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Comparison of rheological properties and hot storage characteristics of asphalt binders modified with devulcanized ground tire rubber and other modifiers

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HIGHLIGHTS

- A devulcanized ground tire rubber (DGTR) was utilized in this study.
- Three base asphalt binders, and three polymers were used to produce PG76 binders.
- Hot storage properties, creep and creep recovery, and multiple stress creep recovery, etc. were tested.
- PG76 binders modified with DGTR had approaching viscosity values compared to GTR or SBS modified binders.
- Binders modified with DGTR exhibited lower phase separation tendency than GTR or SBS modified binders.

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ABSTRACT

The ground tire rubber (GTR) modified binder has been affirmed to improve resistance to rutting, moisture susceptibility, low temperature cracking and durability of asphalt pavement. However, the liable phase separation of GTR modified asphalt binders results in a big issue at construction site. Therefore, an alternative crumb rubber, devulcanized ground tire rubber (DGTR), is manufactured with devulcanization process and as an additive to substitute for GTR or styrene-butadiene-styrene (SBS) in PG76 binders preparation process. The objective of this study was to compare the rheological properties and hot storage characteristics of PG76 asphalt binders produced with DGTR and two alternative polymers for future applications. The Brookfield Rotational Viscometer, Dynamic Shear Rheometer, and hot storage test were performed with all modified asphalt binders. The results indicated that PG76 binders modified with DGTR had approaching apparent viscosity values compared to GTR or SBS modified binders. In addition, the application of DGTR could reach the similar modification effect on the High PG critical temperature as well as GTR modified binders with same concentration. While those binders modified with DGTR exhibited remarkable lower tendency of phase separation than other modified binders regardless of base binder source. Moreover, similar trends were observed from the characteristics of creep and creep recovery, and Multiple Stress Creep and Recovery (MSCR) of all modified binders.

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1. Introduction

Annually, an estimated 13.5 million tons of waste tires are generated worldwide because of an explosive growth in private cars, which leads to serious environmental issue due to its difficult decomposition and huge stockpile. Generally, tires are made up with rubber, carbon black, steel wire, sulfur compound and synthetic fibers [1]. Engineering experiences have proved that rubber and fiber are benefit for improving the pavement performance of asphalt mixtures in paving industry. Scrap tires are processed of removing the steel wire and grounding to the desired size to yield ground tire rubber (GTR). Then GTR is incorporated into hot asphalt to produce rubber modified binder with improvements in rheological properties and as a solution of environmental problem to the waste tires.

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In the last decades, paving with GTR modified binders or Portland cement concrete gains rapidly increasing around the world, including USA and other countries [2–6]. Preparation of rubber asphalt by wet process is one of the major application mode. Florida experiences report the suggested rubber content should be 10–15% by weight of base binder in view of recycling of GTR [7], while Arizona experiences conclude that 20% GTR is a recommended content for producing GTR modified asphalt binder [8]. The difference lies mainly in the various idea of rubber recycling, the former projects emphasis on modification effects of waste rubber on asphalt binder, while the latter focus on modification and the large-scale consumption of waste rubber simultaneously.

Meanwhile, the effect of GTR on the asphalt binder has been obtained much attention by many researchers. A study reports that binders modified with crumb rubber are high viscosity compared to base asphalt binder [9]. Also, the addition of GTR has been found to enhance resistance to rutting, moisture susceptibility, and low temperature cracking of asphalt binder and high RAP mixtures [10]. The final performance of asphalt mixtures by using GTR modified binder is considered to be vitally affected by the physical and chemical characteristics of GTR [11–14]. Additionally, rubber particle size, curing time, temperature and mixing rate are observed to play key role on the rubber depolymerization rate in the binder [15]. Research by Saso et al. indicates that the utilization of surface modified GTR particles results in increasing the viscosity and failure temperature values of modified asphalt binder [16].

However, phase separation of GTR modified asphalt binder is a considerable puzzle in bitumen industry. As we known, crumb rubber particle dispersed in asphalt matrix attempts to settle down due to the differences in specific gravity between the crumb rubber and asphalt binder [17]. It is noted that increasing crumb rubber particle size and storage temperature tend to worsen the storage stability of GTR modified binder [18]. Generally, GTR modified binder is kept at high temperature to achieve a good handleability before mixing with aggregates. Hence, how to improve the hot storage stability of GTR modified asphalt binder gets a lot of attention.

Sulfur or sulfur-based cross-linking agents can help promoting the storage stability of GTR modified asphalt binder [19]. Additionally, a devulcanized ground tire rubber (DGTR) is utilized as a modifier in place of conventional GTR [20]. The rubber generally needs to be vulcanized to improve the temperature stability and strength in the tires production process. One or more sulfur atoms are attached to the polymer chain to form a bridge structure by sulfur crosslink. The vulcanized rubber is a thermoset material, which atomic bridges are composed of S—S, C—S or C—C bonds link the polymer chins together. While, the crosslink bonds in the vulcanized rubber are network structure, and molecular weight is larger than the asphalt binder resulting in liable phase separation in the process of GTR modified binder preparation. The devulcanization is proposed to make S—S and C—S bond link selectively cleaved totally or partially in reclaimed rubber process [21]. Generally, devulcanization of rubber can be generated by the means of mechanical, chemical, ultrasonic, microwave, and microorganisms. The devulcanized rubber powder can partly restore flexibility. The compatibility between DGTR and asphalt can be improved because of the molecular structure of rubber transformed from network to linear structure [22].

The objective of this study was to compare the rheological properties and hot storage characteristics of asphalt binders modified with DTGR and other two polymer modifiers. Three typical base asphalt binders, a common reclaimed crumb rubber, a DTGR and one frequently used SBS were employed to produce the modified binders PG76. The conventional test including RV, PG, hot storage test, frequency sweep, creep and creep recovery, and multiple stress creep recovery were carried out to evaluate the properties of the DTGR modified asphalt binders and other alternative polymers modified binders.

2. Materials and experimental procedures

2.1. Materials

Three base asphalt binders were selected in this study. All asphalt binders are PG 64-22 from different sources referred to as binder A, B and C. Three modifiers, a 40 meshes ambient GTR, one DGTR and a common SBS were utilized and referred to as polymer 1–3, respectively. Polymer 1 and polymer 2 were generally used for producing PG 76-22 binders with a concentration of 10–15% (by weight of base binder). Polymer 3, SBS, is conventional addition of 3.0–4.5% (by weight of base binder) to prepare PG 76-22 binders [9]. The specific concentration of modifier was determined through a laboratory trial with minimum content to achieve the PG76 in the study. In addition, one terminal blended SBS modified binder PG 76-22 was selected as a control binder, referred as BP0.

In this study, the blending time, temperature and stirring speed to produce these binders were 45 min, 177 °C and 2000 rpm, respectively. The names of specimens produced were designated as shown in Table 1.

2.2. Experimental procedure

The base binders and blended binders were tested according to Superpave binder specifications. The viscosity of these binders were evaluated by Brookfield Rotational Viscometer in accordance with AASHTO T316 [23]. About 8.5 g of base binder and 10.5 g of modified binder were investigated to obtain the viscosity value by using a spindle of #21 and #27, respectively. The rotational speed was kept at 20 rpm during the test. In this work, all modified binders were run the viscosity test at 135 °C, 150 °C and 165 °C, respectively. After the desired temperature was at the equilibrium for 5 min, the spindle was started. The viscosity values were recorded after the spindle rotated for 10 min. The viscosity values were obtained per minute, and the average value of the three values was served as the sample viscosity representative value. Each binder was tested three specimens, and the average value of the three samples was characterized the binder viscosity value.

The phase separation of polymer modified asphalt binder is a serious issue in bitumen industry. Therefore, the hot storage test is necessary to characterize the high temperature storage stability of modified binders during transportation and storage period. About 35 g modified binder was poured into an aluminum cigar tube (32-mm diameter, 160-mm height) and then sealed the tube carefully with pliers. The tube was moved to an oven and kept vertically at 163 ± 5 °C for 48 h. Then the cigar tube was took out of the oven and cooled in a refrigerator at −7 °C for 4 h. Subsequently, the frozen cigar tubes were cut into three equal sections. The samples from top and bottom sections were utilized to evaluate storage stability status by means of softening point test and the rheological properties by using Dynamic Shear Rheometer (DSR).

Rheological properties were measured by DSR in a parallel plate configuration with a gap width of 2 mm, which is suggested for crumb rubber modified binders [24]. The DSR samples were employed a oscillation rate of 10 radians per second (1.59 Hz), which simulates the shearing action on the asphalt pavement corresponding to a traffic speed of about 55 mph (90 km/h). The shear stress and shear strain were obtained during each cycle to calculate the complex modulus (G^*), phase angle (δ), and other rheological properties in terms of AASHTO T315 [25].

Table 1
Names of modified asphalt binders.

Binder type	Base binder	Modified asphalt binder PG 76-22			
		Terminally blended with SBS	Laboratory blended Polymer type		
			GTR	DGTR	SBS
PG 64-22	A		AP1 (15% by weight of binder)	AP2 (15% by weight of binder)	AP3 (3.5% by weight of binder)
PG 64-22	B	BP0 (3% by weight of binder)	BP1 (10% by weight of binder)	BP2 (10% by weight of binder)	BP3 (4.0% by weight of binder)
PG 64-22	C		CP1 (10% by weight of binder)	CP2 (10% by weight of binder)	CP3 (4.5% by weight of binder)

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