosity values exhibit better high-temperature performance than those with low viscosity values [2]. Since the Superpave Performance Grade (PG) binder specification, AASHTO M320 [3], was put forward, the high-temperature specification parameter, $G^*/\sin\delta$ at 10 rad/s, is widely used throughout the United States and indeed throughout the world. This parameter represents an

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http://dx.doi.org/10.1016/j.conbuildmat.2015.02.008

improvement over the viscosity parameter because it is measured at a defined rate of deformation and accounts to some degree for the viscoelasticity of the binder via the phase angle. With the increased use of modified asphalt binders, however, the ineffectiveness of $G^*/\sin\delta$ in capturing high-temperature performance has been demonstrated by several researchers [4,5]. Thus, the refinement or replacement of the Superpave high-temperature specification parameter is of great interest to researchers and to practicing engineers [6–15].

The refined or replacement indices that have been proposed can be classified into three categories: (1) those based on dynamic modulus (G^*) and phase angle (δ), (2) those based on zero shear viscosity (ZSV), and (3) those based on creep and recovery tests.

$|G^*|/(1-(1/\tan\delta\sin\delta))$ is a G^* and δ based index suggested by Shenoy [6,7]. Shenoy specifies the high specification temperature (T_{HS}) as the temperature at which the term $|G^*|/(1-(1/\tan\delta\sin\delta))$ takes a value of 1 kPa for the original unaged binder or a value of 2.2 kPa for the rolling thin film oven (RTFO) aged binder. Because this method requires large sets of data generation at various temperatures to form the master curve, Shenoy also proposed an alternative method of using the term $|G^*|/(1-(1/\tan\delta\sin\delta))$ and found that it has the potential to capture field performance [8]. The disadvantage of this index is limited by the phase angle range, when the phase angle is less than 52°, the indicator is invalid [6].

ZSV is defined as the viscosity related to a constant strain rate as the stress approaches zero. Several researchers have used ZSV as a high-temperature index [9–11]. Phillips and Robertus [9] used ZSV to characterize asphalt binders with respect to its contribution to rutting resistance. They performed rutting tests on dense asphalt concrete specimens in a laboratory test track. Two unmodified asphalt binders and two elastomer-modified binders were used for their study. By plotting the rut rate versus viscosity, they observed a good correlation. Rowe et al. [10] proposed a method for using ZSV to describe the asphalt binder high-temperature performance grade, and compared this criterion to the Superpave specification. They found that both methods produce similar results for the unmodified binders, but significantly different results for the modified binders. Anderson et al. [11] calculated ZSV using different methods (Cross model, creep test, loss modulus, etc.), and compared the values obtained from the different methods. They found that ZSV may be determined reliably from either dynamic data or single cycle creep and recovery data, and that the ZSV values determined by the Cross model and by the graphical extrapolation of G''/ω provide similar results.

Creep and recovery tests are another popular method to evaluate the high-temperature performance of asphalt binders. There are several methods based on the basic creep and recovery test, such as the repeated creep recovery test (RCRT) and the multiple stress creep and recovery (MSCR) test. The RCRT was proposed by Bahia et al. [12] as a possible means to estimate the rate of accumulation of permanent strain in the binders. The RCRT test protocol consists of applying a creep load of 0.3 kPa for 1-s duration (loading time) followed by a 9-s recovery period (rest period) for 100 cycles. Bouldin et al. [13] developed a semi-empirical approach to predict the viscoelastic response of binders in RCRTs. To determine the stress dependence of an asphalt binder, the Federal Highway Administration (FHWA) developed the RCRT further and modified it by using increasing stress levels; the FHWA renamed it the MSCR test. The MSCR test is conducted at 11 stress levels from 25 to 25,600 Pa. Each stress level is repeated for 10 cycles and then increased to the next level. D'Angelo et al. [14] developed a test procedure to run creep and recovery testing on one sample at multiple stress levels, thereby developing a property called nonrecoverable compliance (J_{nr}); this property clearly shows the differences between different polymer-modified binders.

The low-temperature evaluation indices of asphalt binders employ low-temperature ductility, the Fraass brittle point, bending beam rheometer (BBR) etc. As a low-temperature evaluation index parameter, the low-temperature ductility value for different penetration-grade binders is restricted in the specifications in China [1]. The higher the ductility value, the better the low-temperature performance of the asphalt binder. The Fraass brittle point is the temperature at which an asphalt binder sample on a steel plate fractures. This test is inexpensive and easy to perform [16]. In the Strategic Highway Research Program (SHRP), two different tests were developed to evaluate the low-temperature performance of asphalt binders: the BBR test and the direct tension test (DTT) [17,18]. The stiffness ($S(t)$) and relaxation ability (m) of an asphalt binder can be measured by the BBR test. The DTT was designed specifically to test asphalt binders that were thought to provide adequate low-temperature performance in a pavement. By combining the BBR test and DTT, the critical cracking temperature can be predicted [19,20]. The glass transition temperature can be obtained by both differential scanning calorimetry and dynamic mechanical analysis [21,22]. The lower the glass transition temperature, the better the low-temperature performance of the asphalt binder. In addition to these test methods, fracture toughness and fracture energy testing also can be used to evaluate the low-temperature performance of asphalt binders.

From the above discussion, it is clear that a high-temperature evaluation index or low-temperature evaluation index can evaluate the high- or low-temperature performance of asphalt binders to some extent, and can rank different asphalt binders in terms of high-temperature performance or low-temperature performance. One problem is that there is no unified option about which index is the best. The other problem is that the high-temperature performance and low-temperature performance of asphalt binders are evaluated separately. In most conditions, binders that exhibit the best high-temperature performance usually do not exhibit the best low-temperature performance, and vice versa.

In order to address this need, this study establishes a new evaluation index R_J based on viscoelastic characteristics that can evaluate not only the high-temperature performance of asphalt binders but also the low-temperature performance of asphalt binders. Different high- and low-temperature evaluation indices including R_J are compared in order to find which one is much more suitable to evaluate the high- and low-temperature properties of asphalt binders.

2. Materials and test methods

2.1. Asphalt binder testing

Five neat asphalt binders and two modified asphalt binders were selected for this study. For the remainder of this paper, these materials are labeled as binders A-50, B-70 I, B-70 II, C-90, D-110, E and F. Table 1 presents the properties of all the binders. Five types of tests were conducted: the dynamic shear test, static shear test, repeated creep recovery test (RCRT), bending beam rheometer (BBR) test and differential scanning calorimetry (DSC) test. The dynamic shear tests, static shear test and RCRTs were performed using the Dynamic Shear Rheometer (DSR).

2.1.1. Dynamic shear test

The purpose of this test is to obtain the new index R_J and the rutting index $G^*/\sin\delta$. For the high-temperature performance testing, the tests were conducted using a 25-mm diameter parallel plate geometry and 1-mm gap setting at 60 °C, and for the low-temperature performance testing, the tests were conducted using an 8-mm diameter parallel plate geometry and 2-mm gap setting at −10 °C. The frequency was 10 rad/s. The controlled stress was different for different binders, and it was low enough to keep the binders in the linear viscoelastic domain.

2.1.2. Static shear test

The static shear test was used to obtain the zero shear-rate viscosity. The shear rate started from 0.01 1/s and increased linearly until the specimen broke. The viscosity was collected by the rheometer with increase of shear rate. The zero shear-