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Laboratory investigation of using acrylated epoxidized soybean oil (AESO) for asphalt modification

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HIGHLIGHTS

- AESO can be used as an additive in asphalt modification.
- AESO decreases viscosity of the neat asphalt binder.
- AESO lowers the mixing and compaction temperatures.
- AESO reduces the compaction effort of HMA.
- LabAESO at high dosages improves resistance against fatigue and thermal cracking.

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ABSTRACT

This investigation examines the modification effect of using two types of acrylated epoxidized soybean oil (AESO) in asphalt binder at various concentration levels. The effects of AESO on rheological performance of neat asphalt binder were evaluated by employing rotational viscosity (RV), dynamic shear rheometer (DSR), and bending beam rheometer (BBR) tests. The results indicate that AESO has positive softening effects on decreasing the stiffness of asphalt binder, thereby reduces viscosity and lowers mixing and compaction temperatures. Moreover, laboratory produced AESO (LabAESO) performs superior to commercial available AESO (ComAESO) in terms of low temperature properties and fatigue life at the same concentration level and shows no separation. These findings suggest that a sufficiently high level of LabAESO is necessary in asphalt modification to dramatically affect rheological properties, and therefore enhance the neat asphalt binder's resistance to fatigue damage at intermediate temperatures and thermal cracking for cold regions pavement applications. Overall, LabAESO shows the potential to be used in asphalt modification with desirable performance improvement, and economic and environmental benefits.

1. Introduction

Flexible pavements using asphalt binder have encountered various pavement distresses due to increased traffic volume and adverse environmental factors throughout history [1–4]. The most critical pavement distresses in flexible pavements are permanent deformation at high temperatures, fatigue cracking at intermediate temperatures, and thermal cracking at low temperatures [1–3,5,6]. Additionally, oxidative aging of asphalt binder in hot mix asphalt is considered another major issue to pavement performance. Aging causes the asphalt binder in asphalt mixtures to be more viscous at high temperatures and more brittle at low temperatures. Thus, aging accelerates the development of pavement failures and shortens the design life of the pavement [3,4,7]. An appropriate stiffness of asphalt binder is desired to achieve a certain rutting resistance at service temperatures, while at the same time the asphalt binder must be fluid enough to allow for pumping and mixing with aggregates [3,8]. To enhance pavement performance and extend longevity of the roadways, polymer modified binders have been widely used in flexible pavement.

Polymers or additives used to modify asphalt to achieve a better performance are mostly inorganic and petroleum based, which has drawn concerns about environmental and economic problems

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[9,10]. To solve these problems, more sustainable alternatives for asphalt performance modification such as bio-based polymers derived from vegetable oils have facilitated research in industrial applications due to their benefits of inherent degradability, low toxicity, universal availability, and economic potential [10–15].

Vegetable oils commonly used as monomers in polymerizations are soybean oil, sunflower oil, castor oil, palm oil, safflower oil, linseed oil, and canola oil [11,16,17]. They are important renewable resources for biopolymers and are recognized as triglyceride oils that consist of three fatty acid chains connected by one glycerol center [11,18,19]. Triglyceride oils can be polymerized into biopolymers with flexible and rubbery properties due to the long fatty acid chains [16]. These fatty acids with carbon double bonds (C=C) are also known as unsaturations, which can be modified to attach functional groups such as converting C=C to epoxy groups through an epoxidation reaction, which is recognized as one of the most effective modification methods [11–13,20]. Since the epoxy groups are very reactive, they can be easily functionalized with other groups [11–13,20]. In industry, soybean oil is commonly used as acrylated epoxidized soybean oil (AESO) through epoxidation of soybean oil (ESO) and acrylation of ESO [11–13,20]. Then AESO monomers can be subsequently stored and used by themselves as surface coating materials or be polymerized to obtain thermoset biopolymers or bio-copolymers [11–13,20].

Since soybean oil is one of the most affordable and abundant vegetable oils in the United States (U.S.), there have been extensive research studies focused on the use of soybean oil as a biofeedstock to yield acrylated epoxidized soybean oil (AESO) monomer used in the production of industrial thermoset biopolymers such as coatings, inks, plasticizers, adhesives, and asphalt modifiers [10,17,19,21]. Biopolymers synthesized from triglyceride oil monomers have rubbery and flexible properties which enable them to be used as alternatives to petroleum-based polymers in asphalt modification [16,22]. Promising performance, environmental, and economical benefits of using biopolymers that were polymerized from the biomonomer AESO in asphalt modification have been shown in previous research conducted by Williams et al., Cascione et al., and Chen et al. [23–26]. According to their research studies, AESO was laboratory copolymerized with styrene to produce poly(styrene-*block*-acrylated epoxidized soybean oil) (PS-PAESO) diblock copolymer and poly(styrene-*block*-acrylated epoxidized soybean oil-*block*-styrene) (PS-PAESO-PS) triblock copolymer for asphalt performance modification [23–25]. Both diblock and triblock biopolymers were found to be beneficial in increasing elasticity, improving rutting resistance, and decreasing temperature susceptibility of the neat asphalt binder at a polymer concentration level of 3% [23–25]. They also performed superior to a commercial petroleum-based styrene-butadiene (SB) polymer in terms of rutting resistance experienced in warm climate regions when used at the same concentration level [23–25]. Current research is focusing on the production of AESO and biopolymers using AESO at commercial scale to conduct hot mix asphalt (HMA) performance testing and forthcoming demonstration-paving projects using biopolymer modified asphalt binders. The synthesis of AESO-based biopolymers has been very successful and their modification effects in asphalt binder have shown great potential in past and current research, however, there is no literature about the use of AESO itself as an additive in asphalt modification.

This research focuses on the modification effect of using two types of AESO in asphalt binder and provides an understanding of how the concentration level of AESO affects the neat asphalt binder performance as well. The modification effects of AESO modified binders were evaluated by Superpave performance grading specifications and rheological properties data for both high and low temperatures that were obtained from rotational viscometer (RV), dynamic shear rheometer (DSR), and bending beam rheometer (BBR). The effects of additional AESO in neat asphalt binder on the resistance of fatigue damage and thermal cracking at intermediate and lower temperatures were evaluated by employing Linear Amplitude Sweep (LAS) tests and BBR tests, respectively. The separation tendency with the additional AESO at different concentration levels was determined by storage stability tests on all AESO modified binders. Therefore, the potential of using AESO for asphalt performance modification was studied and reported through the aforementioned asphalt binder laboratory investigation.

2. Objective and scope

The objectives of this research are as follows:

- To explore the possibility of using AESO in asphalt modification.
- To evaluate the modification effect of using AESO as an additive in asphalt binder by Superpave specifications for performance grading.
- To assess the effects of various concentration levels (low, intermediate, and high) of AESO on the performance of the neat asphalt binder including viscosity, rheological properties at high and low temperatures, fatigue life, and storage stability.
- To compare the modification effects on the neat asphalt binder by using laboratory produced AESO (LabAESO) versus commercially available AESO (ComAESO) and to make recommendations.

3. Materials and methods

3.1. Experimental materials and material preparation

This research focuses on the modification effects of using laboratory produced AESO (LabAESO) and commercially available AESO (ComAESO) at various concentrations in asphalt binders. The PG 64-22 asphalt binder obtained from a U.S. Midwest supplier (Canadian crude source) was utilized as the neat asphalt binder and served as the control group to make comparisons with the AESO modified binders. The properties of the PG 64-22 asphalt binder are shown in Table 1. The commercially available AESO was purchased from Sigma-Aldrich and used as received. The properties of LabAESO and ComAESO are presented in Table 2 and are shown visually in Fig. 1. The main difference between LabAESO and ComAESO is the acrylic functionality of the monomer. The acrylic functionality represents the number of acrylic groups per triglyceride molecule. The AESO monomers with different acrylic functionality levels have different triglyceride molecule structures with different absorbance to light spectrum, which leads them to be shown in different colors (Fig. 1) and physical properties (Table 2). Additionally, different acrylic functionality may also affect the performance of the AESO monomer in asphalt modification differently. Controlling the acrylic groups in the molecule with lower acrylic functionality could reduce the branches of the molecule and thereby makes the monomer or polymer more linear in structure, which may cause better reactions to occur between the monomer and asphalt binder and enables the monomer to show entanglement behavior in modified binders. Therefore, LabAESO monomer with lower functionality was expected to have better compatibility with the neat asphalt binder with polymer entanglement behavior in modified binder compared to that of the high functionality ComAESO.

Table 1
Properties of PG 64-22 neat asphalt binder.

Aging status	Instrument	Properties	PG64-22
Unaged binder	RV	Viscosity at 135 °C (Pa·s)	0.408
	DSR	$G^*/\sin\delta$ at 64 °C (kPa)	1.268
RTFO aged residue	RTFO	Mass loss at 163 °C (%)	0.565
	DSR	$G^*/\sin\delta$ at 64 °C (kPa)	4.296
RTFO + PAV aged residue	DSR	$G^*\ \sin\delta$ at 25 °C (kPa)	2959
	BBR	Stiffness at −12 °C (MPa)	210
	BBR	m-value at −12 °C	0.318

Note: RTFO means Rolling Thin Film Oven; PAV means Pressure Aging Vessel; RV means Rotational Viscometer; DSR means Dynamic Shear Rheometer; BBR means Bending Beam Rheometer.