Journal of Cleaner Production xxx (2016) 1–13

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

Rejuvenation of vacuum tower bottoms through bio-derived materials for use in paving flexible roadways

Joseph H. Podolsky [a,*], Ashley Buss [b], R. Christopher Williams [c], Nacú Hernández [d], Eric W. Cochran [e]

[a] Iowa State University, Department of Civil, Construction, and Environmental Engineering, 174 Town Engineering, Ames, IA, USA
[b] Iowa State University, Department of Civil, Construction, and Environmental Engineering, 490 Town Engineering, Ames, IA, USA
[c] Iowa State University, Department of Civil, Construction, and Environmental Engineering, 486 Town Engineering, Ames, IA, USA
[d] Iowa State University, Department of Chemical, and Biological Engineering, 3125 Sweeny Hall, Ames, IA, USA
[e] Iowa State University, Department of Chemical, and Biological Engineering, 1035 Sweeney Hall, Ames, IA, USA

ARTICLE INFO

Article history:
Received 3 June 2016
Received in revised form
28 November 2016
Accepted 3 December 2016
Available online xxx

Keywords:
Vacuum tower distillation bottoms
Linseed oil
Statistical modeling
Cost-benefits analysis

ABSTRACT

Asphalt, made from the heavy fractions of crude petroleum, is a co-product of the oil refining process. In recent years, the lighter fractions of crude petroleum have increased in value. The lighter fractions of crude petroleum are used for making gasoline and their value increases as the price of gasoline increases. Vacuum distillation is used in oil refining to increase the relative volatility of the crude petroleum creating an efficient method for recovering light fractions. The vacuum tower distillation bottoms (VTB) are a very stiff form of asphalt and have limited use alone for paving. The main objective of this study was the assessment of two linseed oil derived materials for use as rejuvenators of VTB through binder performance, and a cost-benefits analysis. A total of eighteen groups including the control VTB with performance grade (PG) 76-10 were used in the evaluation of the linseed oil derived materials. Using the binder performance results, statistical modeling was done to optimize formulations to achieve a PG 70-22 and a PG 64-22. The measured viscosity results were used in a cost-benefits analysis of the control VTB and rejuvenated VTB at PG 70-22 and PG 64-22, reductions in energy consumption, and greenhouse gas emissions (CO_2, NO_X, SO_X, and CO) were seen.

1. Introduction

The oil refining process distills crude oil into different fractions as part of the manufacturing for many products. Asphalt binder, made from the heavy fractions of crude petroleum, is a co-product of the oil refining process. The lighter fractions of crude petroleum are used for making higher value products such as gasoline and their value is tied to the price of oil. As oil prices rise, the price of products made from the lighter components of crude petroleum also rise, incentivizing increased production. Refineries employ vacuum distillation to further extract light components of crude oil to produce larger quantities of higher-value products. The residuum of the vacuum distillation process, vacuum tower distillation bottoms (VTB), is a very stiff form of asphalt and has limited use alone for paving. The objective of this paper is to create a value added product by rejuvenating VTB (pen grade 20–30, performance grade (PG) 76-10) with two linseed oil derived materials that will meet asphalt grade requirements for use in paving.

Many past and current research studies have been conducted to examine the effect of rejuvenators on aged asphalt binders and recycled asphalt (RAP) binders (Asli et al., 2012; Johnson and Hesp, 2014; Zargar et al., 2012). Rejuvenators are primarily used for the restoration of an aged asphalt binder's properties to its virgin unaged state. Restoration is achieved through the renewal of the volatiles and oils during which adhesion properties are maintained. This makes it possible to return an aged binder's ratio of asphaltenes/maltenes to its original state (Chen et al., 2014a, 2014b; Romera et al., 2006). Presently the use of rejuvenators in RAP has increased significantly in hot mix asphalt (HMA) mixtures (Shen et al., 2007). Current research with rejuvenators in RAP extracted and recovered binder shows that as the dosage increases high and low temperatures decrease linearly for the performance grade (PG)

* Corresponding author.
E-mail addresses: podolsky@iastate.edu (J.H. Podolsky), abuss@iastate.edu (A. Buss), rwilliam@iastate.edu (R.C. Williams), nacu23@iastate.edu (N. Hernández), ecochran@iastate.edu (E.W. Cochran).

http://dx.doi.org/10.1016/j.jclepro.2016.12.011
0959-6526/

(Ma et al., 2010; Shen and Ohne, 2002; Tran et al., 2012). It is also shown that rejuvenators help restore the RAP extracted and recovered binder to a virgin binder performance grade or better (Zaumanis et al., 2014). Due to increasing demand for rejuvenators, waste products such as recycled motor oil (RO) have also been evaluated for use as a rejuvenator and have been shown to lower permanent deformation over time and decrease mixing and compaction temperatures (Romera et al., 2006). In the work by Romera et al. (2006) it was found that by adding 20% recycled motor oil (RO) to an aged asphalt binder (pen grade 0–10) they were able to achieve the same penetration grade as a commercially used pen grade 60/70. The successful use of RO as a rejuvenator of RAP binders has propelled the thought that the same can be done to vacuum tower bottoms (VTB) through the use of linseed oil derived-materials.

When considering what rejuvenator to use in aged asphalt binder an important item to examine is the effect of the rejuvenator on the oxidative aging of the restored binder. Asphalt oxidation occurs when an asphalt's molecules are exposed over time to "polar, oxygen-containing chemical functionalities" causing the asphalt to harden (Petersen, 2009). Depending on how an asphalt binder is affected by oxidation it could shorten a pavement's service life because of substantial premature fatigue cracking. The chemical makeup of asphalt is categorized into four fractions: asphaltenes, saturates, aromatics, and resins. Changing the proportions of the four fractions in an asphalt binder will change the performance grade either making it stiffer or softer. Asphaltenes (heavier component) are the portion of asphalt that gives asphalt its stiffness, while the other three fractions - maltenes (saturates, aromatics, and resins), the lighter components give asphalt its softening effect (Petersen, 2009).

For simulating field aging of asphalt binder in the laboratory there are three stages of aging; unaged, short-term aged, and long-term aged testing. During short-term aging, the binder hardens due to oxidation and volatilization of the lighter components to simulate manufacture and laydown of pavement in the field, while long-term aging is caused by oxidation at in-service temperatures. Over both stages of aging the asphaltene content increases and the maltene content decreases, but at different rates. In short-term aging more of the maltene phase is lost due to volatilization than due to chemical changing into asphaltenes. In long-term aging more maltenes are changed chemically into asphaltenes from oxidation than those lost to volatilization. As asphaltene content increases, flocculation and gelation of the colloidal structure are increased, thus leading to higher viscosity/greater stiffening effect. As stated earlier the role of rejuvenators is to reverse the effect of aging by returning the ratio of maltenes to asphaltenes in the aged binder to its original state (Romera et al., 2006).

Another impact from asphalt binder rejuvenation is that mixing and compaction temperatures as determined through rotational viscosity testing decrease. Mix and compaction temperatures are important because they dictate what temperatures should be used in a hot mix asphalt plant during the drying and mixing of aggregates with asphalt binder as well as the laydown temperatures at the field site. Effects from reduced temperatures are seen in the form of reduced fuel usage, cost savings, as well as reductions in greenhouse gas (GHG) emissions – CO_2, NO_X, SO_X, and CO. Like rejuvenators, warm mix asphalt technologies have similar effects on mixing and compaction temperatures of asphalt mix. There have been numerous studies done on warm mix asphalt (WMA) primarily concerned with the reduction in production temperatures, fuel usage, and emissions, as well as the cost savings associated with these reductions (Almeida-Costa and Benta, 2016; Harder et al., 2008; Rubio et al., 2012). The extreme of WMA is half warm mix asphalt (HWMA) which is produced at even lower temperatures than those used for WMA. Rubio et al. (2013) showed that production of HWMA at temperatures between 60 °C and 100 °C, reduced CO_2 and SO_2 emissions by 58.5% and 99.9% when compared to the emission levels of a HMA control produced between 150 °C and 190 °C.

Two linseed oil (LO)s derived materials will be used in several combinations to modify VTB to obtain asphalt properties optimal for paving. Material evaluation will be performed at high and low in-service pavement temperatures using a dynamic shear rheometer (DSR) and bending beam rheometer (BBR), respectively. Prior to DSR testing, the VTB-LO material will be aged in a rolling thin film oven (RTFO) to simulate aging that occurs during construction. Similarly, prior to BBR testing, the VTB-LO material will undergo long-term aging in a pressure-aging vessel to simulate material properties 7–10 years post-construction. To achieve the objectives, test results are analyzed using a multiple regression model to develop a variety of LO formulations in VTB. From the formulations, rotational viscosity results will be used within a cost-benefit analysis to help quantify the economic and environmental benefits of the LOs to VTB.

2. Experimental materials

2.1. Materials

In this research work one source of vacuum tower bottoms from an Illinois refinery was used. VTBs are a very stiff form of asphalt binder, and typically have a penetration grade of 20–30 and a performance grade (PG) of PG 76-10. Two LO materials were used in this research work – Heat Bodied Linseed Oil (HBL), and Partially Hydrogenated Heat Bodied Linseed Oil (PHBL) – at addition rates between 0% and 6% to create a total of eighteen combination groups. The properties for HBL and PHBL are shown in Table 1.

2.2. Sample preparation, and experimental testing plan

To prepare samples for testing, LOs were blended with the VTB at 155 °C ± 10 °C at 3000 rpm for 1 h using a Silverson shear mill. After all blending combinations were created, the materials were then short term aged in a RTFO and material was reserved for DSR testing to determine the high-temperature grade. The remaining material was aged in a pressure aging vessel (PAV) for subsequent testing in a BBR for determining the low-temperature grade.

The high temperature grade of asphalt is important because it measures the stiffness of the binder at high in-service

Table 1
Properties of LOs HBL and PHBL.

	HBL	PHBL
Physical form	Amber liquid	Solid paste
Specific gravity at 25 °C (77 °F)	1.02	1.05
Molecular weight (Mn) [Da]	3400	3400
T_g [°C][a]	−17.91	−24.89, 16.25
Melting temp. [°C]	–	42.92

Viscosity (Pa S)	Shear rate (1/S)			Shear rate (1/S)		
	50	100	150	50	100	150
at 25 °C (77 °F)	3.57	3.56	3.54	52.6	42.24	36.35
at 35 °C (95 °F)	2.11	2.09	2.06	27.92	21	17.75
at 45 °C (113 °F)	1.2	1.19	1.18	9.26	7.09	6.23
at 55 °C (131 °F)	0.84	0.82	0.8	1.19	0.86	0.8
at 65 °C (149 °F)	0.48	0.48	0.47	0.06	0.14	0.16

[a] Glass transition temperature (T_g) was measured using a TA Q2000 differential Scanning calorimeter equipped with a refrigerated cooling system (ECS90). The heating rate used was 10 °C/min from −60 °C to 100 °C.

Please cite this article in press as: Podolsky, J.H., et al., Rejuvenation of vacuum tower bottoms through bio-derived materials for use in paving flexible roadways, Journal of Cleaner Production (2016), http://dx.doi.org/10.1016/j.jclepro.2016.12.011