

Research Article

Effects of Fiber Finish on the Performance of Asphalt Binders and Mastics

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The objective of this study was to determine the effects of finishes applied to polyester fibers on the properties of asphalt binders and mastics. Asphalt binders were mixed with finishes that were extracted from the fibers, and mastics were also made with binder and fibers (with and without finish) to isolate the effects of the finish. The results indicated that crude source plays a significant role in how the fiber finish affects the binders and mastics. Additionally different finishes had different effects on binder properties. The major finding of this study is that different polyester fibers, even from the same manufacturer, may not necessarily perform the same in an asphalt mixture. It is important to use fibers that are compatible with the particular asphalt binder that is being used because of the significance of the binder source on the interaction between the finish and the binder.

1. Introduction

The utilization of fibers in asphalt mixtures is not a new concept; in fact, it has been in use since the early 1900s when the Warren Brothers Company of Boston, MA, obtained patents for their use of asbestos fibers in sheet asphalts [1]. The purpose of the fibers was to essentially stabilize the mixture and prevent bleeding of asphalt during hot weather service. The use of asbestos fibers in asphalt construction continued in cold-laid asphalt pavements to prevent segregation of aggregate during construction [1]. Use of fibers in hot mix asphalt (HMA) did not come until the late 1950s when the US Army Corps of Engineers, the Asphalt Institute, and the Johns-Manville Co., an asbestos fiber manufacturer, initiated the first evaluation of asbestos fibers in HMA [1]. Results of this study indicated that mixtures containing asbestos fibers showed an increase in tensile strength, compressive strength, stability, ability to sustain load after reaching maximum stability, and resistance to weathering.

Kietzman et al. later determined that the asphalt content of mixtures containing asbestos fibers could be increased 50 percent or more above the optimum asphalt content of control mixtures without sacrificing pavement performance. While mixture stability was maintained with the high binder

content fiber mixtures, durability was improved as evident from testing of recovered binder from pavement sections. Both penetration and ductility values of recovered binder were higher in the mixtures containing fibers as compared to the mixtures without fiber [2].

Kietzman's conclusions were corroborated by Zuehlke in the early 1960s with an evaluation of the Marshall and flexural properties of asphalt concrete mixtures containing the same asbestos fibers. Results of this study also indicated that the addition of the fibers to the mix increased the stability and load carrying ability after maximum stability. The modulus of rupture, tested using a center point bending test, of mixes containing fiber was also improved over the mixes without fiber at both high and low test temperatures (38 and 4°C). This study also evaluated the properties of mixes made with higher than optimum binder contents as determined from the mix design (up to 2% higher). Testing of the high binder content mixtures yielded reduced sensitivity of the asbestos mixes compared to the control mixes with the same binder content [3]. This showed that higher binder contents can be achieved without significantly sacrificing strength, thereby enhancing the durability of the mixture as demonstrated by Kietzman.

Pavement rutting of asphalt concrete mixes containing asbestos fibers was also studied by Speer and Kietzman [4]. This study investigated the rutting potential of asphalt concrete mixtures using a laboratory traffic simulator machine. The mixes containing asbestos fibers showed a marked increase in rut resistance.

Research involving the use of fibers in HMA mixtures continued with use of asbestos, steel, and glass fibers [5, 6]. In the 1970s, with health and environmental concerns associated with the use of asbestos fibers, researchers turned to other types of fibers for use in asphalt including synthetic fibers such as polyester and polypropylene and mineral fibers such as rock wool and slag wool. The 1980s brought more research on the use of synthetic fibers to prevent, or at least retard, cracking in HMA pavements (e.g., reflective cracking). The use of synthetic fibers was explored for reinforcement due to high tensile strengths and durability. Steel fibers, while having high tensile strength, corroded when exposed to water [7], thereby reducing the effectiveness of the fibers.

In the late 1980s research by Freeman et al. concluded that polyester fibers, while increasing the optimum asphalt content, provided reinforcement of the HMA mixtures tested [7]. The reinforcing ability of the fibers was evident by increased toughness and flexibility of the mixes. The performance of these polyester fibers was similar to the asbestos fibers included in the research of Kietzman and Zuehlke in the 1960s. The polyester fibers not only increased mixture toughness, but also significantly reduced the moisture susceptibility of the mixes by producing higher tensile strength ratios than the control mixture without fibers.

The reinforcing capability of polyester fibers was proven in a field study conducted by Maurer and Malasheskie where four geotextiles, one stress absorbing membrane interlayer (SAMI) containing polyester fibers, and one polyester fiber-reinforced HMA surface course were used to defend against reflective cracking in Pennsylvania [8]. Results of the study showed that the HMA mixture containing polyester fibers exhibited the second highest reduction in reflective cracking compared to the control mixture. One of the geotextiles showed the highest reduction in reflective cracking. While proving its effectiveness in reducing reflective cracking, the HMA mixture containing polyester fibers was also the least expensive and the easiest alternative from a construction standpoint when compared to the other treatments. Similar results were obtained by Jiang and McDaniel where polypropylene fibers were used to reinforce HMA mixtures in Indiana [9]. HMA mixtures containing polypropylene and polyester fibers in Virginia also showed increased resistance to moisture damage and rutting [10].

The increased use of porous asphalt, open-graded friction courses (OGFCs), and stone matrix asphalt (SMA) in roadway construction has presented a different role for fibers in asphalt mixtures. While not required for reinforcement, fibers have been added to such mixtures as stabilizing additives. As a stabilizing additive, the main role of the fibers is to prevent the relatively high percentages of asphalt binder from draining from the mixture. Fibers used as stabilizers include mainly cellulose and mineral fibers (e.g., slag wool and rock wool). The effectiveness of cellulose fibers in preventing

binder draindown in porous asphalt mixtures was demonstrated by Decoene in the late 1980s [11]. This research showed that porous mixtures without cellulose fibers lost, on average, approximately 13.5% and 17% binder during the basket drainage and Schellenberger drainage tests, respectively. The addition of 0.3% cellulose fiber by total mixture weight showed a drastic decrease in binder drainage even at higher binder contents.

Mineral fiber has been the preferred fiber of many states for use in OGFC mixes due to its stabilizing ability. Cellulose was not used as frequently, even though it has better stabilizing capacity than mineral fibers [12], due to concerns that the organic cellulose fibers may absorb water and, therefore, be susceptible to moisture damage in the field [13]. Research by Cooley et al. concluded that cellulose fibers performed comparably to mineral fibers, with respect to moisture susceptibility, in both the field and the laboratory [13].

In SMA mixtures, fibers are also added as stabilizing additives. Both mineral and cellulose fibers are the typical fibers used in SMA. Other materials used for stabilization include polymers [14]. A study by Stuart and Malmquist evaluated the performance of different stabilizers in SMA mixtures in Maryland [15]. The stabilizing additives in this study included two loose cellulose fibers, a pelletized cellulose fiber, a loose rock wool fiber, and two polymers. Results of this research indicated that the fibers reduced the drainage of the asphalt binder from the mixture more effectively than the polymers, while showing similar resistance to rutting, low-temperature cracking, and moisture damage as the mixtures containing polymers.

Putman and Amir Khanian also evaluated the performance of different fiber types in SMA mixtures [16]. The results of this study indicated that the four different fibers evaluated (cellulose fibers, waste nylon carpet fibers, waste tire fibers, and polyester fibers) performed similarly with respect to indirect tensile strength, moisture susceptibility, and rutting resistance. Additionally, they highlighted the stabilizing capacity (ability to prevent binder draindown) of the different fibers.

The most comprehensive research of fiber-modified asphalt was conducted by Serfass and Samanos [17]. The fibers included in this study included asbestos, rock wool, glass wool, and cellulose fibers. Testing was performed on asphalt mastics (asphalt binder and fiber), asphalt mortars (asphalt binder, fiber, and fine sand), thin course asphalt concrete, and porous asphalt concrete mixtures. The results of the study concluded that the test fibers had the ability to stabilize and reinforce the mastics, ultimately resulting in richer mixes having high resistance to moisture, aging, fatigue, and cracking. Addition of fibers also reduced the temperature susceptibility of the asphalt mixture providing resistance to rutting at higher temperatures and resistance to cracking at lower temperatures.

There has been a considerable amount of research conducted on the effects of fibers in asphalt mixtures, and the use of polyester fibers has been evaluated in both lab and field studies. However, not all polyester fibers are the same. While the material is the same from fiber to fiber, the surface is often modified during production. When polyester fibers are

manufactured, a finish is typically applied to the fiber after the spinning and drawing process. The specific finish applied to a fiber or yarn depends on the end use of the fiber. Typical finishes are applied to control the build-up of static charge and enhance lubrication to assist with winding and packaging. This type of finish is typically a combination of oils and compounds that are not compatible with water. To address this, surfactants and dispersants are also often included to help with the dispersion of the fibers [18].

The objective of this study was to determine the effects of fiber finishes on the properties of asphalt binders and mastics. To achieve this objective, the study was divided into two phases. Phase 1 was designed to determine if the finish applied to a fiber during manufacture had any effect on the properties of an asphalt/fiber mastic. This involved the evaluation of one polyester fiber product with multiple binder grades and sources. In Phase 2, additional polyester fibers having different finishes were evaluated with a single binder to determine how different finishes affect asphalt binder properties.

2. Experimental Materials and Methods

The experimental design for this two-phase study is illustrated in the flow chart in Figure 1.

2.1. Phase 1: Effects of Fiber Finish on Asphalt/Fiber Mastics. In Phase 1, one polyester fiber was evaluated with two binder grades (PG 64-22 and PG 76-22) from two different crude sources. The fiber evaluated in this phase is consistent with fibers approved for use in asphalt mixtures such as stone matrix asphalt (SMA) and open-graded friction course (OGFC) mixtures by many highway agencies. The properties of the fiber are summarized in Table 1. Two different binder grades and sources were selected for this phase to determine if the effect of fiber finish is binder grade or source dependent. The properties of each of the binders are summarized in Table 2.

As illustrated in Figure 1(a), each binder was tested with four different treatments: binder as delivered (control), binder with extracted fiber finish (extract), mastic of binder with fiber as delivered (unwashed mastic), and mastic of binder with fiber having the finish removed (washed mastic). The preparation of each treatment is discussed separately.

The Control specimens were not treated in any way. The asphalt binder was tested as received from the terminal.

The Extract specimens were prepared by first extracting the finish from the fibers and then mixing the extracted finish with the binder. To extract the finish from the fiber, 3 grams of fiber was weighed in a glass beaker, covered with 150 mL of trichloroethylene, and agitated using spatula for 3 minutes. After agitation, the mixture was allowed to sit undisturbed for 5 minutes. The trichloroethylene was poured over a strainer into another glass beaker to separate the fibers from the trichloroethylene and finish solution. The beaker containing the trichloroethylene was placed in a 110°C oven until all of the trichloroethylene had evaporated leaving only the fiber finish. After cooling, 300 grams of asphalt binder was added to the beaker containing the dried finish and

TABLE 1: Properties of fibers used in Phase 1 (provided by the manufacturer).

Property	Result
Material	100% polyester
Denier	4.5
Length	6.35-mm
Specific Gravity	1.38
Melting Point	257°C
Ignition Point	537°C
Finish	Ethoxylated alcohols and wetting agent

mixed thoroughly with a spatula. The binder temperature was approximately 163°C.

The Unwashed Mastic specimens were prepared by mixing 3 grams of fiber with 300 grams of asphalt binder with a spatula until the fibers were completely wetted by the binder. The fibers in this case were included in their as-received condition and the asphalt binder was heated to approximately 163°C.

The Washed Mastic specimens were prepared in the same manner as the Unwashed Mastic specimens with the exception that the finish was washed off of the fiber. To wash the finish off of the fiber, 15 grams of fiber was weighed in a glass beaker, covered with 300 mL of trichloroethylene, and agitated using spatula for 3 minutes. After agitation, the mixture was allowed to sit undisturbed for 5 minutes. The trichloroethylene was poured over a strainer and discarded to separate the fibers from the trichloroethylene and finish solution. The washed fibers were placed in another beaker and placed in a 110°C oven until the fibers reached a constant mass. After cooling, 3 grams of washed fibers were mixed with 300 grams of asphalt binder and mixed with a spatula until fibers were completely wetted. The binder temperature was approximately 163°C.

Each binder was tested with each treatment in its unaged condition using standard Superpave asphalt binder testing procedures to determine the properties of asphalt binders and mastics at high and low temperatures. The viscosity of the Control and Extract treatments was determined per AASHTO T 316 using a number 27 spindle rotating at a speed of 20 RPM. A 10.5 gram specimen was used for all tests, and the test temperature was 135°C for all specimens. The viscosity of the mastic treatments was not measured as it was difficult to measure the 10.5 grams of the mastic in the sample tube and the viscosity values were extremely high.

The rheological properties of the binders and mastics at high in-service temperatures were measured using a dynamic shear rheometer (DSR) in accordance with AASHTO T 315. A 25 mm parallel plate setup with a 1 mm gap was used for all DSR testing. The test temperature was 64°C or 76°C for the PG 64-22 and PG 76-22 asphalt binders, respectively.

The flexural creep stiffness of each treatment was determined using a bending beam rheometer (BBR) per AASHTO T 313. Again, the specimens were unaged and the test temperature was -12°C for all binders.

Finally, gel permeation chromatography (GPC) was employed to measure the relative molecular size distribution

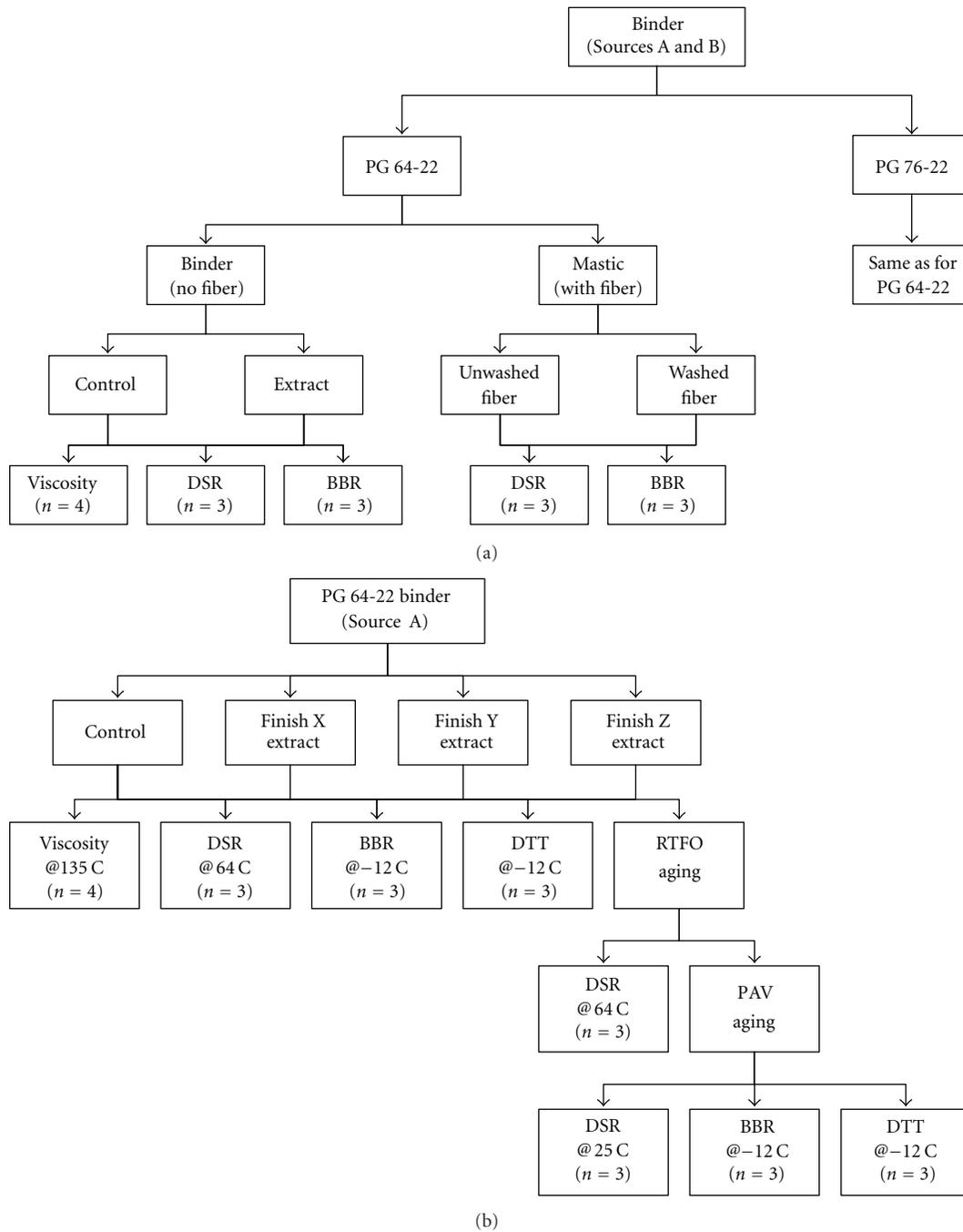


FIGURE 1: Experimental designs for (a) Phase 1 and (b) Phase 2.

(MSD) of each binder and mastic treatment in accordance with the procedures used by Putman and Amir Khanian [19]. A Waters 1515 Isocratic HPLC Pump was used in conjunction with a Waters 2414 Refractive Index Detector. The solvent used was tetrahydrofuran (THF), the dilution ratio was 400 : 1 (solvent : binder), the injection volume was 50 μL , and the elution time was 30 minutes. Two columns were used for the GPC analysis: one Styragel HR3 having a pore size of 1,000 Å and one Styragel HR3 4E having a mixed bed.

Each specimen was prepared by weighing 0.006 to 0.008 g of binder into a 4 mL vial. The appropriate amount of THF

was then added, and the vial was sealed and agitated until the binder was completely dissolved. The binder-solvent mixture was then transferred to a 5 mL syringe where it was filtered through a 0.45 μm syringe filter into an empty 4 mL vial. A gastight syringe was then used to obtain 100 μL of material from the vial after removal of air and then the vial was sealed.

The control drained binders were used as the standard that each binder and mastic was compared. For this reason, more replicates were used for the control binders to establish the appropriate slice width for each binder source. Additionally, a control vial was tested at the beginning and end of each

TABLE 2: Properties of asphalt binders.

Property	Crude Source A		Crude Source B	
	PG 64–22	PG 76–22	PG 64–22	PG 76–22
<i>Original</i>				
Viscosity at 135°C (Pa·s)	0.430	1.475	0.703	1.442
$G^*/\sin \delta$ (kPa) (test temp, °C)	1.279 (64)	1.338 (76)	2.413 (64)	1.177 (76)
δ , ° (test temp, °C)	88.2 (64)	71.4 (76)	79.2 (64)	72.5 (76)
<i>RTFO Aged</i>				
$G^*/\sin \delta$ (kPa) (test temp, °C)	2.810 (64)	2.508 (76)	6.075 (64)	2.929 (76)
δ (°) (test temp, °C)	85.8 (64)	66.1 (76)	73.2 (64)	65.8 (76)
Mass loss (%)	0.0	−0.01	−0.09	−0.22
<i>RTFO/PAV Aged</i>				
$G^* \sin \delta$ (kPa) (test temp, °C)	4074 (25)	2129 (31)	3352 (25)	1372 (31)
δ (°) (test temp, °C)	49.1 (25)	52.6 (31)	50.1 (25)	50.5 (31)
Stiffness (60 s) at −12°C (MPa)	217	212	141	132
m -value (60 s) at −12°C	0.307	0.310	0.359	0.373
Max. tensile strain at −12°C (%)	1.45	1.21	1.17	1.49
Max. tensile stress at −12°C (MPa)	2.94	2.74	2.17	2.23

day of testing for a given source to ensure that the test set-up was producing consistent results.

Analysis of the HP-GPC test results was accomplished by dividing each control chromatogram into 13 slices of equal width for each source. The large molecular size (LMS), medium molecular size (MMS), and small molecular size (SMS) limits were determined as the elution time at the end of slices 5, 9, and 13, respectively [20]. The LMS, MMS, and SMS limits were averaged for each control binder. These average limits were then used as the limits for the binders of the same source.

2.2. Phase 2: Effects of Fiber Finish on Asphalt Binder. In Phase 2, three additional polyester fibers having different finishes were evaluated with the PG 64-22 binder from crude Source A in Phase 1. The fibers were 6 denier, 6.35-mm long, and 100% polyester that were all supplied by a different manufacturer than those used in Phase 1. This manufacturer was selected because they produce fibers for a variety of applications and they have different fiber finish formulations for each application.

For this phase of the research, a similar procedure was used to extract the finish from the binder with a few differences based on recommendations from the manufacturer. To extract the finish from the fiber, 6 grams of fiber was weighed in a glass beaker, covered with 150 mL of methanol, and agitated using spatula for 1 minute. After agitation, another 50 mL of methanol was added to the fibers. The beaker was then covered with aluminum foil and allowed to stand undisturbed for 60 minutes after which the methanol was poured over a strainer into another glass beaker to separate the fibers from the solution of methanol and finish. The fiber was squeezed to remove excess methanol. The beaker containing the methanol was placed in a 105°C oven until all of the methanol had evaporated leaving only the fiber finish. After cooling, the beaker was weighed and 600 grams of asphalt

binder was added to the beaker containing the dried finish and mixed thoroughly with a spatula. The binder temperature was approximately 163°C.

The control and extract binders were evaluated using standard binder testing procedures as shown in Figure 1(b). The unaged binder was tested using the rotational viscometer (AASHTO T316), DSR (AASHTO T315), BBR (AASHTO T313), and Direct Tension Tester (DTT) (AASHTO T314). The binders were then aged using the rolling thin film oven (RTFO) per AASHTO T240 and the RTFO residue was tested using the DSR and further aged using the Pressure Aging Vessel (PAV) using a temperature of 100°C per AASHTO R28. The long-term aged binder from the PAV was tested using the DSR, BBR, and DTT.

3. Results and Discussion

The results of the study are included in Figures 2–16. A statistical analysis was conducted to determine significant differences between the results of each test for each treatment. A t -test for least significant difference (LSD) was used for this purpose with a 95% level of confidence ($\alpha = 0.05$). Results of the t -test are also included in the figures as treatments within each binder source having at least one common letter are not significantly different from each other.

3.1. Phase 1. Figure 2 provides a comparison of the viscosity results of each binder for the control and extract treatments. The results indicate that there were some differences observed in viscosity. While the differences were small, there were statistically significant differences. For both binder grades from Source A, the binder containing the extract exhibited a significantly higher viscosity than the control binder. For Source B, there was no significant difference in viscosity between the control and the extract treatments for the PG 64-22 binder. The extract did, however, have a significant reducing effect

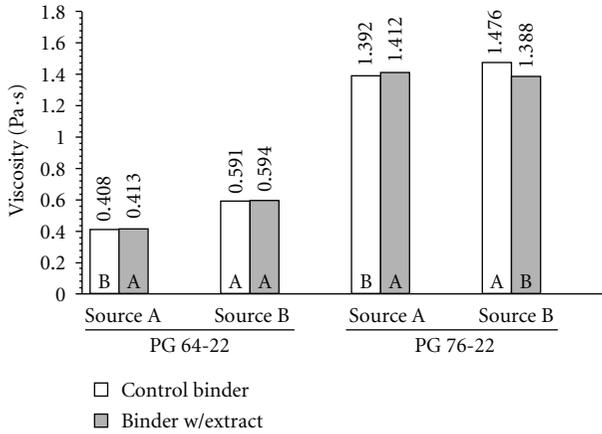


FIGURE 2: Viscosity of binders with and without finish extract (no fibers) at 135°C.

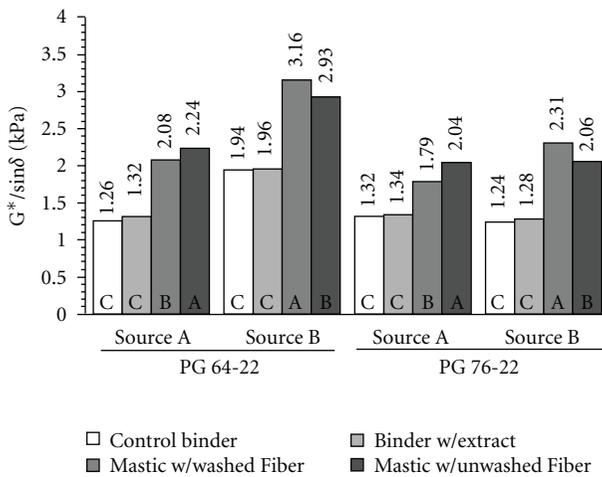


FIGURE 3: $G^*/\sin \delta$ results from the dynamic shear rheometer (DSR). The test temperature was 64°C for the PG 64-22 binders and 76°C for the PG 76-22 binders.

on the viscosity of the PG 76-22 from Source B. These results indicate that the crude source plays a role in how the fiber finish affects the viscosity of the binders with which they are mixed.

Figures 3 and 4 illustrate the results of the DSR testing for each unaged binder and treatment. Figure 3 compares the rutting factor ($G^*/\sin \delta$) for each binder and treatment. For all binders, the extracted finish slightly increases the $G^*/\sin \delta$ when compared to the control, but the difference is not significant. For both Source A binders, the $G^*/\sin \delta$ for the Unwashed Fiber Mastic is higher than the Washed Fiber Mastic. The difference is only significant for the PG 64-22 from Source A. This trend can be attributed to the viscosity increasing effect of the fiber finish. The trend is the opposite for both Source B binders as the $G^*/\sin \delta$ of the Unwashed Fiber Mastic is lower than the Washed Fiber Mastic. The difference is not significant however. This trend is consistent with the lower viscosity results of the binder containing the extracted fiber finish, but not the $G^*/\sin \delta$ results of the binders.

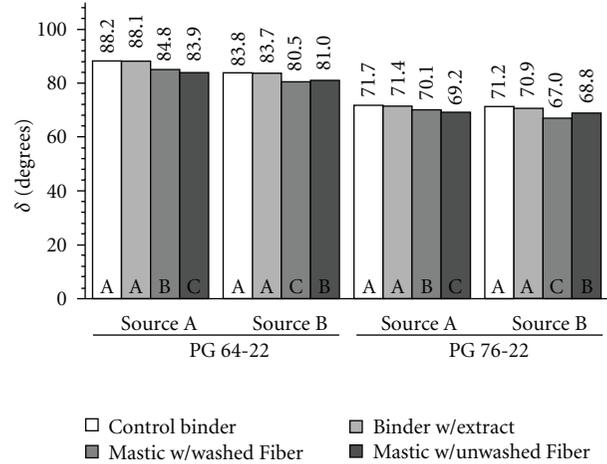


FIGURE 4: Phase angle (δ) results from dynamic the shear rheometer (DSR). The test temperature was 64°C for the PG 64-22 binders and 76°C for the PG 76-22 binders.

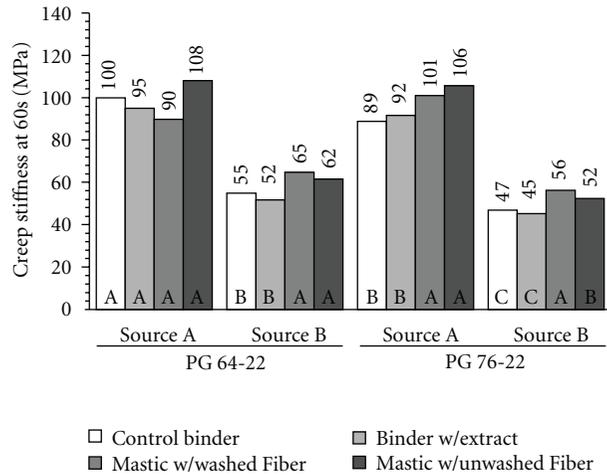


FIGURE 5: Creep stiffness (S) results from the bending beam rheometer (BBR). The test temperature was -12°C for all binders.

Phase angle (δ) is a measure of the ability of an asphalt binder to recover from a given deformation—the lower the δ , the more it behaves like an elastic solid and is therefore able to recover from the deformation. For all binders, the fiber finish had no significant effect on the phase angle (Figure 4). When fibers were added to the binders, there were some significant differences between the Unwashed and Washed Fiber Mastics, but again the trend was different for each binder source. The washed fibers significantly increased the δ for both grades of Source A binder as compared to the unwashed fibers. The trend was the opposite for both Source B binders, but the differences were still significant. This could also be related to the effects of the fiber finish on the viscosity of the binders. As the viscosity of the binder increases, it becomes more like a solid and will therefore have a lower phase angle and vice versa.

Figure 5 summarizes the creep stiffness (S) results from the BBR testing at -12°C. The stiffness results also show

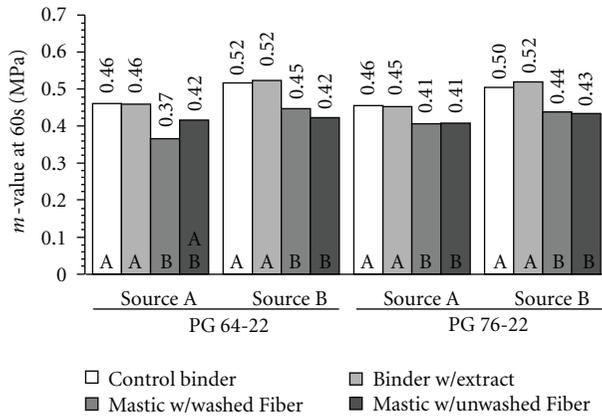


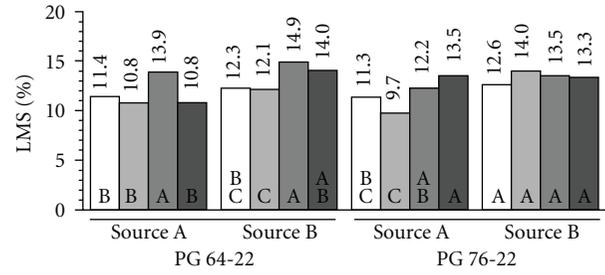
FIGURE 6: *m*-value results from the bending beam rheometer (BBR). The test temperature was -12°C for all binders.

different trends for the different binder sources. The fiber finish had an insignificant increase in stiffness with the extracted finish as compared with the control for the PG 76-22 from Source A. The trend continues with the fiber mastics as the stiffness is higher for the unwashed fibers than with the washed fibers. This difference is also not statistically significant. The results of the Source B binders showed an opposite trend than that seen for Source A. The fiber finish generally reduced the stiffness of the Source B binders (although not significantly), which is evident by comparing the control to the extract and the washed mastic to the unwashed mastic.

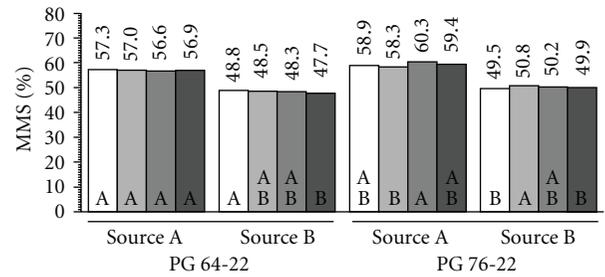
The *m*-value results provided the same trends as the other results (Figure 6)—the Source A binders performed the opposite of the Source B binders when the fiber finish was mixed with the binders, either with or without the fibers. For the Source A binders, the finish slightly reduced the *m*-value when compared with the control, but not significantly. When the fibers were added, the *m*-value was significantly lower than without fibers. The Source B binders reacted differently again as the finish slightly increased the *m*-value as compared to the control, but not significantly.

The results of the binder and mastic testing reveal that the two binder sources generally reacted differently to (or with) the finish applied to the particular fiber evaluated in this phase. For the binders from Source A, the mastics generally followed the trends exhibited by the binders (e.g., when the finish increased the $G^*/\sin \delta$, the unwashed fiber mastic had a higher $G^*/\sin \delta$ than the unwashed fiber mastic). This was the case for all of the properties except for the creep stiffness and *m*-value for the PG 64-22 binder from Source A. This behavior was only observed for the creep stiffness for the Source B binders. This indicates that the binder source will have an impact on the effect of the fiber finish on the binder behavior.

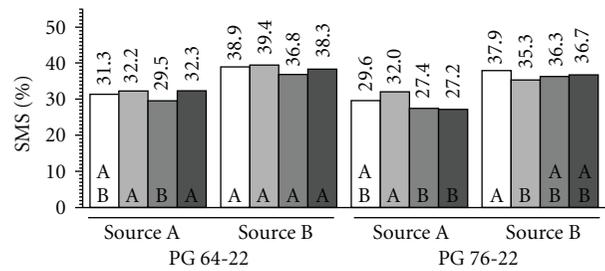
In general, the fiber finish increased the high-temperature and low-temperature stiffness ($G^*/\sin \delta$ and *S*, resp.) of the Source A binders and mastics. However, for Source B, the finish increased the high-temperature stiffness ($G^*/\sin \delta$) of the binders, while reducing the value for the mastics. As for the low-temperature stiffness, the effect of the finish was the same for the binders and mastics—reduction in stiffness.



(a)



(b)



(c)

FIGURE 7: GPC results showing (a) LMS, (b) MMS, and (c) SMS fractions.

To gain an understanding of the effect of the finish on the binders and mastics, the molecular size distribution (MSD) of each binder and mastic was quantified using GPC. The GPC results included in Figure 7 reveal opposite trends between the binders and the mastics for the different binder grades regardless of binder source. For both binder sources, the fiber finish generally decreased the relative LMS content for the PG 64-22 binders and mastics. For the PG 76-22 binders, however, the fiber finish had an opposite effect on the binders than it did for the mastics for both sources. This could indicate that the polymer modifier (SBS) influences the interaction between the binder and the finish in the presence of fibers. In all cases, as the LMS content decreases, the SMS content increases. This is the typical trend because as the relative LMS content decreases, the MSD shifts to the smaller molecular sizes (SMS and MMS). However, the MMS usually remains relatively unchanged and the difference is typically seen in the SMS fraction. It should be noted that as with the binder and mastic properties, many of the differences seen in the GPC results are not statistically significant.

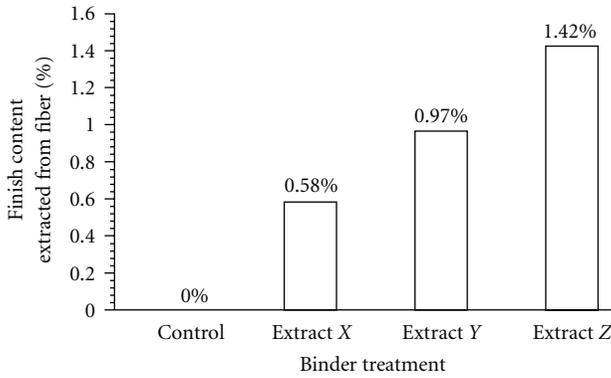


FIGURE 8: Amount of finish extracted from each fiber evaluated in Phase 2.

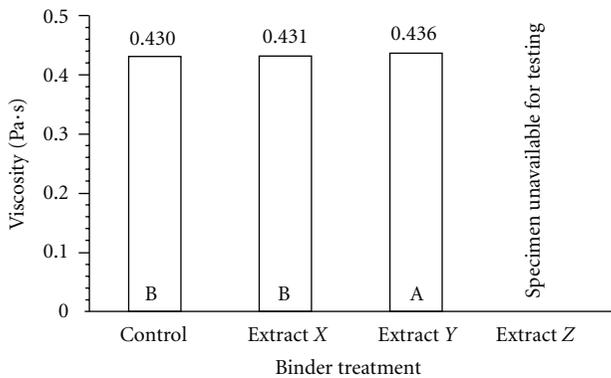


FIGURE 9: Viscosity of control binder and binder with finish extracts (no fibers) tested at 135°C.

The GPC analysis also revealed some other unexpected results. Typically, the LMS content of an asphalt binder MSD has a direct correlation with the viscosity and $G^*/\sin \delta$ [20, 21]. For this testing, however, such trends do not consistently exist. However, the PG 76-22 mastics do follow the trend—as the LMS increases, so does the $G^*/\sin \delta$. The same relationship is seen for the creep stiffness of the PG 76-22 mastics.

Further analysis of the GPC results for the PG 64-22 binders indicates that the LMS of the Washed Fiber Mastic is significantly greater than the Control binder. In both of these treatments the fiber finish is not present. The marked increase in LMS and general decrease in SMS could indicate that some of the SMS binder fraction was absorbed by the uncoated fibers. This result was not seen for the Unwashed Fiber Mastic made with PG 64-22 binder from Source A, which could indicate that the fiber finish prevented the lighter binder fractions to be absorbed by the fiber.

3.2. Phase 2. For the second phase of this research, three fibers from another manufacturer, each having a different finish were evaluated to determine the effects on a binder. Figure 8 summarizes the amount of finish present on each fiber. While the chemistry of each finish could not be disclosed by the manufacturer, it is evident that each fiber had a different amount of finish applied to it.

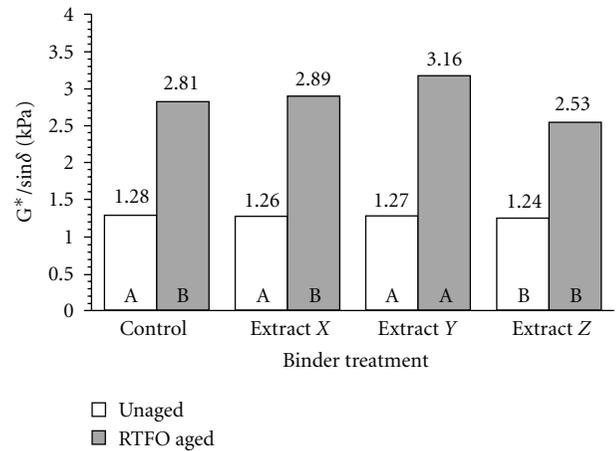


FIGURE 10: Original and RTFO aged $G^*/\sin \delta$ of control binder and binder with finish extracts tested at 64°C. Statistical comparisons were made within each stage of aging.

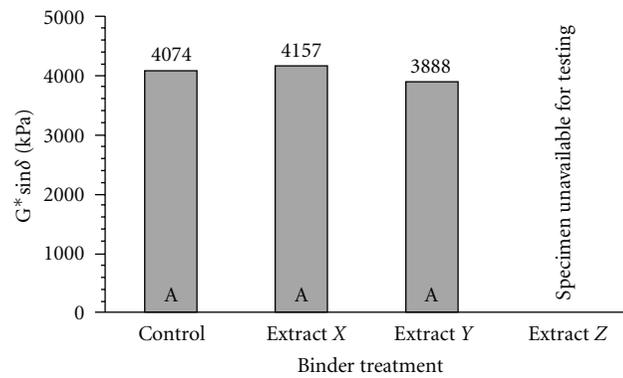


FIGURE 11: PAV aged $G^* \sin \delta$ of control binder and binder with finish extracts tested at 25°C.

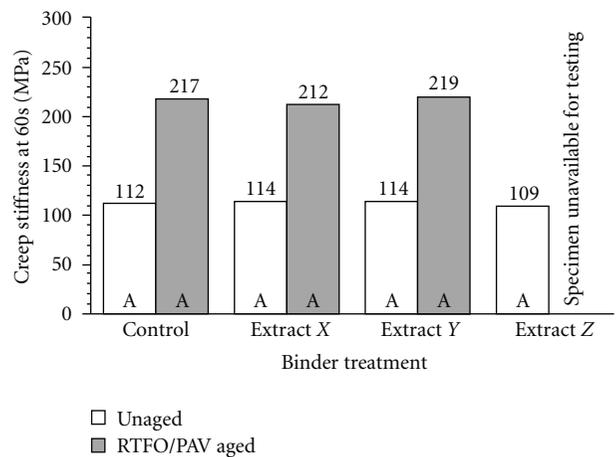


FIGURE 12: Creep stiffness of original and PAV aged control binder and binder with finish extracts tested at -12°C. Statistical comparisons were made within each stage of aging.

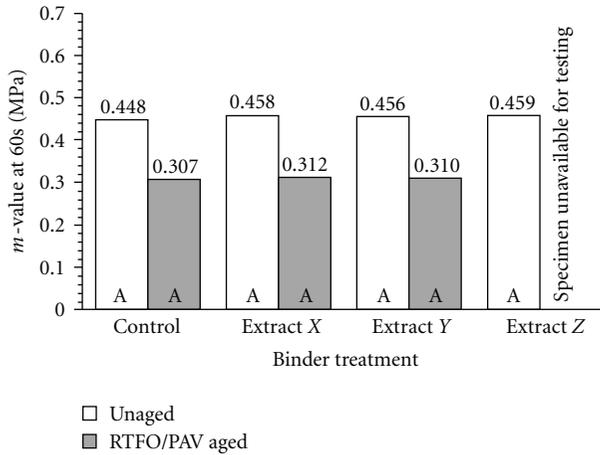


FIGURE 13: m -value of original and PAV aged control binder and binder with finish extracts tested at -12°C . Statistical comparisons were made within each stage of aging.

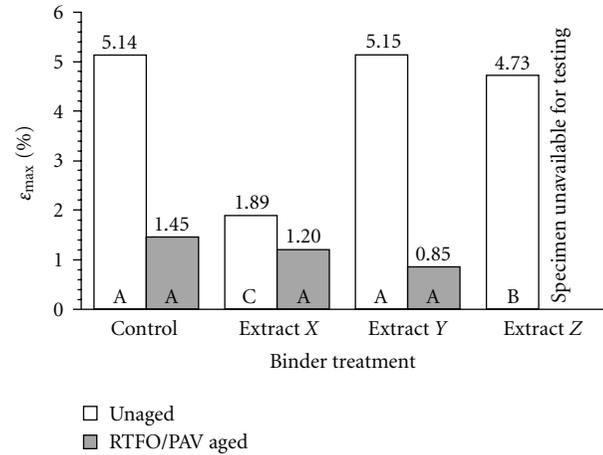


FIGURE 15: Maximum tensile strain at failure of original and PAV aged control binder and binder with finish extracts tested at -12°C . Statistical comparisons were made within each stage of aging.

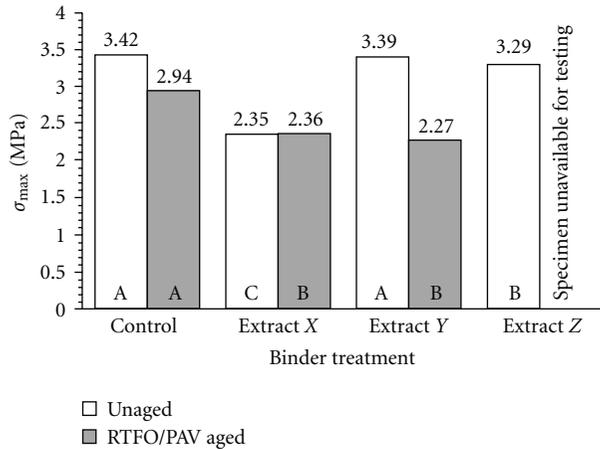


FIGURE 14: Maximum tensile stress at failure of original and PAV aged control binder and binder with finish extracts tested at -12°C . Statistical comparisons were made within each stage of aging.

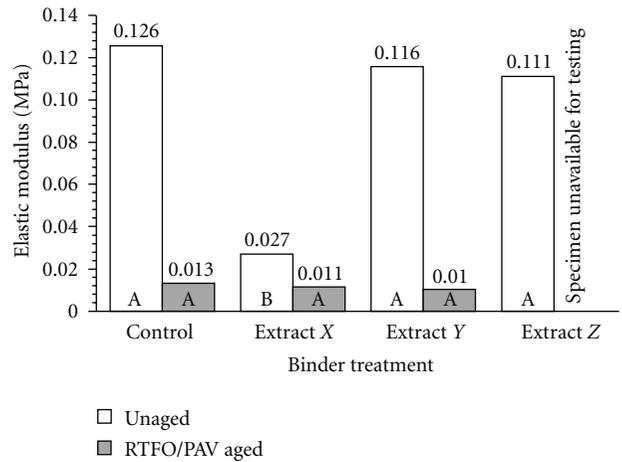


FIGURE 16: Elastic modulus of original and PAV aged control binder and binder with finish extracts tested at -12°C .

As illustrated in Figure 9, Extract Y increased the viscosity of the binder, while Extract X had no such effect. While the effect on viscosity was small, the difference was statistically significant. Unfortunately, there was not enough test material from Extract Z for a viscosity measurement.

Figure 10 presents the $G^*/\sin \delta$ results for the original and RTFO aged binders. For the unaged binder, Extract Z significantly reduced the $G^*/\sin \delta$, while Extracts X and Y had no significant effect. After short-term aging in the RTFO, Extract Y significantly increased the $G^*/\sin \delta$ and Extract Z decreased the $G^*/\sin \delta$, but this decrease was not statistically significant. This result indicates that the different finishes impact the effects of aging on the high temperature stiffness properties of the binder.

The $G^*/\sin \delta$ of the PAV aged binders is presented in Figure 11, and the results indicate that none of the fiber finishes had any significant effect on the stiffness of the binders

at intermediate pavement temperatures. Additionally, Figures 12 and 13 summarize the low-temperature stiffness of the aged and unaged binders. As with the $G^*/\sin \delta$, the finishes did not have any effect on the low-temperature creep stiffness or m -value. The similar trends between binder stiffness at intermediate and low-temperatures are expected as higher stiffness at low-temperatures (low-temperature cracking problems) typically yields higher stiffness at intermediate temperatures (fatigue-related problems).

The real significance of the fiber finishes evaluated in this study was seen in the low-temperature tensile properties of the binders as summarized in Figures 14, 15, 16. Extract X drastically reduced the tensile properties (strength, strain, and modulus) of the binder in the unaged condition. Additionally, Extract Z reduced the tensile strength and strain in the unaged condition; however, the elastic modulus was not significantly affected. For the PAV aged binders, both Extracts X and Y resulted in a significant reduction in tensile strength, but the tensile strain and modulus were similar to

the control. The significant reduction caused by Extract Y after aging that was not evident in the unaged binder indicates that the finish affects the aging properties of the binder. This was also seen in the $G^*/\sin \delta$ results for Extract Y.

4. Conclusions

This research evaluated the effects that the finishes applied to polyester fibers have on the interaction between the fibers and asphalt binders. The effects were measured using binders mixed with extracted finish as well as mastics made with binders and fibers (with and without finish). The study was divided into two phases. In the first phase, two binder sources and two binder grades were evaluated with one fiber. The results indicated that crude source plays a role in how the fiber finish affects the binders and mastics. This was evident from the opposite effects that the finish had on the binder properties from different sources. Further investigation using GPC revealed that the polymer modifier (SBS) used in the PG 76-22 binders in this study potentially influenced the interaction between the binder and the finish in mastics when fibers were present. Analysis of the GPC results also indicated that the fiber finish may affect the fiber/binder interaction by preventing lighter binder fractions from being absorbed by the fibers.

From the results of the second phase of the study, it is evident that the different finishes have different effects on some binder properties (mainly tensile properties). The effect that Extract X had on the unaged binder indicates that there was a weakening effect on the binder that occurs when the fiber containing this particular finish is mixed with the binder. In the case of Extract Y, the effect is only realized after aging, which could indicate that the chemistry of the finish somewhat accelerates the oxidative aging of the binder making it more brittle at low temperatures. This adverse effect on the tensile properties of the binder could potentially indicate that the fiber finish could have an effect on the low-temperature behavior of a fiber modified mixture if a compatible fiber is not selected for a paving application. It is also interesting to note that the amount of finish applied to the fiber was not a significant factor.

The major finding of this study is that different polyester fibers, even from the same manufacturer, may not necessarily perform the same in an asphalt mixture. While the fiber material is the same, different finishes are applied to fibers for different reasons. It is important to use fibers that are compatible with the particular asphalt binder that is being used because the binder source also has a significant effect on the interaction between the finish and the binder.

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