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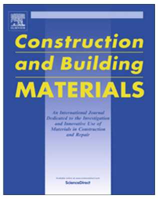

Evaluation of polymer modification in asphalt mixtures through digital image correlation and performance space diagrams

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HIGHLIGHTS

- High and low temperature performance of polymer modified mixtures was completed.
- Performance space diagram showed best mixture performance with PG70-28 binder.
- DIC results displayed increased fracture process zone size with polymer modification.
- Asphalt mixture fracture process zone size shrunk due to test boundaries.
- Asphalt mixture fracture process zone size was a function of test geometry.

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ABSTRACT

Asphalt polymer modification typically yields improved mixture performance. Little research has been conducted to determine how SBS polymer affects mixture performance in interaction plots. Furthermore, research to date has not used digital image correlation to measure the fracture process zone (FPZ) size and its compression with crack propagation. Mixtures containing five distinct asphalt binders were tested at high and low temperatures. Findings demonstrated that the PG 70-28 mixture shifted optimally in terms of high and low temperature properties. It was also found that polymer addition led to increased FPZ size and a lesser degree of FPZ compression with crack propagation.

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1. Introduction

Forensic research of cracking and rutting distresses in the field often demonstrate the superior performance of polymer-modified asphalt compared to unmodified asphalt mixtures. Von Quintus and Mallela [1] and Von Quintus et al. [2] found polymer modification led to increased service life of up to 10 years in Colorado and throughout the United States based on field investigations. In addition, Timm et al. [3] determined that polymer-modified asphalt yielded similar or improved performance compared to companion unmodified asphalt field sections. Field studies such as these provide impetus for laboratory research to understand how polymer positively affects asphalt binder and mixture properties at the macroscale (greater than centimeter scale) and microscale (sub-millimeter scale).

Laboratory investigations have shown that polymer modification leads to improved high and low temperature properties. At high temperatures, Woo et al. [4] noted improvements in shear stiffness in unaged binder via the dynamic shear rheometer test for polymer modified mixtures, which is associated with increased rutting resistance. Further evidence of superior rutting performance was found in laboratory binder studies with multiple stress creep and recovery tests completed by Vahidi et al. [5] and Yan et al. [6]. Finally, low temperature binder performance indicators through measurements of fracture energy density by Yan et al. [6] showed that polymer addition can lead to improved low temperature cracking resistance.

Laboratory research at the mixture macroscale level has produced analogous results to the asphalt binder investigations. Mohammad et al. [7], Vahidi et al. [5], and Timm et al. [3] found improved high temperature performance in polymer-modified mixtures through loaded wheel tests such as the Hamburg wheel tracking test. Furthermore, intermediate and low temperature cracking studies such as Birgisson et al. [8], Montepara et al. [9], Elseifi et al.

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[11], and Braham and Mudford [12] illustrated improved mixture performance resulting from polymer modification.

One method of evaluating macroscale-level improvements to mixtures resulting from polymer modification is to employ interaction plots to simultaneously evaluate high and low temperature mixture properties. This type of plot provides the user with a graphical means to understand shifts in rutting and cracking performance caused by changes in mixture ingredients, mixture composition and/or mixture volumetrics. Zhou et al. [13] and Cooper et al. [14] used this concept to evaluate recycled asphalt sources, binder grades, etc. in terms of rutting and fatigue or reflective cracking. Buttlar et al. [16] used this plot to evaluate field mixtures, binder grades, aggregate types, recycled asphalt pavement, recycled asphalt shingles, and recycled engine oil bottoms in terms of rutting and low temperature cracking resistance. Ozer et al. [15] also demonstrated the use of interaction plots to evaluate asphalt mixtures. However, none of these studies examined how incremental dosage rates of SBS effect mixture behavior in terms of shifts in a high-low temperature interaction space.

Mixture microscale low temperature properties have significance in terms of understanding polymer modification effects on fracture. Research by Birgisson et al. [8] and Montepara et al. [9,10] considered strain amplification/localization at cracks through qualitative assessment of DIC measurements. In Portland cement concrete research, Bazant and Kazemi [17] and Das et al. [18] measured the fracture process zone (FPZ) maximum length through analytical and DIC image analysis, respectively. However, little to no research has been completed to understand the effects of polymer modification in asphalt via a measure of the FPZ. Furthermore, little research has been conducted to consider how the FPZ changes in asphalt with and without modifiers during the period of testing. Measurements of the FPZ may provide meaningful information regarding strain dispersion due to polymer addition in asphalt mixtures thereby explaining how polymer modifiers improve low temperature fracture properties. Thus, the current research study will focus on macroscale interaction plots as well as measures of microscale low temperature mixture properties to further examine polymer modification effects in asphalt mixtures.

2. Objectives

The goal of the current study aimed to evaluate the effects of incremental dosage rates of SBS polymer on high and low temperature mixture performance properties at multiple length scales. First, Hamburg wheel tracking and DC(T) and SCB fracture tests were conducted to evaluate the macroscale properties of the polymer-modified and unmodified asphalt mixtures at high and low temperatures, respectively. Second, the Hamburg-DC(T) diagram was employed to evaluate how the SBS polymer content shifted performance. Third, the microscale properties of the asphalt mixtures at low temperatures using both SCB and DC(T) geometries were examined by measuring the size and dissipation of the fracture process zone using DIC.

3. Methods and materials

3.1. Testing materials

This studied used a 9.5 mm nominal maximum aggregate size (NMAS) mixture to evaluate the incremental dosage rate effects of SBS polymer. Dosage rates of SBS polymer were 1.5% for the PG 70-22 and PG 70-28 binders and 3.0% for the PG 76-22 binder. In addition, two unmodified mixtures containing PG 64-22 (control mixture) and PG 58-28 were used for comparisons between modified and unmodified mixtures. SBS is a common polymer modifier found in asphalt cements. This polymer, which is also used in the shoe sole and tire industries, is a block copolymer consisting of three units. The first unit, polystyrene, is a tough hard plastic providing added stiffness to the asphalt cement. The second unit, polybutadiene, is a rubbery component providing added elastic recovery to the asphalt cement. In addition, SBS is a thermoplastic elastomeric polymer. Asphalt viscosity measurements were completed at 130 °C using a Brookfield Rotational Viscometer under the ASTM D2171 standard. The viscosity results for the PG 64-22, 58-28, 70-22, 70-28, and 76-22 binders were 0.6, 0.4, 0.9, 0.8, and 9.0 Pa s, respectively.

The mixtures contained crushed limestone and natural sand fine aggregate and crushed gravel coarse aggregate. Mixtures designed in the current study followed AASHTO M323 to meet Superpave volumetric requirements. The unmodified mixtures were mixed and compacted at 150 °C while the modified mixtures were mixed at 170 °C and compacted at 150 °C. These temperatures were chosen in order to comply with the mixture design asphalt binder viscosity recommendations according to Roberts et al. [24]. All mixtures and subsequent performance test specimens were aged for approximately 2 h prior to compaction for short term oven aging. Additionally, all mixtures were stirred at approximately 1 h after introduction to the short term aging oven to avoid aging gradients with the sample. The mixture gradations were chosen such that volumetric properties such as the voids in the mineral aggregate (VMA), voids filled with asphalt (VFA), and percent effective binder (P_{be}) were approximately equal to avoid additional variables affecting performance in the DC(T) and Hamburg tests. The volumetric properties for the virgin aggregate and recycled material mixtures are provided in Table 1. The recycled binder contents in percentage form were provided in terms of the asphalt binder replacement ratio (ABR).

3.2. High and low temperature tests

The Hamburg wheel tracking test (HWT) was used to evaluate the high temperature macroscale properties of the asphalt mixtures investigated in this study. Following AASHTO T-324 [19], the HWT was used to measure mixture permanent deformation via external linear variable transducers (LVDT) in a water-immersed state at 50 °C with a 702 N loading applied through a rolling steel wheel. Asphalt mixture gyratory-compacted specimens, 130 mm in height, were cut in half and sawn along one edge to produce a flat face to produce a geometry suitable for the HWT (using the cylindrical geometry option). The heights of the two sides of each gyratory specimen were adjusted to reach equal heights to avoid dynamic loading. All Hamburg tests were conducted until either 20,000 passes was reached or 20.0 mm of rut depth was induced.

Several states specify the HWT to control asphalt pavement rutting. The Illinois Department of Transportation (IDOT) has three specification levels, where the minimum number of wheel passes prior to reaching an average rut depth of 12.5 mm is specified. When a PG 58-28 asphalt binder is specified, a minimum of 5,000 wheel passes is specified. When a PG 64-22 asphalt binder is specified, a minimum of 7,500 wheel passes must be reached prior to reaching a 12.5 mm rut depth. Finally, if mixtures are placed in the Chicago area, they must reach 20,000 passes in the HWT prior to reaching a 12.5 mm rut depth. The current study used the 7,500 wheel pass requirement for the Hamburg-DC(T) diagram, as the control (unmodified) mixture contained PG 64-22 asphalt binder.

DC(T) and SCB fracture test geometries were employed to measure the low temperature macroscale properties of the asphalt mixtures. Both geometries measure the crack propagation potential for asphalt mixtures in tension (Mode I fracture). Marasteanu et al. [20, 21] and Wagoner et al. [22] examined multiple fracture geometries, including the DC(T) and SCB, in Federal Highway Administration (FHWA) and National Science Foundation studies, respectively. Specific details regarding the geometries can be found in Marasteanu et al. [20]. The FHWA study created three minimum DC(T) mixture fracture energy levels based on the amount of traffic (project criticality) at the placement location to add a layer of risk avoidance. The thresholds for low, medium, and high traffic asphalt pavement mixtures were set at 400, 460, and 690 J/m^2, respectively, for short-term oven aged (2 h oven aged) samples.

The DC(T) and SCB tests evaluated fracture energy by measuring the area under the load-crack mouth opening displacement (CMOD) gauge curve, shown in Fig. 1, and normalizing it by the fractured surface area as shown in the following equations:

$$A = \int_0^{\delta_{max}} P(\delta)d\delta \tag{1}$$

$$G_f = \frac{A}{bL} \tag{2}$$

Table 1
Mixture design summary.

Total asphalt content (%)	6.6
ABR (%)	0.0
Air voids (%)	4.0
VMA (%)	15.2
VFA (%)	74.0
Effective asphalt content (%)	4.9
Dust/effective AC	1.1