Construction and Building Materials 153 (2017) 695–703

Contents lists available at ScienceDirect

Construction and Building Materials

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

Development of paving performance index system for selection of modified asphalt binder

Chao Wang [a,b], Lidong Zhao [c], Wei Cao [d,*], Dongwei Cao [c], Bo Tian [c]

[a] *Key Laboratory of Road Structure & Material Ministry of Transport, Beijing, PR China*
[b] *Department of Road and Railway Engineering, Beijing University of Technology, Beijing 100124, PR China*
[c] *Highway Engineering Research Center, Research Institute of Highway Ministry of Transport, Beijing 100088, PR China*
[d] *Louisiana State University, Louisiana Transportation Research Center, 4101 Gourrier Ave., Baton Rouge, LA 70808, USA*

HIGHLIGHTS

- A comprehensive paving performance index (PPI) is established for modified asphalt.
- PPI considers various mechanical performances of asphalt binder.
- An adequate linear relationship is observed between PPI and binder cost.
- The performance per unit price is utilized to assess the cost-effectiveness.

ARTICLE INFO

Article history:
Received 27 March 2017
Received in revised form 18 June 2017
Accepted 19 July 2017

Keywords:
Modified asphalt
Rutting
Fatigue
Yield resistance
Elastic recovery
Cost effectiveness

ABSTRACT

The objective is to establish a comprehensive paving performance index (PPI) for quantifying the cost-effectiveness of modified asphalt binders. Eight modified binders were characterized using a suite of mechanical tests for the rutting, fatigue, yield, and recovery properties. The current specification parameter for each test was evaluated to establish the individual performance index (IPI). The developed PPI considered contributions from all IPIs and was found to correlate reasonably well with cost via a linear function, except for the crumb rubber (CR) modified binder. By evaluating the binder performance per unit price, CR was identified as the most cost-effective modifier.

1. Introduction

In the past two decades, modified asphalts have been widely utilized in pavement engineering and demonstrated better performance than conventional neat asphalts in many aspects such as rutting, thermal cracking, fatigue cracking, stripping, and temperature susceptibility. Polymer additives, such as styrene-butadienestyrene (SBS), styrene-butadiene rubber (SBR), and ethylene vinyl acetate (EVA), have seen success when used in heavily trafficked pavements. Among various polymer modifiers, SBS is probably the most widely used, although the addition of SBS may raise economic concerns and perhaps compatibility and stability issues [1,2].

Crumb rubber (CR) is another popular modifier that refers to the application in which ground recycled rubber and paving asphalt are combined [3]. Additional economic advantages can be obtained from the CR modified asphalt when the rubber is recycled from automotive and truck tires. The United States Federal Highway Administration (FHWA) conducted a life cycle cost analysis (LCCA) for modified asphalt mixtures, which indicated that CR modified asphalt is the most cost effective among all evaluated materials [4]. Furthermore, high modulus asphalt binders (HMABs) which are normally manufactured from hard-grade asphalt, rock asphalt modification, and polyolefin modification, are widely adopted in several European countries as well as in South Africa, China, and Korea for enhancing the rutting resistance of pavement structure [5–8]. High viscosity (HV) modified asphalt, polyphosphoric acid (PPA) modified asphalt, and also various alternative binders from

---

* Corresponding author.
E-mail addresses: wangchao@bjut.edu.cn (C. Wang), 472110053zld@163.com (L. Zhao), wcao@lsu.edu (W. Cao), caodongwei@vip.126.com (D. Cao), tbb73@yahoo.com (B. Tian).

http://dx.doi.org/10.1016/j.conbuildmat.2017.07.151
0950-0618/© 2017 Elsevier Ltd. All rights reserved.

biomass have been recently investigated for sustainable asphalt pavement technology [9–11]. In summary, various modified asphalt binders have been verified for improved paving performance in both laboratory and field. However, it should be noted that the asphalt pavement infrastructure is becoming increasingly costly in terms of construction and maintenance during service life due to asphalt modification. Therefore, in practice there is an urgent need to comprehensively quantify the performance improvement achieved by asphalt modification and to optimize material selection by incorporating the cost-effectiveness analysis.

A significant amount of research has been conducted to develop a performance related purchase specification for asphalt binder. During the United States Strategic Highway Research Program (SHRP), a series of rheological test procedures were proposed to determine the performance grade (PG) of asphalt binder with the use of dynamic shear rheometer (DSR) and bending beam rheometer (BBR) [12]. However, the SHRP specification parameters are measured within the linear viscoelastic (LVE) domain of asphalt binder, and thus no damage related material characteristics were accounted for in distinguishing the binder performance. Besides, the SHRP study was mainly conducted with neat (unmodified) asphalt materials. These existing limitations were addressed in the subsequent NCHRP Project 9–11 which focused on modifications to the SHRP binder specification in order to accommodate modified binders. Several new damage-based testing approaches for rutting and fatigue resistance were explored and developed, based on which the role of modified binder in rheology and damage resistance behavior of asphalt mixtures were more clearly observed [13,14]. However, these new test procedures from the NCHRP 9–11 study were time-consuming and experimentally intense, and thus finally were not implemented for binder specification.

In recent years, a continuing effort is being made to improve the PG specification system of asphalt binder by incorporating new damage-based performance tests [15]. The multiple stress creep recovery (MSCR) test (AASHTO TP 70) was developed as a specification procedure for evaluating the rutting potential of asphalt binders at high temperature. This methodology was successfully verified by correlating the obtained material parameter to rutting performance of asphalt mixtures and field pavements [16–18]. On the other hand, to develop a new fatigue evaluation approach for asphalt binder is challenging, as the test procedure should be practical to implement, without the time-consuming efforts typically associated with conventional fatigue testing. Johnson et al. [19–21] developed the linear amplitude sweep (LAS) test (AASHTO TP 101) as an accelerated fatigue procedure to predict the binder fatigue life under cyclic loading. Recently, Wang et al. [22] improved the prediction accuracy of the LAS-based binder fatigue life by establishing a unified energy-based failure criterion. Meanwhile, the newly released AASHTO TP 123 [23] procedure specifies binder testing at intermediate temperature using a monotonic constant shear rate loading, which consists of two performance tests, namely the binder yield energy test (BYET) and DSR-based elastic recovery (DSR-ER) test. Measuring the binder yield properties from BYET has been shown promising for predicting fatigue cracking and even thermal cracking at low temperature [24–26]. Besides, the ER test of asphalt binder also provides a reliable means to characterize asphalt modification with a traditional ductilometer [27]. Efforts has been successfully conducted to measure binder elastic recovery on DSR, which is the main device in the current PG specification [28,29].

This paper presents a framework to establish a paving performance index (PPI) for modified asphalt binders based on both the advanced performance tests and material costs. It is aimed to provide an effective approach to the selection of optimum binder modification for asphalt materials in practice.

2. Materials and testing

2.1. Materials

In this study, a total of eight modified asphalt binders were evaluated, which covered two typical SBS binders, HV binder, SBS + HV compound modified binders, CR modified binder, and two different HMABs. Details of the various modifiers are summarized in Table 1. All these modified binder materials are frequently applied to heavily trafficked pavement structures and/or extreme climate conditions in China. The material cost of each binder is also given in Table 1. The prices of SBS binders and CR binder are directly provided by the material producer. The costs of HV, two SBS + HV and HMABs binders are calculated using the unit prices of the base binders and modifiers. The final costs of all modified binders are utilized to analyze the cost-effectiveness of binders later.

2.2. Testing methods

The modified asphalt binders were subjected to a short-term aging condition in the conventional rolling thin-film oven (RTFO) test (AASHTO T 240) to simulate the asphalt aging process during mixture production and pavement construction [30]. All RTFO-aged binders were tested using an Anton Paar MCR 302 Rheometer, which is capable of all the rheological tests conducted in rotational and oscillatory modes. The modularity of the system allows the integration of a wide range of temperature devices and application-specific accessories. The standard 25-mm parallel plates with 1-mm gap and 8-mm parallel plates with 2-mm gap configurations were employed respectively for the high and intermediate temperature performance testing.

2.2.1. Multiple stress creep recovery (MSCR) test

Each cycle in the MSCR test consists of a creep load of 1-s duration followed by 9-s recovery with zero load. The load profile consists of ten creep-recovery cycles under the creep stress of 0.1 kPa immediately followed by another ten creep-recovery cycles with an increased creep stress level of 3.2 kPa [16]. The total testing time is 200 s. A typical strain history from the MSCR test with the SBS-R binder is given in Fig. 1.

The performance indicators of the MSCR test are percent recovery (R) and non-recoverable compliance (J_{nr}). For a given creep-recovery cycle, R and J_{nr} are calculated according to Eqs. (1) and (2), respectively:

$$R = \frac{\gamma_p - \gamma_n}{\gamma_p - \gamma_0} \tag{1}$$

$$J_{nr} = \frac{\gamma_n - \gamma_0}{\tau} \tag{2}$$

where, γ_0 represents the shear strain at the beginning of the cycle, γ_p is the peak strain after 1 s creep loading, γ_n represents the non-recoverable strain at the end of this cycle after 9 s of recovery, and τ represents the creep stress in each cycle. For each stress level, the R and J_{nr} values were averaged from the 10 creep-recovery cycles. Thus, totally four parameters, $R_{0.1}$, $J_{nr0.1}$, $R_{3.2}$, and $J_{nr3.2}$ can be determined, and $J_{nr3.2}$ is currently the specification parameter for distinguishing the rutting resistance of asphalt binders.

2.2.2. Linear amplitude sweep (LAS) test

The standardized LAS procedure (AASHTO TP101) consists of two steps [19]. First, a nondestructive frequency sweep test is conducted to determine the undamaged material response. Second, a linear oscillatory strain sweep with strain amplitudes ranging from 0.1% to 30% within 5 min is employed to assess the asphalt binder damage tolerance. The LAS test data interpretation is built upon the simplified-viscoelastic continuum damage (S-VECD) theory of asphalt concrete fatigue modeling [31–33].

Recently, an energy-based failure analysis approach is proposed for the LAS test to more accurately simulate the control-strain cyclic fatigue life (N_f) of asphalt binder, in which the LAS loading duration of 5 min were respectively extended to 10 min and 15 min [22]. This improved LAS-based binder fatigue evaluation approach is able to produce three material characteristic functions, i.e., dynamic shear modulus mastercurve, damage characteristic curve, and failure criterion. Fig. 2 (a)–(c) respectively presents the three material functions of the SBS-R binder, followed by the final N_f prediction result in Fig. 2 (d). The damage characteristic curve, which is independent of loading history, presents a unique relationship between the material integrity indicated by pseudo stiffness (C) and the internal state variable of damage intensity (S). The failure criterion gives the characteristic function between the releasing rate of pseudo strain energy (G^R) and the fatigue life N_f, which is also unique for any loading histories. The details regarding the establishments of the LAS-based binder fatigue modeling approach are provided elsewhere [22]. The predicted fatigue life for 3% strain, denoted as 3%N_f as shown in Fig.2(d), is utilized for fatigue performance comparison in this study.