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Investigation of Rheological and Physical Properties of SBS and WCO Composite Modified Bitumen

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ABSTRACT

Nowadays, the use of waste materials in various industries is becoming widespread in order to promote waste recycling. Thus, scientists are researching the use of waste materials in bitumen modification. In this study, it was aimed to investigate the effect of waste cooking oil (WCO) on the physical and rheological properties of unaged Styrene-Butadiene-Styrene modified bitumen (SBSMB) by adding WCO at different ratios (1, 3, 5, 7, and 9%) to SBS modified bitumen. Accordingly, rotational viscosity (RV) tests and rheological tests with dynamic shear rheometer (DSR) based on the determination of complex shear modulus (|G*|) and phase angle (δ) were conducted along with the traditional bitumen tests. As a result of the experimental study, it was observed that adding WCO increased the workability and fatigue resistance of SBSMB, however, decreased its rutting resistance. Therefore, the mixing and compaction temperatures of SBSMB can be decreased by adding low amounts of WCO without excessive performance loss. Thus, during the construction of asphalt pavements, environmental damage can be reduced by utilizing waste materials and reducing CO_2 emissions.

Keywords: Styrene-butadiene-styrene, polymer modified bitumen, waste cooking oil, workability, rheology.

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1. INTRODUCTION

Styrene-butadiene-styrene (SBS) additive is the most commonly used polymer type in bitumen modification. When SBS is added to the base bitumen, the rutting, fatigue and stripping resistance as well as the elasticity and viscosity of the bitumen increase [1-6]. However, due to the increase in viscosity, the mixing and compaction temperatures of bitumen also increase [7]. Therefore, during application, energy consumption increases, additional costs arising to achieve the required workability, and the construction time is extended.

Warm mix asphalt (WMA) technology is widely used to eliminate the negative effect of SBS on the workability of bitumen. WMA additives can reduce the viscosity of Styrene-butadiene-styrene modified bitumen (SBSMB) and increase its workability [8, 9]. On the other hand, waste oils have a similar effect on bitumen. Regarding sustainability and environmental awareness, using waste oils as a bitumen modifier is more interesting than other additives. Accordingly, when the studies in the literature in which waste oils are used as a bitumen modifier were examined, it was seen that it is generally used as a rejuvenating or softening material [10-22].

Studies using waste oil with SBS are also available in the literature. However, the main goal in these studies was not to increase the workability of bitumen. Generally, waste oils were used as rejuvenators [23-25] or compatibilizers [26] of SBSMB. In addition, there are studies aiming to examine the effects of waste oils on fatigue life [27], aging resistance [28], and chemical and rheological properties [29-32] of SBSMB. In these studies, it was observed that some performance losses could be recovered by adding waste oils to aged bitumen. It was stated that it would be suitable for use in recycled asphalt pavements (RAP) applications [25]. In addition, it has been noted that adding waste oil can increase aging and fatigue resistance [27, 28, 33].

Waste oils are a broad concept and include various oil types such as bio-oil, waste engine oil, waste vegetable oil, and waste soybean oil. In this study, the oil used was the waste cooking oil (WCO) and it was subjected to filtration and dehydration processes. Besides, studies in which SBS and WCO were used together were also examined in the literature and it was observed that the number of studies was relatively low. In addition, in these studies, it was determined that the rejuvenation feature of WCO was especially benefited from [25, 28]. In other studies, involving SBS and WCO, other polymers were used in addition to SBS, and a composite modification was investigated [34, 35]. Thus, to the best of the authors' knowledge, there was no study to add WCO to increase the workability of an unaged SBSMB. Therefore, this study is aimed to close the relevant gap in the literature.

In this study, it was aimed to examine the effect of WCO additive added to increase the workability of SBSMB on physical and rheological properties. Accordingly, WCO was added to 5% SBSMB at the ratios of 1%, 3%, 5%, 7% and 9%, in addition to the studies in the literature, to comprehensively evaluate the effect of WCO on SBSMB on a wide scale. Then, penetration, softening point, ductility, Nicholson stripping, rolling thin film oven (RTFO), rotational viscosity (RV), and rheological tests were carried out. Thus, the workability, high-temperature performance, adhesion capacity, and aging resistance of the composite-modified bitumen were investigated.

2 MATERIALS AND METHODS

2.1. Materials and Sample Preparation

SBSMB, which has high resistance to rutting, has become increasingly common in Türkiye. SBSMB, which was prepared by adding 5% SBS by weight to 50/70 penetration grade base bitumen, was obtained from Isfalt Company. In addition, the company stated that the performance grade of SBSMB is PG76-16. The physical properties of SBSMB and limit values of these physical properties specified in the Highways Technical Specification [36] for modified bitumens are given in Table 1. From this table, it can be seen that the physical properties of SBSMB meet the specification limits.

Table 1 - Physical properties of the SBSMB.

Properties	Value	Specification limits	Specification
Penetration @ 25°C, dmm	35	25-55	TS EN 1426 [37]
Softening point, °C	65.5	≥60	TS EN 1427 [38]
Ductility @ 25°C, cm	100+	-	TS EN 13589 [39]
Specific gravity @ 25°C, g/cm^3	1.034	1.0-1.1	TS EN 15326 [40]
Flash point, °C	340	≥220	TS EN ISO 2592 [41]
Mass loss, %	0.23	0.8	TS EN 12607-1 [42]
Increase in softening point, °C	0.5	≤10	TS EN 1427 [38]
Retained penetration, %	91.4	≥45	TS EN 1426 [37]
Viscosity @ 135°C, cP	1850	-	ASTM D4402 [43]
Viscosity @ 165°C, cP	450	-	ASTM D4402 [43]

WCO was used as variable additive of the composite modified bitumen. The WCO used was obtained from Degam Company. This company collects WCOs from all over Türkiye and purifies them from pollutants, oxidant products, and particles. WCO, which had undergone these processes, was added to the SBSMB at different ratios (1%, 3%, 5%, 7%, and 9%) by weight of the SBSMB.

Table 2 - Physical properties of the aggregates.

Properties	Value	Specification
Volume specific gravity, g/cm^3	2.580	TS EN 1097-6 [44]
Apparent specific gravity, g/cm^3	2.645	TS EN 1097-6 [44]
Absorption, %	1.41	TS EN 1097-6 [44]
Polishing value	61.7	TS EN 1097-8 [45]

To prepare the composite modified bitumen samples, WCO was added to SBSMB samples at 150°C, as it is a material that can easily mix with bitumen, by using a mechanical stirrer at a rotation speed of 1000 rpm for 30 minutes. In addition, since it was predicted that composite modified bitumens may age due to the effect of temperature during the preparation process, the same mixing procedure was applied to the control sample (SBSMB). Then, the preparation of composite modified bitumens and control sample for testing was completed.

Basalt aggregates with dimensions between 4.75-9.50 mm were used to evaluate the adhesion between composite modified bitumen and aggregate. The physical properties of the aggregates are given in Table 2.

2.2. Methods Used to Evaluate Binder Performance

The penetration test is carried out to determine the hardness of bitumen samples at 25°C following the ASTM D5 [46] standard. An increase in the penetration value of a bitumen sample is an indication of its softening. Similarly, the softening point test can be used to determine the consistency of bitumen. In this test, ring and ball test apparatus conforming to ASTM D36-14 [47] standard is used. Bitumen sample is placed in the test apparatus and heated in a water bath at a heating rate of 5 °C/min. The temperature value when the bitumen-coated ball touches the bottom plate is recorded as the softening point.

Since bitumen is a thermoplastic material, it softens with an increase in temperature and hardens with a decrease in temperature. This behavior is called temperature sensitivity. The penetration index (PI) of a bitumen sample gives an idea of the temperature sensitivity of that sample. High PI values indicate that bitumen has low-temperature sensitivity. The PI value is calculated with the help of Equation (1):

$$PI = \frac{1952-500\times\log(Pen25)-20*SP}{50\times\log(Pen25)-SP-120} \tag{1}$$

where SP is the softening point temperature, and Pen25 is the penetration of the bitumen sample at 25 °C.

Ductility test carried out following the ASTM D113 [48] standard. In this test, a tensile force at a speed of 5 cm/min at 25°C is applied to the bitumen samples placed in certain molds, and the distance the samples can extend without breaking is measured. This distance is recorded in cm as ductility value.

RTFO test performed following the ASTM D2872 [49] standard. With this test, short-term aging of the bitumen is simulated. The mass loss is determined with the help of Equation (2). It occurs due to the loss of volatile substances in the bitumen samples due to high temperatures. It is thought that the higher this value, the more the bitumen will be affected by the short-term aging.

$$Mass\ Loss, \% = \frac{Unaged\ Mass-Aged\ Mass}{Unaged\ Mass} \times 100 \tag{2}$$

PAV test was performed according to ASTM D6521 [50] to simulate the long-term aging that bitumen is exposed to due to climate and oxidation effects during its service life. For this test, 50±0.5 g of bitumen was taken from RTFO-aged samples and placed in test vessels. Then, the samples were aged for 20 h at 100 ◦C under a pressure of 2.10 MPa.

The Nicholson stripping test is used to determine the resistance of bitumen against stripping. 100±0.5 g of crushed aggregate between 9.5-6.3 mm diameter is kept at 140-150°C for 1 hour. Then, approximately 5.0±0.1 g of bitumen is added to the aggregates and mixed until all aggregates are covered with bitumen. The prepared aggregate and bitumen mixture is transferred to petri dishes, and at least 3 cm height water is added and kept in an oven at 60°C for 24 hours. As a result, the separation of bitumen from the aggregate surface is determined visually in percent with the help of a light source.

RV test carried out following the ASTM D4402 [43] standard. With this test, information about the workability of bitumen can be obtained. According to the Superpave specification, the viscosity value of the bitumen sample obtained from the RV test should not exceed 3000 cP. It is also possible to determine the mixing and compaction temperatures at which bitumen will be used with the RV test. Accordingly, the viscosities of the samples were measured in the Brookfield DV2T rotational viscometer using spindle no #29 at 135°C, 165 °C, and 180°C temperatures. Then, results were marked on a graph and combined with a trend line. On this line, the temperatures corresponding to the viscosity values of 170±20 cP and 280±30 represent the mixing and compaction temperatures of the bitumen sample, respectively [51].

It is possible to examine the rheological properties of bitumen with various tests carried out using dynamic shear rheometer (DSR). Tests based on determining the complex shear modulus (|G*|) and phase angle (δ) of bitumen, carried out according to ASTM D7175, are one of these tests. Thanks to this test, information can be obtained about the resistance against rutting at high temperatures and fatigue cracking after repeated loading at intermediate temperatures of the asphalt pavement, which tested bitumen will be used. Unaged, RTFO or PAV aged bitumen samples are placed between two parallel plates of the DSR device that a controlled-strain testing mode was used and exposed to oscillating motion with a frequency of 1.59 Hz by the top plate. The diameter of the plates is 25 mm for unaged and RTFO-aged samples and 8 mm for PAV-aged samples. In addition, the gap between the plates is 1 mm for unaged and RTFO-aged samples, while this value is 2 mm for PAV-aged samples. After tests carried out with DSR, which are carried out under the specified conditions, the complex shear modulus (|G*|) and phase angle (δ) of the bitumen are determined. Its viscous and elastic behavior is characterized. |G*| is the indicator of the total resistance of the bitumen to deformation, while δ is defined as the phase difference between stress and strain. The |G*|/sinδ value obtained using the |G*| and δ values are the rutting resistance parameter of the bitumen. This value should be at least 1.00 kPa for unaged bitumen and at least 2.20 kPa for RTFOT aged bitumen. In addition, the |G*|·sinδ value is the fatigue resistance parameter of bitumen, and this value should not be more than 5000 kPa for PAV aged samples.

3. RESULTS AND DISCUSSION

3.1. Physical Properties of Modified Bitumen

The results obtained from the penetration and softening point tests are given in Figure 1. As seen in Figure 1(a), when WCO was added to SBSMB at the rates of 1%, 3%, 5%, 7%, and 9%, an increase of 48.5%, 125.7%, 240%, 322.9, and 414.3% was observed in the penetration value, respectively. Additionally, it is seen that when 1%, 3%, 5%, 7% and 9% WCO is added to SBSMB, the softening point value decreases by 5.11%, 6.71%, 10.76%, 14.19% and 17.25%, respectively. In parallel, the results of the two tests indicate that when WCO is added to SBSMB, a softening occurs with an increasing WCO ratio; in other words, the consistency of SBSMB decreases. In addition, it was stated in similar studies in the literature [24, 26, 28] that oils or waste oils increase the penetration value of SBSMB while decreasing the softening point.

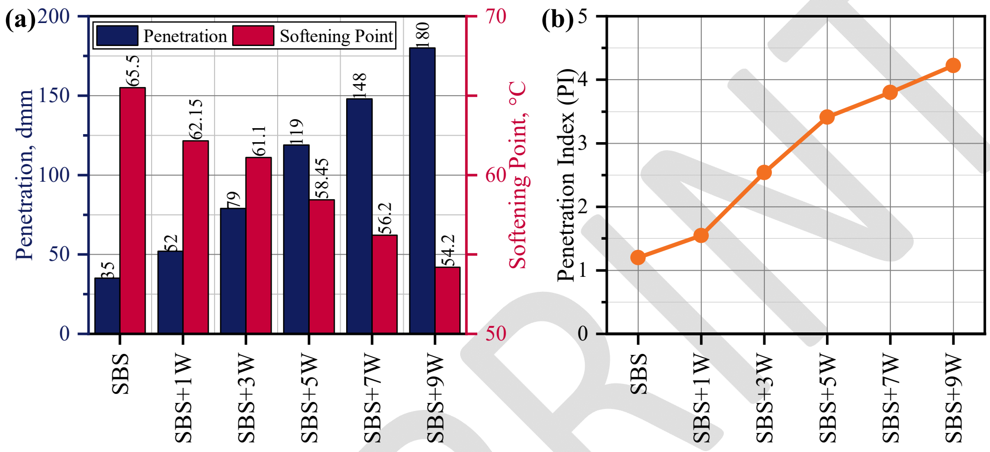

Figure 1 - Physical test results of the bitumen samples: (a) penetration and (b) penetration index (PI).

PI values were calculated with the help of Equation (1), and the results are given in Figure 1(b). When 1%, 3%, 5%, 7% and 9% WCO was added to SBSMB, an increase of 29.2%, 111.7%, 184.2%, 216.7% and 252.5% was observed in the PI value, respectively. These results show that the addition of WCO to SBSMB reduces the thermal sensitivity of SBSMB.

As a result of the ductility tests, no breaking was observed in any of the samples within a distance of 100 cm, which is the maximum tensile length of the test device. In other words, this shows that the ductility does not change or is not adversely affected by the addition of WCO to the SBSMB within the measurement limits of the test device. Cong et al. [28] reported that the ductility value increased with the addition of corn oil based WCO to base or SBSMB, and the ductility of bitumen containing WCO was greater than 100 cm. In another study, it was stated that the ductility of bitumen containing waste bio-oil and SBS was higher than that of SBS modified bitumen [26].

3.2. Short Term Aging

Mass losses of the samples were determined after RTFO tests carried out to examine the level of exposure of bitumen samples to short-term aging after mixing and compaction processes in asphalt pavement construction. The percent mass losses obtained are shown in Figure 2. When Figure 2 is examined, it is seen that all modified bitumen samples exhibit a mass loss of less than 1%, which is the upper limit of the ASTM D6373 [53] standard. This indicates that all samples can perform in the pavement after short-term aging without critical disadvantage. In addition, with the addition of 1%, 3%, 5%, 7% and 9% WCO to SBSMB, the mass loss values decreased by 26.08%, 39.13%, 39.13%, 43.47% and 52.17%, respectively. These results show that the addition of WCO to SBSMB can increase the resistance of SBSMB to short-term aging. Similar to these results, in a previous study by Kumandaş et al. [54], it was determined that the aging resistance of modified bitumen increased with WCO addition.

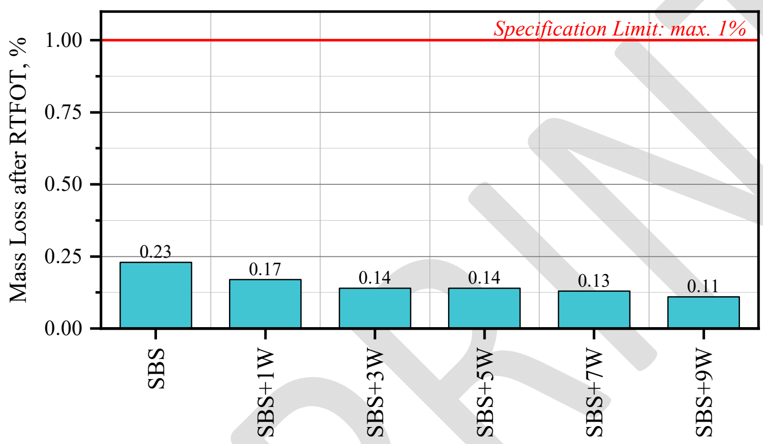

Figure 2 - Mass losses after RTFO test.

The results obtained by applying penetration and softening point tests to short-term aged bitumen samples are shown in Figure 3(a). When this figure was examined, it was observed that the obtained values increased for softening point values and decreased for penetration values after short-term aging compared to unaged bitumen samples. In order to obtain more detailed information about this hardening phenomenon caused by aging, the softening point differences (ΔS) and retained penetration percentages are determined and given in Figure 3(b). Although an increase in aging resistance was observed with the increasing amount of WCO according to the mass loss percentages, a similar relationship could not be observed for softening point difference values and penetration decrease percentages. Especially, in terms of penetration decrease percentages, SBSMB was least affected by hardening in the RTFOT effect, with 8% penetration decrease. On the other hand, it was determined that there was a decrease in the penetration values of bitumens containing WCO, varying between 24.4% and 38.7%. It is thought that this result cannot be attributed to bitumens containing WCO being more affected by aging compared to SBSMB. Regardless of the additive, a softer bitumen can be expected to harden more after aging than a bitumen with less penetration. In other words, SBSMB has already largely completed its hardening by modifying the base bitumen with SBS. Since SBSMBs containing WCO are much softer compared to SBSMB, they were more affected by the decrease in penetration after RTFOT. However, it can be said that this is due to the softness of the bitumen rather than the effect of WCO on aging. For this reason, it is thought that the percentage of penetration decrease in SBSMBs with and without WCO may not be a suitable indicator for resistance to aging.

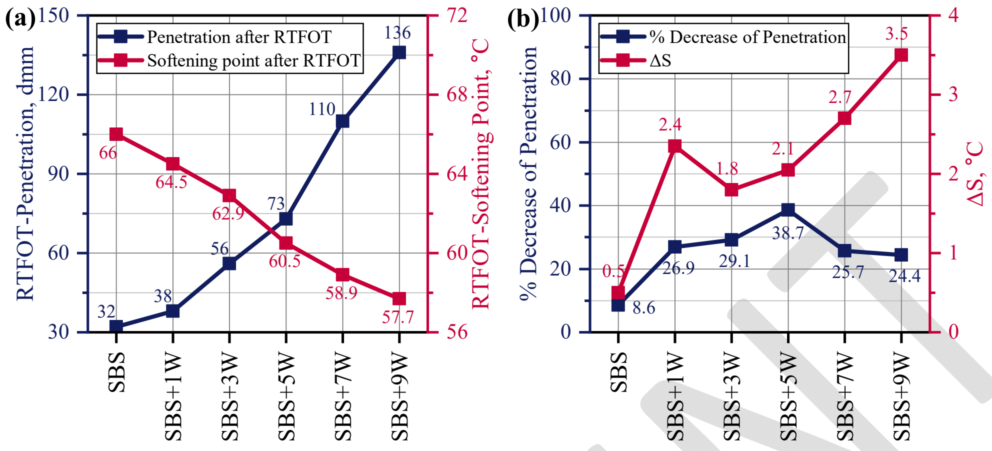

Figure 3 - Test results after RTFO: (a) penetration and softening point, and (b) decrease of penetration and difference in softening point.

3.3. Interaction Between Bitumen and Aggregate

The results from the Nicholson stripping tests are given in Figure 4 and Figure 5. When 1%, 3%, 5%, 7%, and 9% WCO was added to SBSMB, the Nicholson stripping ratios were 87.5%, 90%, 90%, 92%, and 94%, respectively. As can be understood from these results, the

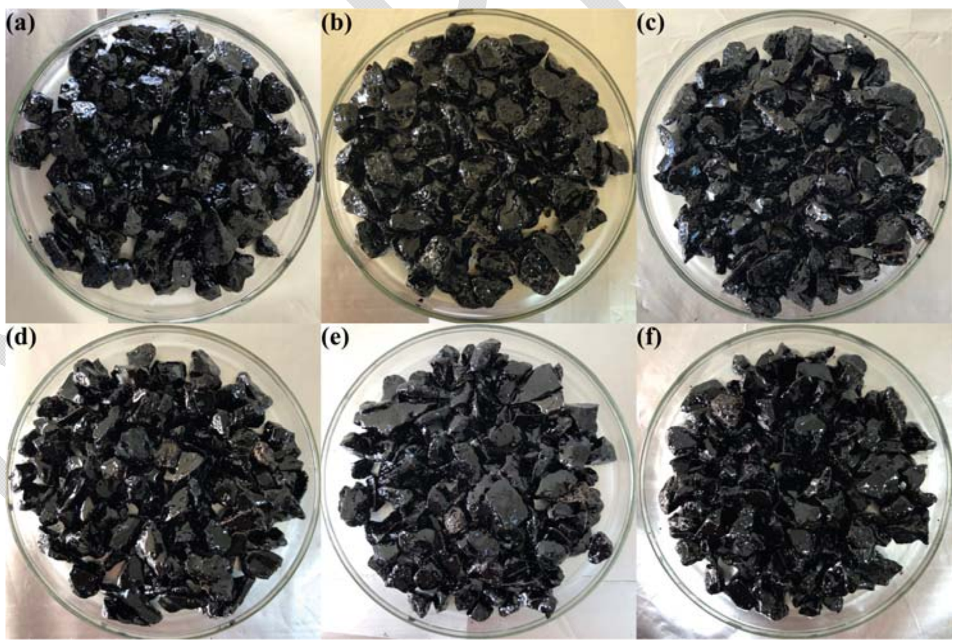

Figure 4 - Images of the samples after the Nicholson stripping test: (a) SBS, (b) SBS+1W, (c) SBS+3W, (d) SBS+5W, (e) SBS+7W, and (f) SBS+9W

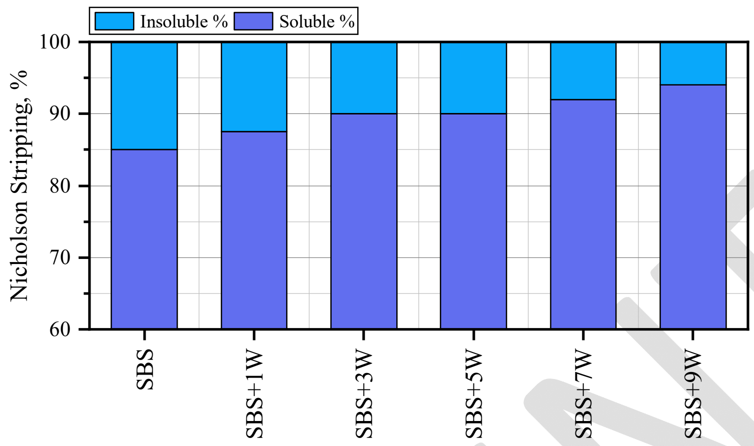

Figure 5 - Nicholson stripping test results.

adhesion of SBSMB with aggregate increased with the increasing amount of WCO. SBSMB already has high cohesion and interacts strongly with the aggregate. On the other hand, the addition of WCO softens the SBSMB, helping it to spread more easily on the aggregate surface. Thus, WCO enables the adhesion-enhancing effect of SBS to show in a larger surface area of the aggregate.

3.4. Impact of the WCO on the Workability of SBSMB

The results of RV tests conducted at 135°C are shown in Figure 6(a). When Figure 6(a) is examined, it is seen that all samples have a viscosity lower than the upper limit of the specification [53]. According to these results, it is predicted that all samples will not pose a problem in terms of mixability and compactibility.

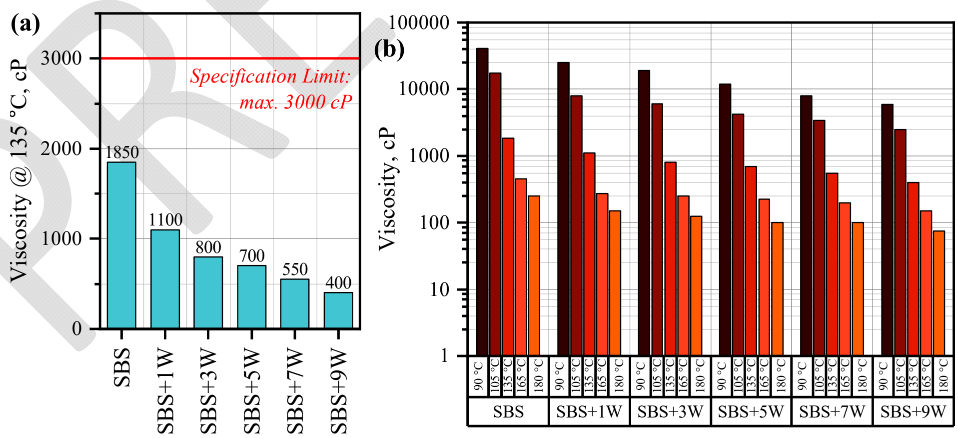

Figure 6 - Results of RV tests: (a) comparison with the specification limit at 135°C, and (b) viscosity values at different temperatures between 90 °C and 180 °C.

To better understand the viscosity-temperature behavior of the samples, the results of the RV tests carried out in a wide temperature range (90°C, 105°C, 135°C, 165 °C, and 180°C) are shown in Figure 6(b). As shown in this graph drawn on the logarithmic axis, SBSMB has the highest viscosity values, and SBS+9W has the lowest viscosity values at all temperatures. Similar to these results, Sun et al. [30] added WCO based bio-oil to SBS modified bitumen in their study and stated that the viscosity of SBS modified bitumen decreased in parallel with increasing bio-oil addition. In another study by Cong et al. [28], it was emphasized that the viscosity of the control asphalt gradually decreased with increasing WCO based bio-oil addition. In addition to the findings in the literature, it was determined in this study that the addition of WCO increased the workability of unaged-SBSMB.

The percentage changes in the viscosities of the samples were determined according to the results of the RV tests and shown in Figure 7. Especially when looking at the data in the temperature range of 135-165°C on this figure, it is seen that the percentage change in the viscosity of SBSMB is higher than the other samples. This result indicates that in parallel with the PI results, SBSMB is more affected by the heat change than the other samples, and this effect rate decreases with increasing WCO addition. In other words, SBSMB has the highest thermal sensitivity, and SBS+9W has the lowest thermal sensitivity among the tested samples.

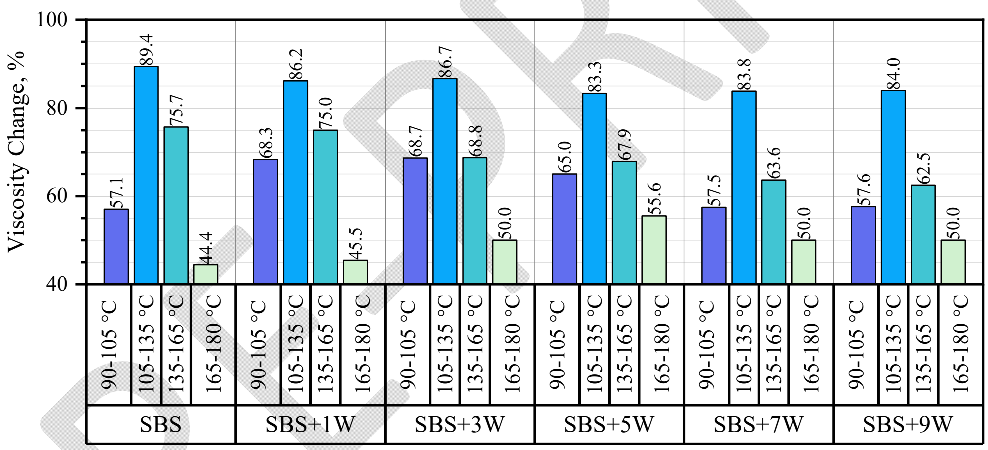

Figure 7 - Percentage change of viscosities.

In addition to the tests carried out on the viscosities of the samples, the results from the RV tests at 135°C, 165 °C, and 180°C were placed on a logarithmic axis and combined with a trend line (Figure 8(a)). This trend line was used to determine mixing and compaction temperatures of the samples and the results are shown in Figure 8(b). In this figure, the average of the temperatures corresponding to 170±20 cP is given as the main mixing temperature. Similarly, the average of temperatures corresponding to 280±30 cP is stated as the mean compaction temperature. Additionally, the lower and upper limits of mixing and compaction temperatures are shown on the graph with error bars. When Figure 8(b) is examined, it is understood that the mean mixing and compaction temperatures of SBSMB are approximately 186 and 177.8°C, respectively. Although this result is generally encountered in polymer-modified bitumen, it can create an economic disadvantage by increasing the energy consumed during construction and increase the damage to the environment by increasing carbon emissions. When WCO is added to SBSMB, it is seen that there is a significant decrease in mixing and compaction temperatures. Especially in the WCO+9W sample, the mixing and compaction temperatures decreased to 162.6°C and 149.4°C, respectively. This result indicates that the addition of WCO can both provide significant savings in terms of energy consumption and play a critical role in reducing the amount of carbon released to the environment.

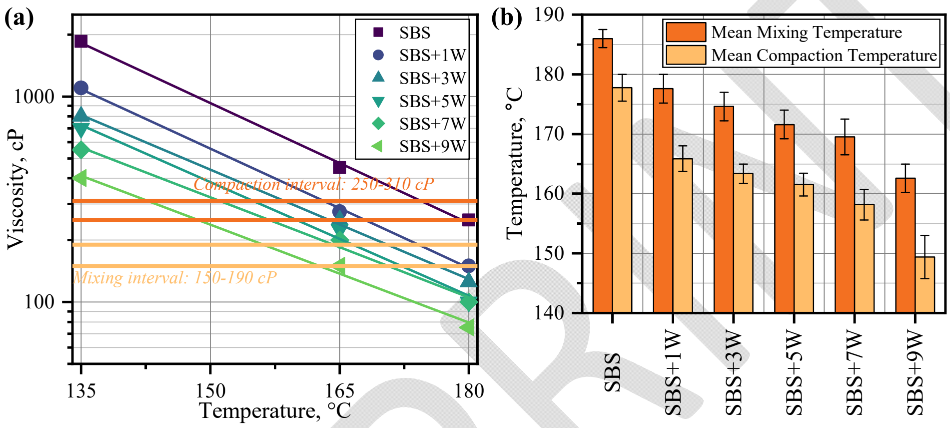

Figure 8 - Determination of mixing and compaction temperatures: (a) limit temperature intervals, and (b) mean mixing and compaction temperatures.

3.5. Rheological Behavior of SBS+WCO Modified Bitumen

|G*| and δ parameters obtained from tests conducted with DSR are shown in Figure 10(a) and Figure 9(b), respectively. As seen in Figure 9(a), there was a decrease in |G*| values with both increasing temperature and increasing WCO ratio. While the decrease occurring with the increase in temperature is due to the nature of the bitumen itself, the decrease occurring with the increasing additive ratio is an indicator of the softening effect of WCO. Additionally, when Figure 9(b) is examined, it is seen that the phase angles also decrease with WCO addition. However, there is no clear trend between the increase in the WCO ratio and the decrease in phase angle; the highest decrease occurred at 7% WCO and the lowest decrease occurred at 3% WCO. Therefore, it was not possible to make a definitive judgment regarding the effect of WCO addition on the elasticity of SBSMB based on phase angle values. |G*|/sinδ rutting parameters of all samples are given in Figure 10(a). Similar to |G*| values, increase in temperature and WCO ratio decreases |G*|/sinδ values of the samples. It has been shown in many studies that waste oils adversely affect the rutting resistance of bitumen [17, 26, 30, 31, 35]. Similar results with the literature are obtained in this study. On the other hand, all samples at 64°C, all samples except SBS+9W at 70°C, and all other samples except SBS+7W and SBS+9W samples at 76°C met the 1.0 kPa rutting resistance specification limit value. Additionally, continuous grades (CGs) of all samples are given in Figure 10(b). CGs of all samples, determined by finding the temperature at which they meet the specification value. As seen in Figure 10(b), increasing the WCO ratio caused a decrease in the CG values of

SBSMB. These results show that the addition of WCO causes a decrease in the rutting performance of SBSMB. For this reason, rutting performance should be considered as critical parameter when selecting the WCO ratio to be added to SBSMB. If WCO is to be added to SBSMB on roads with high density or heavy traffic, it would be appropriate to choose low ratios such as 3% and 5% to avoid loss of performance.

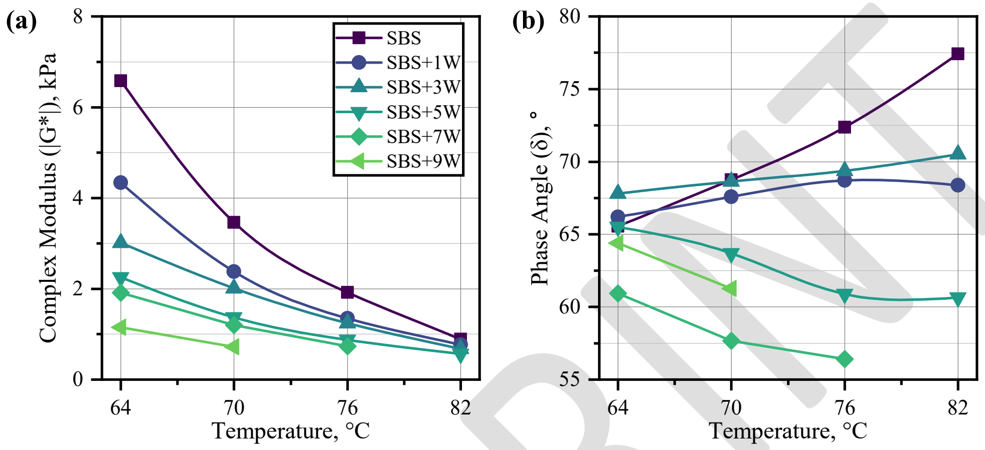

Figure 9 - Unaged samples: (a) |G| values, and (b) phase angles.*

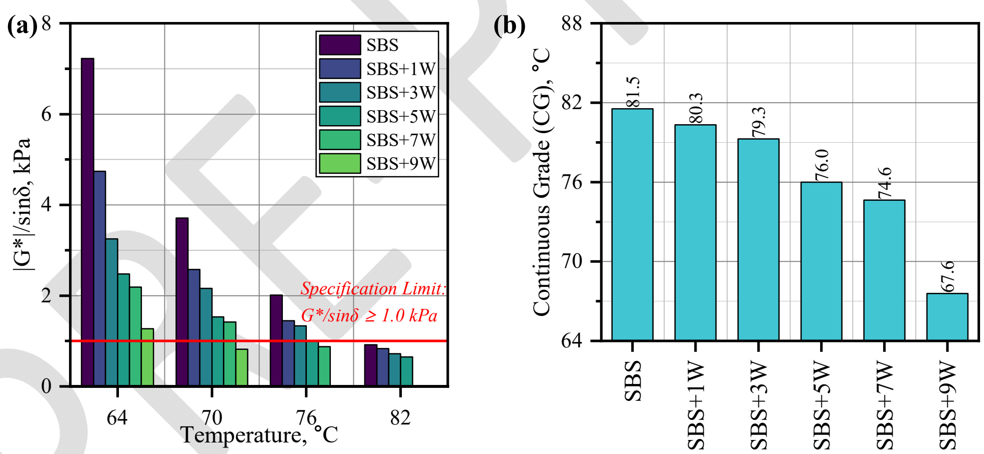

Figure 10 - Unaged samples: (a) Rutting performance, and (b) continuous grades.

The |G*| and δ values of the RTFO-aged samples are shown in Figure 11(a) and Figure 11(b). It is seen that |G*| values decrease with increasing temperature and additive ratio, similar to the results obtained from unaged samples. On the other hand, when Figure 11(b) is examined, it can be said that increasing temperature increases the phase angle values. This is an expected result due to the nature of bitumen. However, it was not possible to talk about a clear trend regarding the effect of WCO addition on the phase angle.

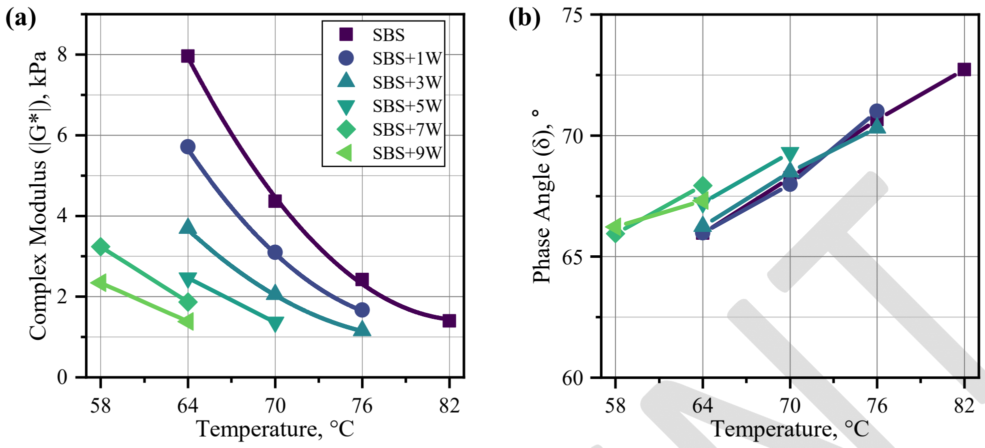

Figure 11 - RTFOT aged samples: (a) |G*| values, and (b) phase angles.

ASTM D6373 [53] standard recommends using RTFO-aged samples to evaluate rutting performance. |G*|/sinδ and CG values of the RTFO-aged samples are given in Figure 12(a) and Figure 12(b), respectively. When Figure 12(a) is examined, it is seen that the specification limit of 2.2 kPa is met by SBS, SBS+1W, SBS+3W, and SBS+5W samples at 64°C, SBS, SBS+1W SBS+3W samples at 70°C and only SBS samples at 76°C. On the other hand, when Figure 12(b) is examined, it is observed that there is a decrease in CG values with the addition of WCO, similar to the unaged samples. However, the results obtained from RTFO-aged samples are lower temperatures compared to the results obtained from unaged samples. This shows that RTFO-aged samples reached the specification limit earlier. Therefore, if WCO is to be added to SBSMB in the application, RTFO values of RTFO-aged samples must be considered.

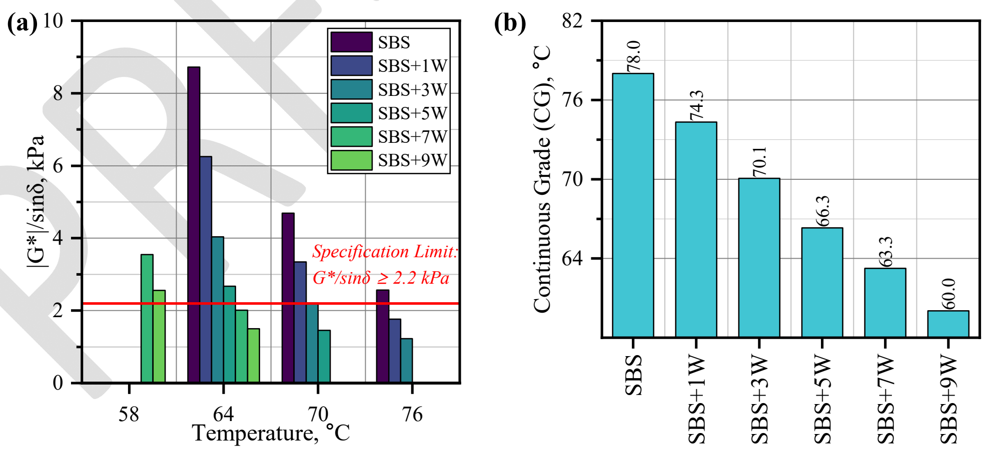

Figure 12 - RTFOT aged samples: (a) Rutting performance, and (b) continuous grades.

|G*|·sinδ parameters of the PAV-aged samples at intermediate temperatures are given in Figure 13. As can be seen from the Figure 13, samples did not exceed the specification limit of 5000kPa at all temperatures. It is seen that the |G*|·sinδ value decreases with the increase in the amount of WCO added. These results indicates that WCO increases the fatigue resistance of SBSMB. This positive effect of WCO on fatigue resistance is consistent with the results of previous studies. In a study by Mollamohammadi and Hesami [25], it was determined that composite WCO consisting of soybean, rapeseed, palm, and sunflower oils significantly improved fatigue performance. In addition to the findings in the literature, in this study, it was found that the addition of WCO increased the fatigue resistance of unaged-SBSMB.

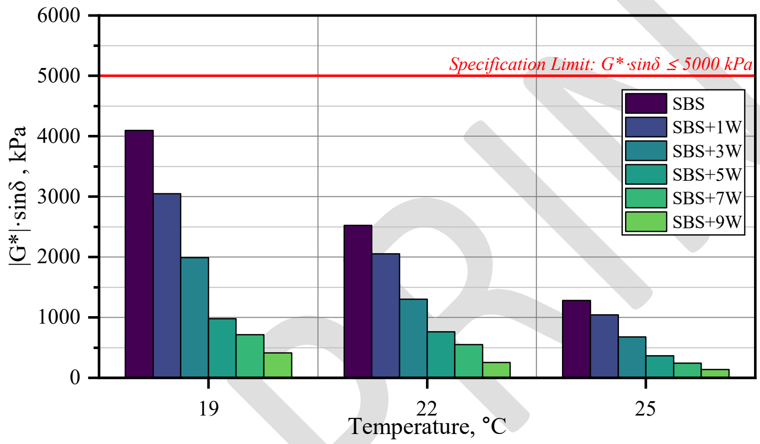

Figure 13 - Fatigue parameter values of PAV-aged samples.

As mentioned above, the findings obtained from the tests carried out with DSR show that WCO increases the fatigue resistance of SBSMB while reducing the rutting resistance. Examining the effect of WCO on rutting and fatigue resistance of SBSMB with MSCR and LAS tests, respectively, may provide more reliable results. However, since this study mainly focuses on examining the workability of SBSMB, further studies may contribute to the literature by comprehensively examining the effect of WCO on the rutting and fatigue resistance of SBSMB with MSCR and LAS tests, respectively.

4. CONCLUSIONS

In this study, unlike the existing studies in the literature involving SBS and WCO, WCO was used as flow improver in unaged SBSMB. In other words, this study was carried out to increase the workability of unaged-SBSMB with the addition of WCO rather than the use of WCO as a rejuvenator or a fatigue resistance enhancer in SBSMB. In this context, 1%, 3%, 5%, 7%, and 9% WCO was added to 5% SBS modified bitumen (SBSMB) and the physical and rheological properties of the obtained composite modified bitumen were investigated by experimental methods. The results obtained from the tests carried out in this direction are summarized below:

- When the physical properties of composite modified bitumen are examined, it can be said that the consistency and thermal sensitivity of SBSMB decrease with the addition of WCO.
- When the stripping resistance of the composite modified bitumen and aggregate mixture was examined, the stripping resistance of SBSMB improved with the addition of WCO.
- The results from the RV tests showed that the workability of SBSMB was significantly improved with the addition of WCO. With the addition of 9% WCO, the mixing and compaction temperatures of SBSMB decreased by 13% and 16%, respectively.
- When the rheological behavior of composite modified bitumen was examined, it was observed that while the rutting resistance of SBSMB decreased with the addition of WCO, the fatigue resistance increased. In addition to these results, the resistance of SBSMB to short-term aging improved with the addition of WCO.

Adding WCO to unaged-SBSMB can contribute to environmental health by increasing workability, reducing carbon emissions during asphalt pavement construction, and promoting waste materials in different areas. In addition, it can also be economically beneficial by lowering energy consumption during construction. Finally, WCO can soften the SBSMB and enable the bitumen to better envelop the aggregate. Thus, the increase in adhesion between the bitumen-aggregate can positively affect the stripping resistance of the pavement. In future studies, it is thought that it will be helpful to determine the performance of SBS+WCO composite modified bitumen at low temperatures and the properties of asphalt mixture samples to be prepared with this bitumen.

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