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Research Article

Physical and Rheological Properties of Asphalt Binder Modified with Recycled Fibers

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The price of asphalt binder has increased dramatically due to the increase in oil prices and the increase in traffic volumes occurring worldwide. This situation has prompted calls for greater viscosity, lower-cost asphalt for pavement construction, and the development of alternative materials that have a good rheological effect, are less expensive, and have a reduced negative impact on human health and the environment. The application of fibers in asphalt mixes has been studied over the past few decades to improve pavement performance around the world. This study was conducted on three types of asphalt binders that were modified with two types of fibers: brown recycled wool fiber (BRWF), available locally in Iraq, and China polyester fiber (CPF), which is considered as waste, to produce fiber-modified asphalt binders. The samples were conducted using traditional physical testing (penetration, softening point, and rotational viscosity tests) as well as the Dynamic Shear Rheometer (DSR) test. In comparison to the original asphalt binders, the fiber-enhanced asphalt binders had greater softening point, viscosity, and complex modulus but decreased penetration. The tests revealed that using both kinds of fibers as modifiers for asphalt binders improves their high-temperature performance by increasing the grade of the control binders (PG). This increase in asphalt binder stiffness is anticipated to enhance pavement rutting resistance. Consequently, these fibers can be used as additives for asphalt binders and asphalt mixtures to enhance their performance.

1. Introduction

Fibers are increasingly being employed in scientific study and technical practice as the modern economy develops. When it comes to prolonging the service life of matrix materials, using fibers as reinforcements can frequently provide greater economic and performance benefits [1–4]. Many researchers in the field of road engineering have studied asphalt mixes reinforced with various fibers and discovered that natural and synthetic fibers might significantly improve the performance of asphalt binders and asphalt mixtures [5–7]. Fibers are primarily mixed with asphalt in asphalt mixes, and the two together play a critical role in asphalt mixtures. Some research suggests that the impact of fiber on asphalt is closely related to the influence on the asphalt mixture [8, 9].

The performance of the asphalt mixture may be considerably enhanced and the service life of the asphalt pavement can be extended by adding a specific quantity of fiber to the asphalt binder or mixture. Because of their outstanding performance and low cost, fiber-reinforced asphalt mixes are widely utilized in a variety of road grades [10–14]. The types of fiber used to strengthen asphalt mixes are becoming more diverse as technology advances. Many fibers are employed in asphalt mixtures to increase performance, including asbestos, lignin, polymer, glass, and basalt fibers [15–19]. In conclusion, there are two major kinds of fiber applications: (a) for open-graded and gap-graded asphalt mixes, primarily to reduce bitumen drain-down and improve tensile performance, and (b) increasing the rutting resistance of thick graded mixes [20, 21]. In this regard, a wide range of findings on the efficacy of various types of fibers have been reached. However, the majority of these findings came from mixture-scale research rather than binder-scale research.

The effects of fiber characteristics (length, adhesion, absorption, and swelling) on bitumen are complicated. Fibers are added to bitumen to improve its viscoelastic characteristics, for example, by increasing the viscosity and stiffness of the bitumen [22]. Fibers are typically utilized in stone matrix asphalt and gap-graded mixes to keep the binder from draining away during mixing and compaction [23, 24]. Fibers can strengthen asphalt mastic by forming a three-dimensional network and absorbing the asphalt binder and adhering to the mix [22, 25]. Fibers can also improve moisture resistance [26], fatigue resistance [27–32], rutting resistance, and creep compliance [22, 24, 27–29, 33].

The data on the influence of cellulose-based fibers on the physical and rheological characteristics of bitumen may be split into binder scales based on the test temperature levels. The most frequent techniques are low-temperature analysis with a Bending Beam Rheometer (BBR) and intermediate/high-temperature levels using a Dynamic Shear Rheometer (DSR). When different types of cellulose fibers were introduced to the binders at low temperatures, the literature indicated that the binders enhanced stiffness [34]. The rubberized fibers, on the other hand, were shown to be able to reduce stiffness in the same study. A study found that the complex shear modulus of fiber-added bitumen compound rose at intermediate and high temperatures, which might lead to enhanced rutting resistance for the binders and extended scale in the mixes. Furthermore, the inclusion of different fibers decreased the phase angle of asphalt binders, increasing the elastic component of the viscoelastic characteristics of asphalt binders [35].

Many studies have focused on the effect of fibers on the rheological properties of modified asphalt binders in recent years. For example, Chen et al. [22] demonstrated that adding cellulose fibers to an asphalt binder reduces the susceptibility of the binder to temperature changes and improves its performance against high-temperature damage such as rutting. The modified binder exhibited a stronger resistance to rutting than the control samples, according to their findings. Ye and Wu [35] looked at the characteristics of a binder which had been changed with cellulose fibers and discovered that the fibers enhanced the elastic component of the viscoelastic behavior of the binder, increased its hardness and viscosity, and improved its resistance to permanent deformation. Using the cone penetration test to investigate the rheological characteristics of fiber-modified binders, it was discovered that the quantity of fiber has a substantial impact on the binder's softening point, penetration value, and viscosity. The number of fiber reinforcements to is increased to a particular value, based on the type and length of the fibers, to increase the impact [36].

Ye and Wu [37] investigated the rheological properties of fiber-reinforced asphalt binders. Cellulose fiber, polyester fiber, and mineral fiber were employed as additives with concentrations of 0.1, 0.3, 0.5, and 1% by weight of asphalt binder. The experimental results indicated that the viscosity and complex shear modulus (G^*) of fiber-reinforced binders were increased by the addition of fibers, especially, polyester fiber, which indicates that the use of fiber additives can enhance the stiffness of asphalt binders. The elastic part of the viscoelastic behavior of asphalt binders was also enhanced by the addition of fibers, which is indicated by the reduction in phase angle (δ).

Muniandy et al. [38] carried out an investigation to determine the rheological properties of fiber-modified asphalt. The study was conducted to take advantage of the large number of oil date palm trees to produce cellulose fiber to be used as an additive to the asphalt binder. Control content (0%) and five percentages of fiber content (0.075, 0.15, 0.225, 0.3, and 0.375%) by weight of total mix were used with asphalt binders. The results indicated that fibers enhanced the rheological performance of the asphalt binder. The control sample, which was categorized as PG58, was enhanced to be PG76 with 0.375% date palm fiber.

Chen et al. [4] have investigated the properties of asphalt binder modified with corn stalk fiber. The results of this study indicated that the addition of corn stalk fiber improved the physical and rheological properties of the modified asphalt binder, especially at high service temperatures [4].

Fibers were widely utilized in stone matrix asphalt (SMA) mixes in the asphalt paving business. Fiber's impact in SMA is often considered to be stabilizing and absorbing asphalt to avoid the drain-down of asphalt binder from the mixture. As a result, this study is a laboratory experimental work to investigate how recycled wool fiber and China polyester fiber affect the properties of three asphalt binders (80/100, 60/70, and PG76). Fibers are commonly employed to strengthen the binder phase, and the optimum amount is highly dependent on the types of fibers utilized. Furthermore, taking into account cost considerations, determining the appropriate fiber concentration that enhances bitumen characteristics to a desirable level is essential. As a result, this research aims to define the physical characteristics of recycled fiber-modified asphalt binders, evaluate the influence of fibers on the rheological properties of asphalt binder, and determine the optimal fiber concentration in asphalt binder.

2. Materials and Methods

2.1. Asphalt Binders. Three types of asphalt binders were used in this research paper, where the ability of these species to resist loads inflicted by traffic was taken into account. The penetration grade (80–100) asphalt binder is considered the weakest type among the asphalt binders used despite being free from any modifications; it was used to obtain the actual effect of the fiber additives. Asphalt binders of penetration grade 60–70 and PG76 performance grade asphalt were used in this research for extra understanding of fiber on different binders. Table 1 shows the physical properties of the three base asphalt binders used in this study.

2.2. Additives. Two types of fibers were used as additives in this study.

Table 1: Physical properties of asphalt binder.

Asphalt properties	Specification	80–100	60–70	PG76
Penetration (25°C, 100 gm, 5 sec.) (0.1 mm)	ASTM D5	85	63.0	32.5
Softening point (ring and ball) (°C)	ASTM D36	46.0	48.6	74.5
Viscosity at 135°C (cP)	ASTM D4402	298.6	385.1	1542.6
Ductility (25°C, 5 cm/min).	ASTM D113	>100	>100	>100
Specific gravity at 25°C (g/ **cm**^{3})	ASTM D70	1.037	1.04	1.03

2.2.1. Brown Recycled Wool Fiber. Wool is a protein fiber found at the skin of the sheep and then called animal fiber, as shown in Figure 1. This type of fine wool was used as a second-class use, which is widely available in the international and local markets. The wool was rehabilitated and cleaned by the dry method before starting to use in the laboratory. Table 2 shows the physical properties of brown recycled wool fiber.

2.2.2. China Polyester Fiber. Polyester fibers form a three-dimensional network structure that mainly plays a strengthening role in increasing the thickness of the asphalt film for the surface of the aggregate. In addition, this type of additive increases the bond strength between the aggregate and the asphalt [39, 40] (Zhang et al., 2014). Table 3 shows the technical indexes of China polyester fiber.

The polyester fibers used in this study are mainly waste or used grade II as shown in Figure 2, which are abundant in Iraq and are not biodegradable. As this additive is used in polyester medical pillows after being cleaned and rewashed by the dry method to ensure that their mechanical and chemical properties are not altered, and since the construction of asphalt pavement is growing rapidly in the country, the use of these fibers, which are mass-produced, would lead to a disposal problem resulting in environmental concerns in the asphalt mixtures needed for exploration for the benefit of both the pavement and the environment [41].

2.3. Modified Asphalt Binder Preparation. Wet mixing was utilized in this study since we were focused on the performance of fiber-modified asphalt binders. As a result, the fiber was mixed directly into asphalt binders. Wet mixing also has the benefit of making the fiber more uniformly distributed in the asphalt binder as compared to dry mixing. The drawback is that if the asphalt binder with wet mixing is not utilized right once, the fiber and asphalt will separate after some time in storage. In most cases, the wet mixing technique will also extend the time and expense of the building process [4, 13, 42].

The fiber-modified asphalt binders were obtained through mixing fibers with asphalt binders by a high shear mixer with a revolution of about 1000 rpm at 160. The fiber contents were 0.15, 0.3, 0.45, and 0.6% by weight of asphalt for brown recycled wool fiber, while the contents of the China polyester fiber used were 0.5, 1.0, 1.5, and 2.0% by weight of asphalt.

The process of blending was maintained for 30 minutes, to create a uniform combination while keeping a steady 160°C combining temperature. The temperature has been carefully monitored through a double thermometer to avoid the reverse impact of excessive heat. The sample is removed from the mixing can after completion, divided into a tiny contained metal container, and then maintained at room temperature for subsequent testing. Due to temperature and rotational circumstances, the processes of combining fibers with binder induce the aging in modified binder samples. The control sample was also moved in the mixer for 30 min at mixer temperature to replicate these circumstances for control binders and compare the samples under equal conditions.

2.4. Penetration Test. The penetration test at 25°C is the most used technique for bitumen categorization throughout the globe. The test includes measuring the vertical penetration of a standardized steel needle into a bitumen sample at a particular temperature to determine bitumen consistency. The loading duration is 5 seconds, and the needle load is 100 g. The needle penetration depth in the bitumen sample is 0.1 mm; therefore the penetration unit is 0.1 mm. The penetration is a numerical representation of the bitumen's reaction to temperature changes. AASHTO T49 explains how to conduct the test [21].

2.5. Softening Point Test. The bitumen's thermal stability is represented by its softening point. This implies that the greater the bitumen's softening point, the higher the temperature required to achieve the same viscosity. The softening point was included in the characterization of bituminous compounds in this study to investigate the impact of various fiber additions on thermal stability. The test entails determining the "typical" temperature at which asphalt reaches a certain consistency. The ring and ball technique is often used to evaluate the softening point of bitumen (R&B) [21]. Softening point is also an empirical test, which measures the temperature at which the asphalt binder becomes soft and cannot support the weight of a metal ball and begins to flow. The rings and assembly are placed in a water bath to a depth of 105 ± 3 mm, a 9.5 mm steel ball bearing (weighing 3.50 ± 0.05 g) is centered on each specimen, and the temperature is raised by a rate of 5 ± 0.5°C per minute. The average of two temperatures at which the two balls fall and touch the base plate is recorded as the softening point. The test procedure is described in AASHTO T53 [43].

2.6. Rotational Viscosity Test. The viscosity of bitumen is an essential physical characteristic for determining its flowability and deformation. By creating viscosity-temperature profiles, it is always helpful to evaluate the flow behavior of bitumen at

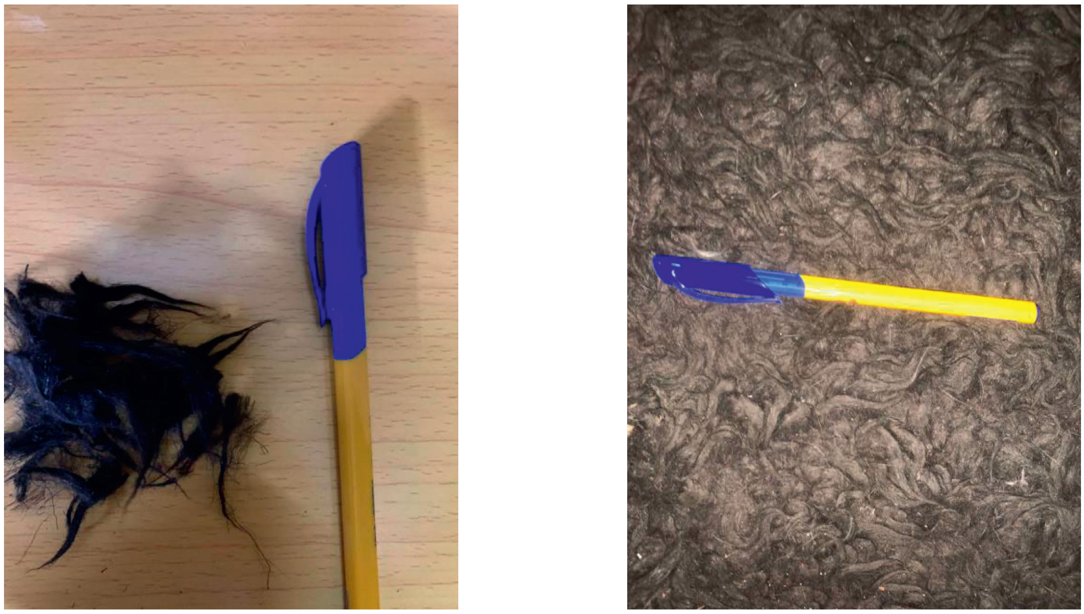

Figure 1: Black and brown recycled wool fiber.

Table 2: Physical properties of brown recycled wool fiber.

Properties	Test result
Color	Brown
Grade	Recycled
Pattern	Raw
Specific gravity	1.13
Moisture regain	13–16%, very absorbent, decrease strength when wet, seem warm, will shrink in washing.
Strength	Tenacity dry = 1.35 g/d, wet = dry 0.69 weak
Diameter	Merino wool of 19.5 micron and finer

Table 3: Technical properties of polyester fibers [41].

	Property	Pavement requirements
Length (mm)	12 ± 2	≥3
Diameter (μm)	20 ± 2.5	20 ± 5
Strength (MPa)	500–680	≥500
Elongation at break (%)	15–35	≥15
Young's modulus (GPa)	>13.5	-
Proportion	1.36	1.36 ± 0.05
Melting points (°C)	259	≥258

high temperatures when monitoring field production and laboratory design. In the high-temperature range of manufacturing and construction, the Rotational Viscometer (RV) is used to determine the viscosity of asphalt binders. The basic RV test determines the torque needed to keep a cylindrical spindle rotating at a consistent speed (20 RPM) while immersed in asphalt binder at a constant temperature using a Thermosel temperature control system. After that, the torque is transformed into viscosity. The RV test results guarantee that the asphalt binder is fluid enough to pump and mix. The rotational viscosity of the asphalt binders was measured using a Brookfield viscometer following AASHTO T316. The rotational viscosity test is performed on the asphalt binders to ensure that they can be pumped and handled at the hot mixing facility [21, 43, 44]. The viscosity was determined at a constant temperature of 135°C.

2.7. Temperature Sweep Test at High Temperature. The DSR test was used to examine the viscosity and elasticity of binders at high and intermediate temperatures. At the desired temperatures and frequencies, the device monitors the binders' complex shear modulus (G^*) and phase angle (δ), providing a complete picture of binder behavior at the pavement's service temperature [19].

A Bohlin Dynamic Shear Rheometer (DSR) was used to determine the complex shear modulus (G^*) and phase angle (δ) of the asphalt binder. The complex modulus is defined as

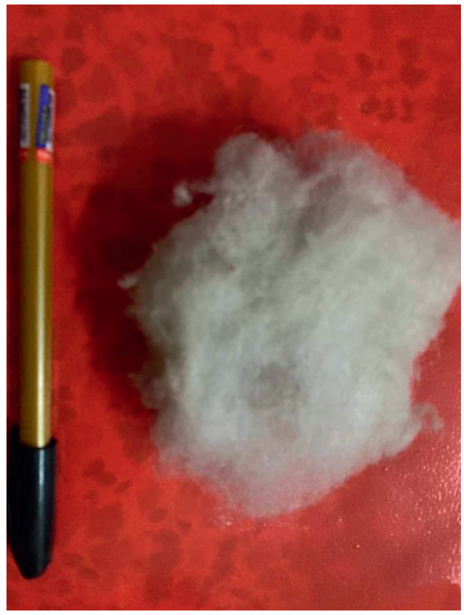

Figure 2: Polyester fibers used in the study.

the ratio of maximum shear stress to maximum shear strain and it provides a measure of the total resistance to deformation during shear loading. The phase angle is defined as the time lag between the applied stress and the resulting strain, and it is an indicator of the relative amounts of recoverable and nonrecoverable deformation. The test is conducted on unaged asphalt binders [43].

The samples are determined to be placed between two parallel plates of 25 mm diameter with a gap of 1 mm to make measurements by DSR at high testing temperatures. The procedure of the test is described in AASHTO T315. The stress has been directed at a low level (0.12 kPa) to keep all of the tests that were conducted within the linear viscoelastic limit. Moreover, the rutting factor ($G^*/\sin\delta$) was calculated to measure the shear resistance and hardness of asphalt binders. According to Superpave specification, to minimize the permanent deformation (rutting), the rutting parameter ($G^*/\sin\delta$) must be greater than or equal to 1.00 kPa for the unaged asphalt binder.

3. Results and Discussion

3.1. Physical Properties of Asphalt Binder. Conventional tests were conducted, such as penetration (ASTM D5), softening point (ASTM D36), and viscosity (ASTM D4402), for asphalt without and with fiber additives.

3.1.1. Penetration Test. Penetration is a traditional test for determining the hardness of bitumen. The average of three readings was used to get the penetration value. The penetration test results for fiber-modified asphalt binders are shown in Figure 3 and 4. From these figures, it can be seen that as the percent of modifiers increases, the penetration value decreases, indicating an increase in asphalt binder consistency, regardless of the binder type. Furthermore, the results show that the China polyester fiber-modified binders have higher penetration values compared to the asphalt binder samples modified by brown recycled wool fiber. At the same time, fibers had a negligible impact on the penetration of PG76 asphalt binder. This is almost because the PG76 binder has already been polymerized, so the fibers' effect on the asphalt binder was not noticeable.

3.1.2. Softening Point Test. The softening point has been linked to the permanent deformation of asphalt mixtures. The softening point test results for the three asphalt binder types and two fiber types are shown in Figure 5 and 6. The results of softening point test were opposite to the results of penetration test for all types of asphalt; with increasing the fiber percentage, the softening point increased. The magnitude of the increase in softening point is a function of fiber content. There were rather significant changes in the softening point values compared to the base binder. However, the softening point values of high-grade asphalt (PG76) modified by the two fibers were not significantly altered.

In general, the penetration and softening point values of an asphalt binder reflect its relative viscosity. At high temperatures, asphalt binders with low penetration numbers and high softening points may withstand deformation.

3.1.3. Viscosity Tests. Figure 7 and 8 illustrate the rotational viscosity results of the control and fiber-modified samples at 135 °C in Pascal-seconds (Pa s). The viscosity values proved that the modified fiber binders have higher viscosity values than the binders without fibers, regardless of the binder type.

This increase in viscosity is caused by fibers' propensity to absorb binder, causing them to stick together [45]. Furthermore, the presence of fibers in the binder has the same effect as the skeleton in the body, enhancing binder

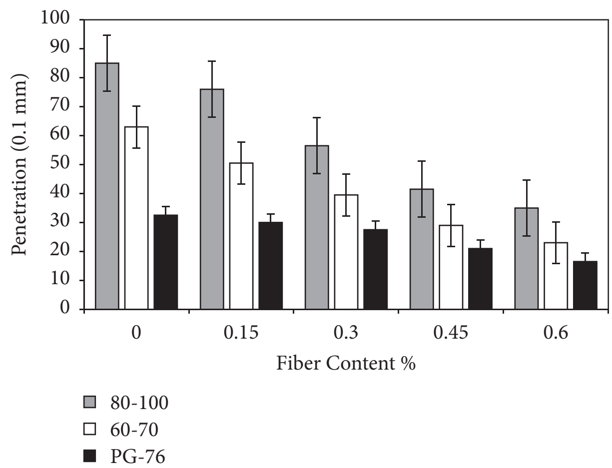

Figure 3: Penetration test results for brown recycled wool fiber-modified binders.

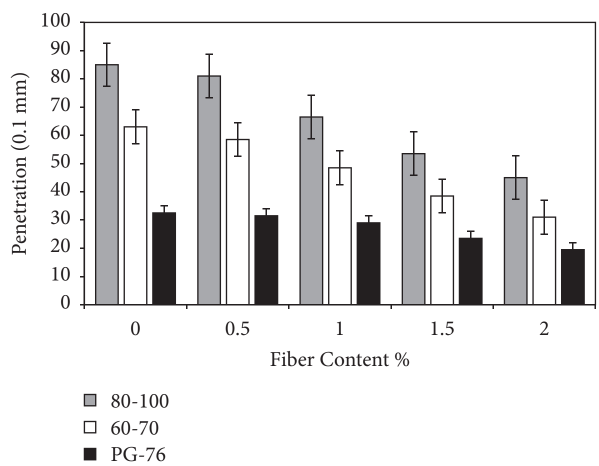

Figure 4: Penetration test results for China polyester fiber-modified binders.

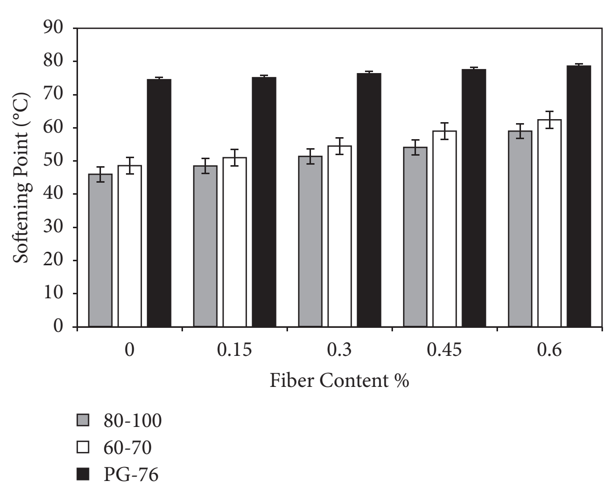

Figure 5: Softening point test results for brown recycled wool fiber-modified binders.

hardness and reducing deformation at the same temperature. This increases the mixing temperature, decreases workability, and increases expenses [46]. Furthermore, when the viscosity of the binder increases, the heat resistance of the asphalt mixture will be improved, and the high-temperature damage will be decreased [19].

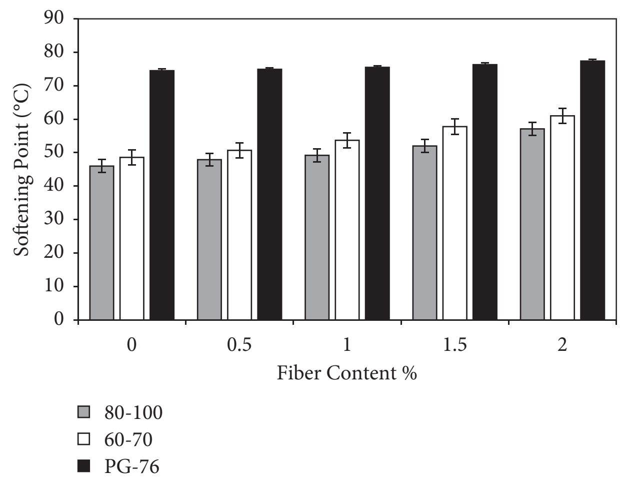

Figure 6: Softening point test results for China polyester fiber-modified binders.

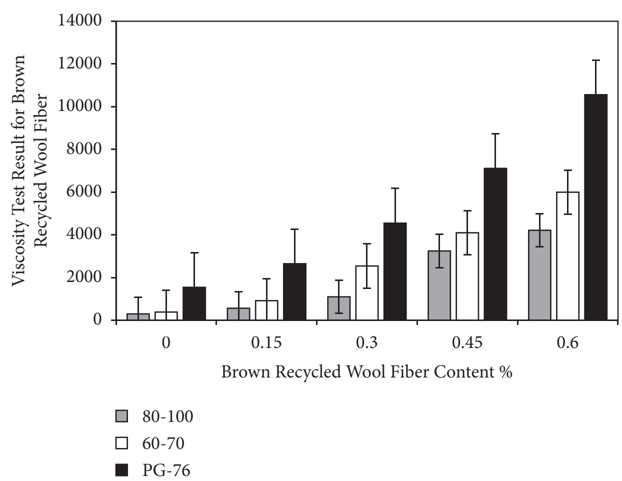

Figure 7: Viscosity test result for brown recycled wool fiber.

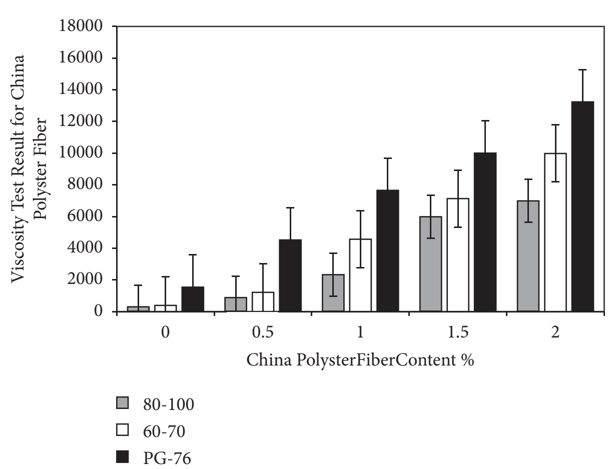

Figure 8: Viscosity test result for China polyester fiber.

It is noticeable that the addition rate of China polyester fiber is relatively high compared to brown recycled wool fiber. This possibly could be because of the high solubility and homogeneity of polyesters in asphalt binder compared to brown recycled wool fiber.

Since AASHTO considers 3 Pa s as the upper limit of viscosity at 135°C for convenience in workability, pumping, and transporting, the brown recycled wool fiber-modified asphalt binders with 0.3 percent for 80–100 and 60–70 binders and 0.15 percent for PG76 binders have met this standard, whereas binders with more fiber content have not. At the same time, the China polyester fiber-modified asphalt binders with 1.0% for 80–100 binder and 0.5 for 60–70 binder have met this standard, while it was noted that there is a rapid effect of the change in the percentage of fiber in the case of the PG76 binder so that it exceeds the permissible limit with the first percentage of added fiber, and this can be attributed to the fact that this binder was originally modified by polymer and does not need further modification.

3.2. Rheological Properties of Modified Asphalt Binder. The impact of fibers on the high-temperature performance and rutting resistance of binders was investigated using the DSR at 40, 46, 52, 58, 64, 70, 76, and 82°C on unaged binders. The rutting factor (G*/sin) is used in DSR tests to assess asphalt's high-temperature performance. The asphalt satisfies the requirement when the rutting factor is higher than 1.0 kPa [36, 47]. The effect of fiber type and content for the three asphalt binders used in this study on rutting parameter ($G^*/\sin\delta$) at different temperatures can be seen in Figures 9–14 as an output of the temperature sweep test conducted on asphalt samples at high service temperatures. It can be seen from these figures that as the fiber content increases, the blends become stiffer, regardless of the fiber or asphalt binder type.

The effect of fiber content on stiffness depends on fiber and binder type as can be shown in Figure 15 and 16, for the effect of recycled wool fiber and China polyester fiber, respectively. These figures show the failure temperature of fiber-modified asphalt binders against fiber percent for the effect of each fiber type and content on each binder type. Failure temperature is the maximum temperature that meets the rutting criteria. It was noticed that the 80–100 asphalt binder was the most affected by the presence of both fibers, followed by the 60–70 and PG76 binders. For the effect of recycled wool fiber on 80–100 asphalt binder, the failure temperature was increased from 66°C (pure asphalt) to 75.6°C at 0.6% fiber content. This means an increase in performance grade of asphalt binder of almost 2 steps, from PG64 to PG76. Meanwhile the effect was less on the other asphalt binders (60–70 and PG76). For the effect of China polyester fiber on 80–100 asphalt binder, the failure temperature was increased from 66°C (pure asphalt) to 73°C at 2.0% fiber content, meaning an increase in performance grade of one grade from PG64 to PG70.

After comparing the obtained failure temperatures with Superpave requirements, the pure and fiber-modified asphalt binders were classified into performance grade (PG) categories as presented in Tables 4 and 5, for recycled wool fiber and China polyester fiber, respectively. Generally, the results indicate that the control samples can be modified and raised to higher PG grades depending on the fiber type and

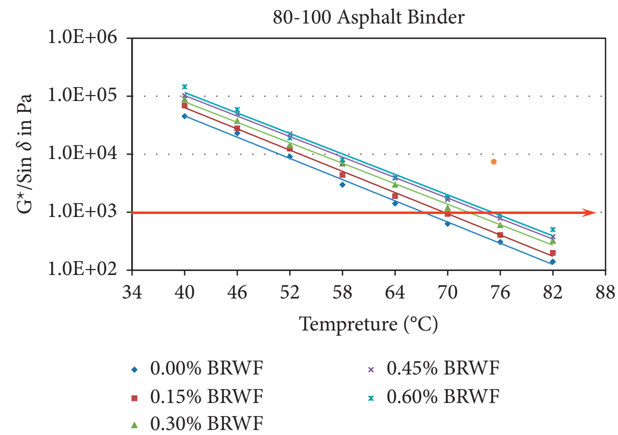

Figure 9: Temperature sweep test for 80–100 asphalt binder with brown recycled wool fiber.

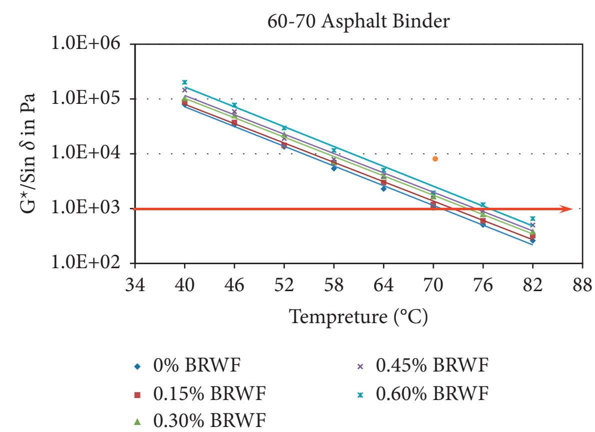

Figure 10: Temperature sweep test for 60–70 asphalt binder containing brown recycled wool fiber.

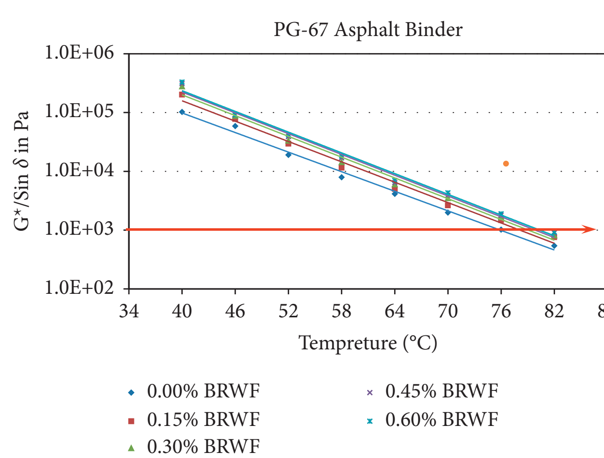

Figure 11: Temperature sweep test on PG76 asphalt binder using brown recycled wool fiber.

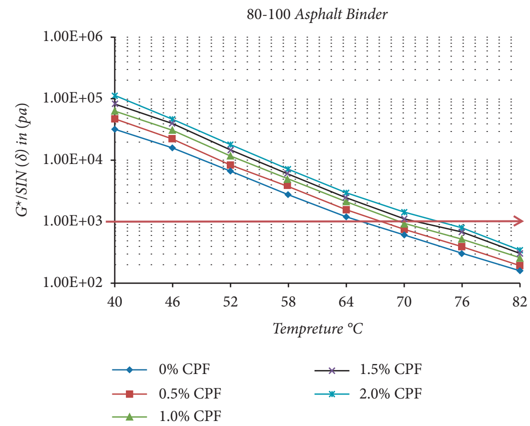

Figure 12: Temperature sweep test for China polyester fiber-modified 80–100 asphalt binder.

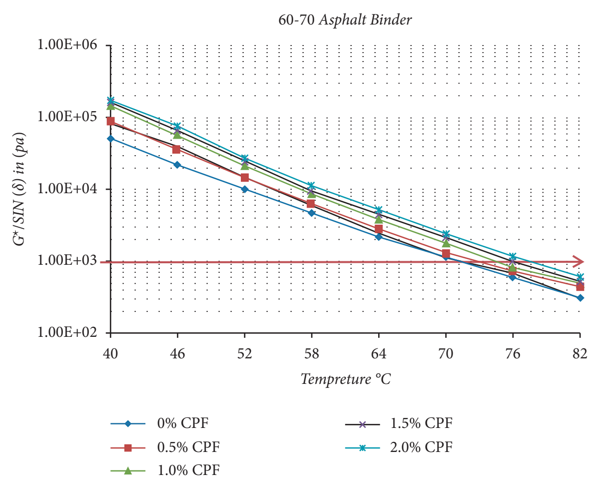

Figure 13: Temperature sweep test for 60–70 asphalt binder modified with China polyester fiber.

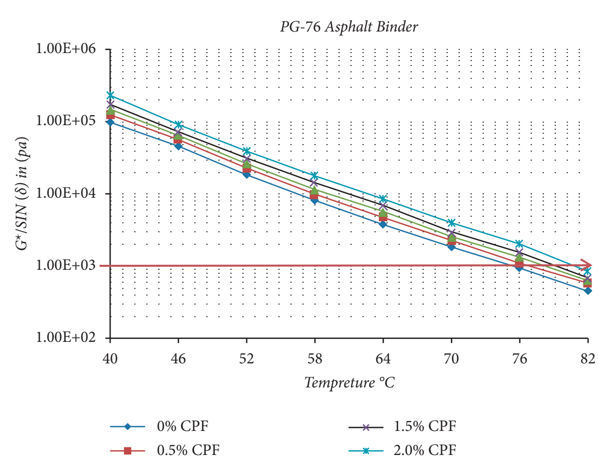

Figure 14: Temperature sweep test for China polyester fiber-modified PG76 asphalt binder.

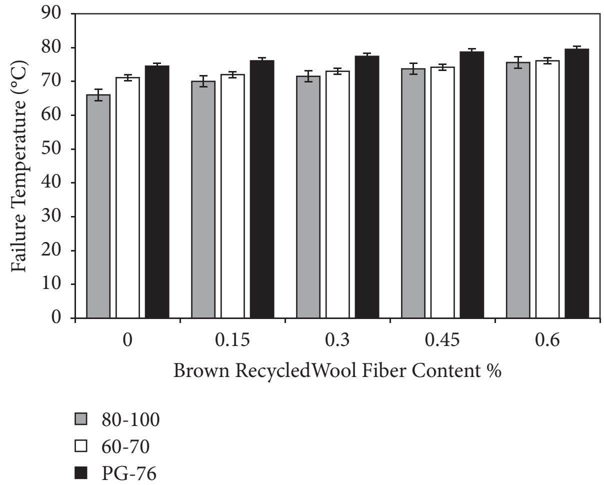

Figure 15: Failure temperature of brown recycled wool fiber with different asphalt types.

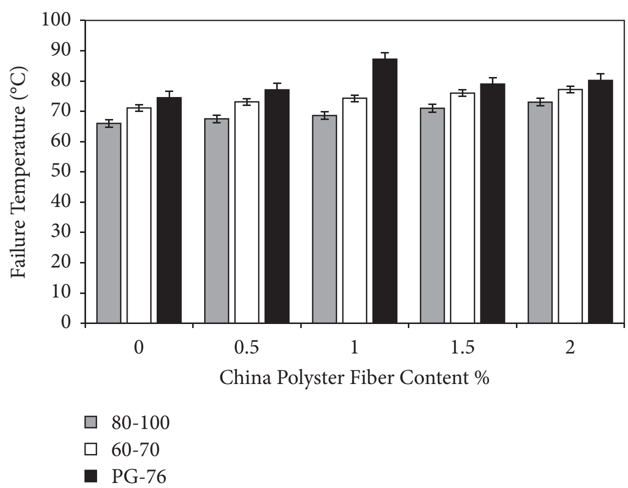

Figure 16: Failure temperature of China polyester fiber with different asphalt types.

Table 4: High-temperature grades for recycled wool fiber-modified asphalt binders.

Binder type	Fiber content				
	0%	0.15%	0.3%	0.45%	0.6%
80–100	PG64	PG70	PG70	PG70	Near to PG76
60–70	PG70	PG70	PG70	PG70	PG76
PG76	PG76	PG76	PG76	PG76	PG76

Table 5: High-temperature grades for recycled China polyester fiber-modified asphalt binders.

Binder type	Fiber content				
	0%	0.5%	1.0%	1.5%	2.0%
80–100	PG64	PG64	PG64	PG70	PG70
60–70	PG70	PG70	PG70	PG76	PG76
PG76	PG76	PG76	PG76	PG76	PG76

content, as well as the base asphalt binder type. Therefore, the use of the two fibers can be suitable for areas with high-temperature conditions.

4. Conclusions

On modified specimens, traditional tests such as penetration and softening point, as well as SHRP tests such as rotational viscosity and Dynamic Shear Rheometer, were conducted to investigate and assess the impact of using two fiber types (recycled brown wool fiber and China polyester fiber) in binders. This may lead to better knowledge of fiber-modified binders and fiber-reinforced asphalt mixes in general. The following are some broad conclusions:

(i) For all fiber percentages tested, the fiber-modified asphalt binders had less penetration and a greater softening point than the control asphalt binders, suggesting less susceptibility to temperature fluctuations and better resilience to deformation at high temperatures

(ii) Since the control samples were changed and elevated to higher PG with the rise of fiber content, fiber addition enhanced the rheological characteristics of the asphalt binder

(iii) The fiber type and its contents have a significant influence on asphalt binder's high-temperature performance

(iv) Recycled wool fiber and China polyester fiber are suitable additives to increase the resistance of binder and asphalt mixture against rutting and permanent deformation because using these fibers in binders increases their stiffness and elastic properties [48–50]

Data Availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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