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Physical and Rheological Properties of Asphalt Modified with Cellulose Date Palm Fibers

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***Abstract*—**Fibers are extensively used in civil engineering applications for many years. In this study, empty fruit bunch of date palm trees were used to produce cellulose fiber that were used as additives in the asphalt binder. Two sizes (coarse and fine) of cellulose fibers were pre-blended in PG64-22 binder with various contents of 1.5%, 3%, 4.5%, 6%, and 7.5% by weight of asphalt binder. The physical and rheological properties of fiber modified asphalt binders were tested by using conventional tests such as penetration, softening point and viscosity; and SHRP test such as dynamic shear rheometer. The results indicated that the fiber modified asphalt binders were higher in softening point, viscosity, and complex shear modulus, and lower in penetration compared to pure asphalt. The fiber modified binders showed an improvement in rheological properties since it was possible to raise the control binder (pure asphalt) PG from 64 to 70 by adding 6% (by weight) of either fine or coarse fibers. Such improvement in stiffness of fiber modified binder is expected to improve pavement resistance to rutting.

***Keywords*—**Cellulose date palm fiber, fiber modified asphalt, physical properties, rheological properties.

I. Introduction

THE drastic increase in traffic volume during the last few decades has resulted in a premature pavement deterioration of the most heavily trafficked roads in the Kingdom of Saudi Arabia, KSA. Pavement permanent deformation (rutting) is one of the most common and destructive pavement distress being observed in flexible pavements. Stone Matrix Asphalt (SMA) has become a popular asphalt mix for surfacing heavily trafficked roads in many parts of the world [1]. The main advantage of SMA is its ability to resist rutting due to the coarse aggregate gradation used. The problem with SMA mixtures is the binder draindown during transportation and construction stage resulting from the relatively high binder content and the aggregate gap-gradation. This problem is usually mitigated by using additives such as fibers, rubbers, and polymers [2].

The addition of fibers to asphalt has attracted many researchers. Results of previous researches have shown that fibers have better performance than other additives in reducing draindown of asphalt concrete mixtures, and this is the reason why fibers are widely used in SMA [3]. Previous researchers have demonstrated that the addition of fibers result in a significant influence in the physical and rheological properties of asphalt binders. Ye and Wu [4] carried out an investigation to study the rheological properties of fiber reinforced asphalt binders. Cellulose fiber, polyester fiber, and mineral fiber were employed as additives with a concentration of 0.1, 0.3, 0.5, and 1% by weight of the asphalt. Experimental results indicated that the viscosity and complex shear modulus (G*) of fiber reinforced binders were increased by the addition of fibers, especially, polyester fibers, which indicates that the stiffness of asphalt binders can be enhanced by the use of fiber additives. The elastic part of viscoelastic behaviors of asphalt binders was also enhanced by the addition of fibers, which resulted in a reduction in phase angle (δ).

There appears to be a growing interest in developing parts of the world in using locally available plant-based materials such as coconut, jute, palm, and sisal as sources of fibers. Muniandy et al. [5] carried out an investigation to determine the rheological properties of fiber modified asphalts. A study was conducted to take advantage of the bunch of date and oil palm trees to produce cellulose fiber to be used as additives to the asphalt binder. Control content (0%) and five percentages of fiber contents (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 asphalt binder. The control sample which was categorized as PG58 was enhanced to PG76 with 0.375% date palm fiber. The oil palm fiber has also increased the grade to PG70 with 0.3% oil palm fiber.

This research is a laboratory study to evaluate the effect of Cellulose Date Palm Fiber (CDPF) size and content on the characteristics of fiber modified asphalt.

II. Materials

A. Asphalt Binder

The performance grade PG64-22 is used as a control asphalt binder for this study. The source of asphalt binder is obtained from the Riyadh Refinery. The properties of the pure asphalt cement are presented in Table I.

B. Cellulose Date Palm Fiber

The date palm bunches were collected from plantation in Al-Qasab area which is about 150 Km northwest of Riyadh city. The collected bunches were cut into small pieces, crushed and then grinded to a powder. The fibers were then separated by sieving into two sizes:

i. Coarse fibers: Fibers passing sieve #100 (150 μm) and retained on sieve #200 (75μm).
ii. Fine fibers: Fibers passing sieve #200 (75μm).

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The abbreviations "C" and "F" were used for coarse and fine fibers, respectively. The chemical composition of the date palm bunch is given in Table II [6].

TABLE I
PROPERTIES OF THE PURE ASPHALT CEMENT

Property	Test Reference	Value
Penetration @ 25°C (dmm)	AASHTO T 49	62
Softening Point (°C)	AASHTO T 53	48
Ductility (cm)	AASHTO T 51	+100
Rotational Viscosity @ 135 °C (cps)	AASHTO T 316	450
Specific Gravity	AASHTO T 228	1.025
Rolling Thin Film Oven Test@ 163°C for 85 minutes, (% wt loss)	AASHTO T 240	0.11
High Temperature Grade (°C)	AASHTO T 315	64
Low Temperature Grade (°C)	AASHTO T 313	-22

TABLE II
CHEMICAL COMPOSITION (%) OF DATE PALM BUNCH

Property	Percentage
Cellulose	43.05
Hemicelluloses	27.48
Lignin	29.47
Ash	1.8

III. BLENDING OF FIBER MODIFIED ASPHALT

The fiber modified asphalt binder was obtained through mixing fibers with asphalt by high shear mixer at 156°C. The fiber contents were 1.5%, 3%, 4.5%, 6%, and 7.5% by weight of asphalt binder. The fibers were added slowly into the preheated asphalt and mixed for two hours to produce homogenous blend.

IV. EXPERIMENTAL PROCEDURES

The tests conducted to characterize the properties of fiber modified asphalt binder, include penetration at 25ºC, softening point, viscosity and complex shear modulus.

A. Penetration

The penetration test is an empirical test which measure the distance in tenths of millimeter (e.g., if the needle penetrates 6 mm, the asphalt penetration values is 60). A standard needle penetrates into the sample under 100 grams load for 5 seconds and a temperature of 25 C. The test procedure is described in AASHTO T 49.

B. Softening Point

Softening point is also empirical test, which measures the temperature at which the asphalt becomes soft and cannot support the weight of a metal ball and begins to flow. The rings and assembly are placed in a liquid bath filled with water 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 5 ± 0.5 C per minute. The average of the two temperatures at which the two asphalt specimens fall and touches the base plate is recorded as the softening point. The test procedure is described in AASHTO T 53.

C. Rotational Viscosity

The rotational viscometer test is performed on the asphalt binder to ensure that it can be pumped and handled at the hot mixing facility. Brookfield viscometer is employed to measure the rotational viscosity of asphalt binders according to AASHTO T 316. The viscosity is determined by measuring the torque required to maintain a constant rotational speed (20 revolutions per minute) of a cylindrical spindle while submerged in an asphalt binder sample (8-11 grams) at constant temperatures (135, 150, 165 and 180 °C).

D. Complex Shear Modulus

A Bohlin Dynamic Shear Rheometer (DSR) is used to determine the complex shear modulus, G*, and phase angle, δ, of the asphalt binder. G*is defined as the ratio of maximum shear stress to maximum shear strain and it provides a measure of the total resistance to deformation during shear loading. δ 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 non-recoverable deformation. The test is conducted in unaged and RTFO aged binders. Samples are placed between two 25mm parallel plates, the gap is adjusted to 1mm for both unaged and RTFO aged binders at high testing temperatures. The procedure of the test is described in AASHTO T 315.

In Superpave specification, in order to minimize the permanent deformation (rutting), the parameter $G^*/\sin\delta$ must be greater than or equal to 1.00 kPa for the unaged asphalt binder and 2.20 kPa for the RTFO aged asphalt binder.

V. RESULTS AND DISCUSSION

A. Penetration and Softening Point

The change in penetration and softening point due to increasing fiber content for both coarse and fine fiber modified asphalts (FMA) are shown in Figs. 1 and 2. The penetration value for pure asphalt is in the range of its specified grade of 60-70 pen, while its softening point temperature is approximately 48 °C. The penetration and softening point of processed asphalt (subjecting pure asphalt to the same blending process but without fiber) are about 21% lower, and 10% higher than the pure asphalt values, respectively. Higher softening point and lower penetration of processed asphalt are due to hardening resulted from loss of volatile materials and oxidation.

Addition of coarse fibers causes a slight increase in softening point of modified binder compared to fine fibers. For the coarse size, as the fiber content increases the softening point reaches a maximum value at 6% fiber content and then decreases, which indicates that the binder reached a maximum hardness at this content. The decrease in softening point after 6% fiber content most probably due to the reduction in cohesiveness of the binder at warm temperature. For the fine size, there is no effect for the addition of fiber on softening point of modified binder compared to processed asphalt. Generally, coarse fibers increased softening point more than that caused by fine fibers.

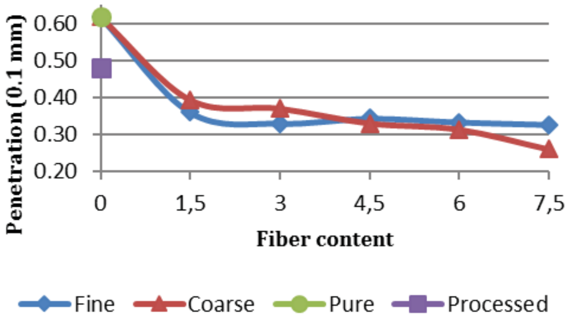

Fig. 1 Penetration of fiber modified asphalts versus fiber content

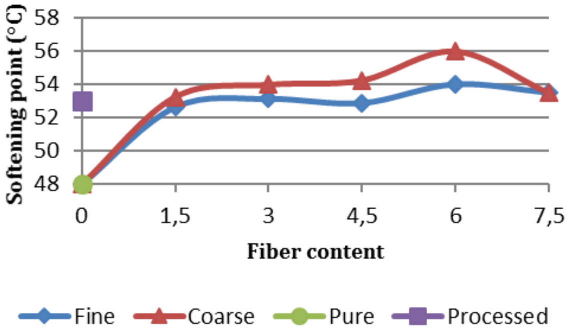

Fig. 2 Softening point of fiber modified asphalts versus fiber content

The graph of penetration for coarse fiber modified asphalt shows that the addition of fiber content causes noticeable gradual reduction in penetration. For the fine size, at 1.5% fiber content there is a sharp reduction in penetration compared to pure asphalt (about 42%), after that penetration does not change with increasing fiber content. The reduction in penetration due to the addition of both fiber sizes is about the same.

B. Rotational Viscosity

The viscosity at 135 ºC for pure, processed as well as fiber modified asphalts are shown in Fig. 3 and Table III. It can be seen from Table III that processing pure asphalt under the same blending conditions but without fiber increases its viscosity about 1.11 times. As with the softening point and penetration, there is a hardening caused by fiber addition. From Fig. 3, it can be seen that the viscosity of fiber modified asphalt gradually increases as the fiber content increases. The increase in viscosity of fiber modified asphalt is caused by both aging effect resulted from heating during processing, and stiffening effect resulted from fiber addition. The Superpave specification requires that the maximum viscosity of asphalt binder should be less than 3000 centipoises (cp) at 135 ºC for storage and pumping in construction period, Table III shows that the viscosity for all asphalt binders fulfilled Superpave specification requirement.

Fig. 4 shows the viscosity temperature chart for different fiber contents for both fiber sizes. The viscosity curves show an increase in viscosity with increase on fiber content over the entire temperature range from 135°C to 180 °C. Mixed results were obtained regarding ranking of the effect of fiber size on viscosity. At some percentages fine fibers have more effect while at others coarse fibers give more viscosities than fine. The increase in viscosity due to modification indicates that the fiber modified asphalts are expected to be stiffer than the pure bitumen at high service temperatures. Therefore, fiber addition is expected to reduce rutting potential of asphalt mixes.

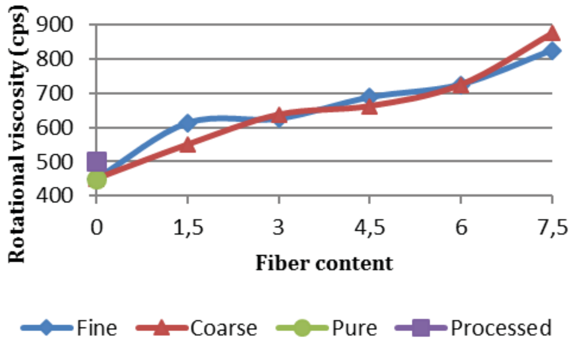

Fig. 3 Rotational viscosity at 135 °C for pure, processed and fiber modified asphalt as a function of fiber content

TABLE III
ROTATIONAL VISCOSITY AT 135 °C FOR PURE, PROCESSED AND FIBER MODIFIED ASPHALT AS A FUNCTION OF FIBER CONTENT.

Fiber Content	Pure	Processed	Fine fiber	Coarse fiber
0%	450	500	-	-
1.5%	-	-	612.5	550
3%	-	-	625	637.5
4.5%	-	-	687.5	662.5
6%	-	-	725	725
7.5%	-	-	825	875

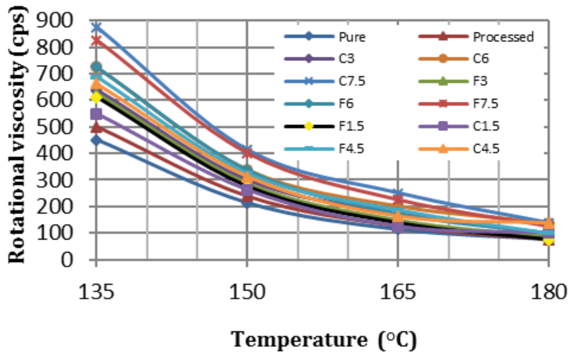

Fig. 4 Viscosity temperature chart for pure, processed and fiber modified asphalts

C. Complex Shear Modulus

The complex shear modulus for pure, processed and fiber modified asphalts are presented in Fig. 5. The figure presents complex shear modulus for unaged and RTFO aged blends as a function of fiber content at a temperature of 70 °C. For both aged and unaged binders, as the fiber content increase the blends becomes more stiff as measured by G*. It is clear that the effect of fibers content on stiffness depends on fiber size. It is observed that for unaged condition, fine fibers caused a greater G* than coarse fibers in all fiber contents. For aged condition there is no clear effect for fiber sizes on G*. The higher stiffness for fine fiber is most probably due to its higher surface area for a given weight of fiber which in turn consumes more asphalt to coat it, and thus tend to stiffen the binder more than coarse fiber.

As would be expected there is an increase in G* for RTFO aged blends compare to unaged blends, since they were exposed to heat at 163 °C and air for 85 minutes. Effect of fiber content on rutting parameter (G*/sinδ) at 70 °C can be seen in Fig. 6. The plots are similar to those seen for complex shear modulus trends. Fine fiber modified asphalts have higher G*/sinδ parameter values, which indicate higher rutting resistance than other blends.

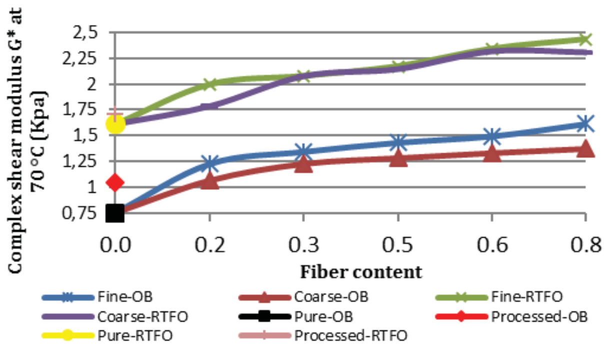

Fig. 5 Complex shear modulus versus fiber content

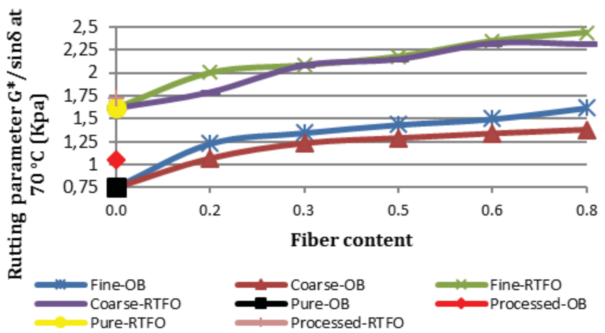

Fig. 6 Rutting parameter versus fiber content

Fig. 7 shows the failure temperature of fiber modified asphalts against percent of fiber. Failure temperature is the maximum temperature that meets the rutting criteria. Failure temperatures of fine fiber modified asphalts at unaged condition are higher than those for coarse fiber modified asphalts in each percentage of fiber content. The failure temperature was increased from 67.7 °C (pure asphalt) to 74.2 °C and 72.9 °C for fine and coarse fiber modified asphalts; respectively. In RTFO aging condition the addition of fiber increased failure temperature from 67.65 °C (pure asphalt) to 70.9 °C and 70.5 °C for fine and coarse fiber modified asphalts; respectively. There is no difference between the failure temperatures of fine and coarse fiber modified asphalts for 3% up to 6% fiber content.

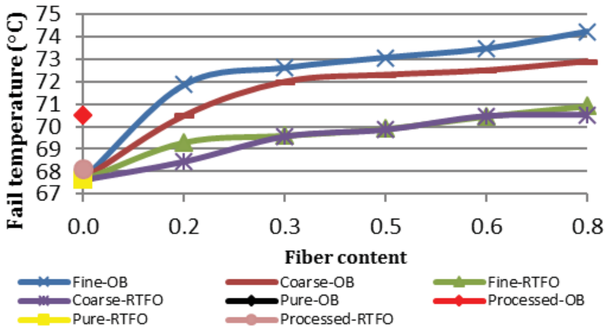

Fig. 7 Failure temperature versus fiber content

After comparing the obtained failure temperatures with superpave requirements, the pure, processed, and fiber modified asphalts were classified into performance grade (PG) categories as presented in Tables IV and V. It can clearly be observed that the pure asphalt is classified as PG 64 for both aged and unaged conditions. For unaged condition, asphalt processing without fiber is enough to satisfy the high temperature requirement of PG 70, and showed no enhancement by adding fiber content up to 7.5% stayed at PG 70. In RTFO condition, the fiber content of 6% for both fiber sizes is the lowest to satisfy the high temperature requirement of PG 70. Therefore, this content could be considered as an optimum fiber content for modified asphalt. Generally, the results indicate that the control sample which satisfies PG 64 can be modified and raised to PG 70 by adding 6% fiber content of fine or coarse fibers.

TABLE IV
HIGH TEMPERATURE GRADES (UNAGED CONDITION)

Binder Type	Fiber Content					
	0%	1.5%	3%	4.5%	6%	7.5%
Pure	PG 64	-	-	-	-	-
Processed	PG 70	-	-	-	-	-
Fine Fiber	-	PG 70	PG 70	PG 70	PG 70	PG 70
Coarse Fiber	-	PG 70	PG 70	PG 70	PG 70	PG 70

TABLE V
HIGH TEMPERATURE GRADES (RTFO AGED CONDITION).

Binder Type	Fiber Content					
	0%	1.5%	3%	4.5%	6%	7.5%
Pure	PG 64	-	-	-	-	-
Processed	PG 64	-	-	-	-	-
Fine Fiber	-	PG 64	PG 64	PG 64	PG 70	PG 70
Coarse Fiber	-	PG 64	PG 64	PG 64	PG 70	PG 70

VI. CONCLUSION

- Heating asphalt during fiber blending at 156 °C for 2 hours causes a hardening effect on binder as indicted by an increase in softening point, viscosity, and complex shear modulus, and a decrease in penetration compared to pure asphalt.
- The fiber modified asphalt binders have less penetration and more softening point compared to pure asphalt for all fiber percentages assessed.

- Fiber addition increased the viscosity of the binder significantly over the entire temperature range from 135°C to 180 °C.
- Fiber addition improved the rheological properties of asphalt binder, since the control sample which satisfies PG 64 can be modified and raised to PG 70 by adding 6% (by weight) of either fine or coarse fiber.

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