



Rheological property investigations for polymer and polyphosphoric acid modified asphalt binders at high temperatures



Feipeng Xiao ^{a,*}, Serji Amirkhanian ^b, Hainian Wang ^c, Peiwen Hao ^c

^a Key Laboratory of Road and Traffic Engineering of the Ministry of Education, Tongji University, Shanghai, 201804, China

^b Department of Civil, Construction, and Environmental Engineering, University of Alabama, Tuscaloosa, AL 35487, USA

^c School of Highway, Chang'an University, Xi'an, China

HIGHLIGHTS

- Rheology on SBS and three alternative binders with/without PPA was studied.
- Two base asphalt binders, four polymers, and one PPA were used to produce binders.
- Viscosity, $G^*/\sin\delta$, amplitude and frequency sweep, creep recovery, etc. were tested.
- 0.5% PPA could reduce by 1.0% the polymer needed to produce the PG 76-22 binder.
- Rheology of binders is dependent on polymer type, asphalt source and test temperature.

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ABSTRACT

Polymer modified asphalt binders have been used with success in mitigating many major causes of asphalt pavement failures (e.g., permanent deformation, moisture induced damage, fatigue, etc.). The styrene butadiene styrene (SBS) is commonly used for producing PG 76-22 binder, but the market was hit with a shortage of butadiene back in late 2009, which affected both supply and cost of PG 76-22 throughout the entire United States. Therefore, some alternative modifiers such as elastomers, plastomers, recycled ground tire rubber, sulfur additives, and polyphosphoric acid (PPA) to substitute for SBS in PG 76-22 asphalt binders have been investigated for future applications in the industry. The objective of this study was to investigate the high temperature rheological properties of SBS and three alternative polymer modified binders with/without PPA. Two base asphalt binders (PG 64-22), four polymers, and one PPA were used to produce the modified binders. The tested rheological properties include rotational viscosity, fail temperature, $G^*/\sin\delta$, phase angle, viscometry, amplitude sweep, frequency sweep, creep and creep recovery, and relaxation. The test results indicated that the PG 76-22 binders with two alternative polymers had noticeably lower viscosity values compared to SBS modified binders and thus need lower energy for mixing and compaction. In addition, for the binders used in this research work, the utilization of 0.5% PPA could reduce by 1.0% of additional polymer needed to produce the PG 76-22 binder. Moreover, the characteristics of viscometry, amplitude sweep, frequency sweep, creep and creep recovery, and relaxation spectrums of all modified binders were generally dependent upon polymer type, asphalt source, and test temperature.

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1. Introduction

In many cases, heavy traffic loading and severe weather conditions will result in some serious functional damage of asphalt pavements. Therefore, polymers have been incorporated into asphalt binders as a way to mitigate many major causes of asphalt

pavement failures, including permanent deformation at high temperatures and cracking at low temperatures, as well as some other failures such as fatigue, raveling, and stripping damage for many years [1–3]. These polymer modified asphalt (PMA) binders also have been used with success at many locations of high stress such as interstates, intersections, and airports [4]. The PMA has been commonly used materials in high quality asphalt pavement industry in many parts of the United States (US). PMA has proven itself to be an essential element in the paving process.

* Corresponding author. Tel.: +1 864 6504821.

E-mail address: fpxiao@gmail.com (F. Xiao).

Of all the polymer modifiers, styrene butadiene styrene (SBS), which was originally developed by Shell Chemical Co., is widely used in the majority of the modified asphalt binders in the US [5–7]. SBS creates a three dimensional network within the virgin asphalt phase, resulting in an excellent bonding strength to aggregates that leads to a durable and long-lasting pavement [8,9]. Currently, in the United States, the most commonly used polymer for asphalt modification is the SBS followed by other polymers such as GTR (ground tire rubber), SBR (styrene butadiene rubber), EVA (ethylene vinyl acetate) and polyethylene [10–12]. According to a modified asphalt market survey in 2005–2006, 80% of states, including South Carolina, across the US used SBS as a modifier [13].

Although they cost more than conventional binders, SBS-modified PG 76-22 asphalt binders have been utilized for many years by many state DOTs on interstate projects in order to increase the life of asphalt pavements. The high cost associated with the SBS modification process is mostly due to the SBS material. The SBS market was hit with a shortage of Butadiene back in late 2009, which affected both supply and cost of PG 76-22 throughout the entire US. Due to many reasons, it is important to have some alternative modifiers such as elastomers, plastomers, other polymers, GTR (from recycled passenger and truck tires), sulfur additive, and PPA (polyphosphoric acid) to substitute for SBS in PG 76-22 asphalt binders.

Polymers, having long-chain molecules of very high-molecular weight, used by the binder industry are classified based on different criteria including two general categories: elastomers and plastomers. An elastomer may be defined as an amorphous, cross-linked polymer above its glass transition temperature [14–16]. The load–deformation behavior of elastomers is similar to that of a rubber band such as increasing tensile strength with increased elongation, which may reach 1300% of the original length, and ability to recover to the initial state after removal of load. Plastomers exhibit high early strength but are less flexible and more prone to fracture under high strains than elastomers [17–19].

In an attempt to change its rheological characteristics and improve its performance properties, asphalt is often modified with an elastomer [20,21], a plastomer [22,23], a thermoset [24,25], sulfur [26], or a mineral acid [27]. The interest in using polyphosphoric acid (PPA) as a modifier to change asphalt features has increased in recent years [28]. It has been reported, by itself or in combination with a polymer, PPA provides a means of asphalt modification usually produced cheaper than one with a polymer alone [28].

PPA is an oligomer of H_3PO_4 . High-purity material is produced either from the dehydration of H_3PO_4 at high temperatures or by heating P_2O_5 dispersed in H_3PO_4 [29–31]. The dehydration method tends to produce short chains, whereas the dispersion method usually produces chains with more than 10 repeat units [32]. The literature indicates that the PPA has found increasing use as a straight additive without the need for air blowing to improve the grade range. Typical results are high-temperature grade improvements of less than 6 °C [31]. The increase in grade is thought to occur because of a reaction between the asphaltenes and acid [31,32].

Kodrat et al. reported the effect of PPA on the Superpave grading properties was found to be significant, with the high-temperature grade increasing by varying amounts depending on the crude source and the low-temperature grade [33]. King et al. found that contained asphalt binders modified with both PPA and anti-striping agent and tested using a Hamburg Wheel Tracking Device and an Asphalt Pavement Analyzer and found poor performance in these mixtures with acid–amine binders [34]. Ajideh et al. indicated that the resistance to moisture damage of asphalt mixtures modified with only PPA was not as good as that of those modified with other polymers [35]. In addition, they also found that asphalt mixtures modified with only PPA exhibited significantly improved resistance to rutting and fatigue. Baumgardner et al. studied the mechanism of how PPA interacts with asphalt binder and found that the interaction depends on the base (virgin) asphalt [32,36].

The objective of this study is to investigate the high temperature rheological properties of SBS and three alternative polymer modified binders with/without PPA. Two base asphalt binders, four polymers, and one PPA are used to produce the modified binders. The tested rheological properties in this study include viscosity, fail temperature, $G^*/\sin \delta$, phase angle, amplitude sweep, frequency sweep, creep and creep recovery, and relaxation.

2. Materials and experimental procedures

2.1. Materials

The bitumen materials used in this study included two asphalt base binders, which were from southeast area of USA. Both asphalt binders are PG 64-22 from different sources, commonly used by various state departments of transportation (DOTs). The basic rheological properties of two base binders are shown in Table 1. It can be noted that binder A generally has a higher viscosity, fail temperature, and $G^*/\sin \delta$ at unaged and rolling thin film oven (RTFO) states compared to binder B, but has a lower $G^*/\sin \delta$ and stiffness after a long term aging process. Therefore, it could be concluded that binder A has a better aging resistance.

Four polymers used in this research were SBS, oxidized polyethylene, Propylene–maleic anhydride, and –40 mesh ambient produced recycled crumb rubber and are referred to as 1–4, respectively. The main physical and chemical properties of these materials are shown in Table 2. Polymer 1, SBS, is commonly used for producing PG 76-22 binders (AP1 and BP1) with a concentration of 3.0% (by weight of base binder). Polymer 2 generally has a lower melting point and is often used for reducing the mixing and compaction temperature of asphalt mixtures. Approximately 3.0% (by weight of base binder) of polymer 2 was blended with base binders A and B to produce PG 76-22 binders (AP2 and BP2). Similarly, 3.0% of polymer 3 was used to produce the modified binders AP3 and BP3. When using recycled crumb rubber, approximately 10% –40 mesh crumb rubber was blended with base binders A and B and the produced binders were referred to AP4 and BP4.

The blending time and temperature to produce these PG 76-22 binders in this study were 30 min and 165 °C, respectively. However, when blended with 0.5% PPA, only 2% of polymers 1–3 and 10% crumb rubber were blended with the base binders for 30 min first and then PPA was added to the modified binders and blended another 30 min as recommended by the manufacture. The produced materials were designated as shown in Table 3.

2.2. Experimental procedure

The base binders and produced modified binders were tested according to Superpave binder specifications. Brookfield rotational viscometer was employed to measure the viscosity of these binders per AASHTO T316. Approximately 10.5 g base binders were tested to obtain the viscosity value by using a spindle of #21

Table 1
Rheology of base binders A and B.

Binder type	Source	Aging states						
		Unaged			RTFO			
		Viscosity (135 °C) (cP)	Fail temp. (°C)	$G^*/\sin \delta$ (64 °C) (kPa)	$G^*/\sin \delta$ (64 °C) (kPa)	PAV	Stiffness (–12 °C) (MPa)	<i>m</i> -Value (–12 °C)
PG 64-22	A	645	68.8	2.03	4.94	1429	103	0.376
PG 64-22	B	465	66.4	1.28	2.87	3229	257	0.312

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