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ORIGINAL PAPER

Green and sustainable production of waste styrofoam-modified bitumen: a laboratory-based investigation on physical, rheological properties, and storage stability

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Abstract

The motivation of this study was to investigate the feasibility of production of green and sustainable bitumen modified with waste styrofoam (WS) that contributed to the base bitumen in certain rate. To achieve it, not only basic but also rheological properties and storage stability of WS-modified bitumen were taken into consideration. In this respect, bitumen with 70/100 penetration grade was modified with WS in different rates ranging from 1 to 5% with 1% increment. Basic test methods including penetration, softening point, rotational viscometer were conducted on the bitumen samples to analyze physical properties, while dynamic shear rheometer and bending beam rheometer tests were performed on the samples for rheological assessment. Rolling thin film oven and pressure aging vessel tests, which are aging methods in rheological evaluation, were followed to supply short- and long-term aged samples, respectively. Storage stability test was conducted on the modified samples to determine the compatibility between the two materials at different contribution WS rates. The results showed that significant changes occur on both physical and rheological properties of WS-modified bitumen. Compatibility between WS and bitumen was not observed except of the bitumen modified up to 2% WS as examined with softening point, but up to 3% WS as examined with penetration test. Overall, disposal of WS within bitumen modification can be a green and sustainable as considering the ecological and economic aspects.

Keywords Bitumen · Modification · Waste styrofoam · Green production · Sustainability

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Introduction

Bitumen is a kind of by-product extracted from the heaviest fraction of crude oil. It has a complex chemical structure that consists of a mixture of hydrogen, carbon, oxygen, sulfur and other metals. However, its components can be characterized under four general groups, which are saturate, aromatic, resin, and asphaltene (SARA) [1, 2]. Bitumen is widely used in flexible pavement construction due to their certain technical aspect including waterproofing, binding and viscoelastic properties. Although, the contribution rate of bitumen used in flexible pavements construction is lower than 8% by weight in general; it takes a significant role on both functional and structural performance of them. However, significant raise in the traffic loads and volume of heavy axles cause permanent damage to pavements [3–5]. Inability of traffic flexible pavements to bear such heavy loads at high temperatures drives researcher to seek solutions that can decrease the temperature and stress sensitivity and therefore improve some physical, rheological, chemical properties of them. The solutions highlighted by researchers focused on modification bitumen with various additive including fabricated ones for commercial purpose or the waste materials emerged following usage [6–8]. Because, the properties desired in bitumen are generally being resistant against rutting and cracking, having a good durability and low-temperature resistance for a long-lasting and sustainable road construction [9, 10].

Sustainable practices is essential in today world, where the natural resource provides a safe environment for all living-beings and support human-being economic activities [11–13]. Consuming significant amount of energy, emerging greenhouse gas is encountered due to economic activities [14], which increases in daily basis with increase in population [15, 16]. Fortunately, it is possible to reduce usage of energy in economic activities, and therefore, the emerging greenhouse gases released into the air by advanced technology [17], and certain amount of waste are emerged following economic activities. Wastes are valuable and versatile materials, and wastes can be not only economical sources but also significant acquirements by means of environment, human health, and aesthetic concern [18]. There are numerous kinds of waste sources including residential [19], industrial [20], commercial, institutional [21], constructional [22], clinical [23], and agricultural origin [24]. All mentioned waste could be in the form of solid, liquid and gas.

Plastics are one of fabricated materials that has long-chain polymeric molecules [25]. They are versatile material, and their use has dramatically increased due to the excellent properties that provide certain benefits by means of societal health, safety, and energy [26]. There are two principal kinds of plastic: thermoplastic and thermoset. Thermoplastics are the ones that can be molded repeatedly on heating, for example, high and low density polyethylene (PE), polyethylene terephthalate (PET), polypropylene (PP), polyvinyl chloride (PVC) and polystyrene (PS), expanded polystyrene (EPS). The other that is thermoset ones cannot be heated and remolded, for example, polyurethane (PUR) and epoxy resins or coatings [27]. The excellent properties of a wide range of plastics have opened many new opportunities including lightweight packaging, agricultural fields for improved crop production, cosmetics, detergents, and more advanced applications, among many others [28]. However, more than one-third of the entire mass of plastics produced globally is used to make packaging, which typically is not recycled, but ends up as waste [26, 27, 29].

Recycling and/or recovering of waste materials is one of recent popular task interested in by many researcher [30, 31]. The reason can be linked with the decrease in natural resources beside of environmental and economic concerns [32]. Unfortunately, it is impossible to degrade the plastics readily in the ambient environment. But the easy way to dispose the waste is burning, which need higher heat sources for melting. However, toxins such as carbon black and carbon monoxide, which are hazardous for living-being and environment health, are released to the atmosphere during the disposal process [30, 33]. On the other hand, degradation of them in the ambient environment takes long time that may be more than a few hundred year [34]. For this reason, environmental pollution from plastics has been as an important problem all over the world [29]. Approximately, 50 million metric tons of plastic waste emerges, globally [35], and only 14% of all plastic is collected for recycling or recovering. Unfortunately, the rest is deposited in the ground and stored in the depths of the oceans [36] and/or disposed by burning [37]. However, such methods rather than recycling and/or recovering cause series hazard to the environment and living health and habitat. Some hazardous impacts of plastic pollution may include the changes to carbon and nutrient cycles; habitat changes within soils, sediments, and aquatic ecosystems; co-occurring biological impacts on endangered or keystone species; eco-toxicity; and related societal impacts [38].

Styrofoam, known also technically as expanded polystyrene (EPS), such as other plastic is commonly manufactured from fossil fuels and formed with styrene monomers [33]. It is widely preferred in the packaging and food industries due to lightweight mainly, in various construction facilities thanks to heat and acoustic insulation properties, protecting any items considered for commercial purpose, marketing and some domestic applications due to durability properties [39]. Moreover, common use of EPS may be listed as loose foam packaging, food containers, plastic tableware, disposable cups, plates and cutlery, boxes for compact discs and cassettes [27, 40]. Considering its wide range of uses, significant amount of their wastes are generated in daily life [41].

The use of synthetic plastic materials such as EPS and its derivatives has increased considerably during the pandemic of coronavirus 2019 disease and accordingly their waste [42]. Waste of EPS can degrade in ambient environment throughout a long period. However, it can be burned as exposed to high temperatures for disposal. In this way, certain greenhouse gas releases into air during the process [43]; fortunately, it can be recycled or recovered for a specific purpose owing to some superior properties of such plastics and waste of them. Being recycled make them a valuable and versatile source for especially, in different engineering applications. The list of applications can be given in concrete [44], bitumen [45], soil improvement applications [46] as well as using as potential air filter media [47] in nanofiber technology and as a sorbent and absorbent cleanup impurity in water [48, 49]. Among the other, using the waste EPS in bitumen as modifier due to their thermoplastic properties is the common one focused on by researcher recently.

A brief literature review

In the scope of this study, the waste EPS, called in this study at the following as waste styrofoam (WS), used as a modifier to in bitumen by means of sustainable applications. As surveying the recent and earlier studies, it can be seen that there is limited number of study. To highlight the effect of WS used as a modifier into bitumen and/ or hot mix asphalt (HMA) on physical, rheological and mechanical properties of them, it is worth to introduce some of available studies briefly in the current study.

Nassar et al. [50] mentioned that WS contribution rate is one of leading factors on enhancing the physical and mechanical properties of bitumen and functional and structural performance of pavement as used in HMA production. Fang et al. [51] indicated the improvement in viscoelastic characteristics of bitumen at the end of bitumen modified with Baker et al. [52] modified bitumen with WS in three different rates (5, 10, and 15% by weight of bitumen), and they implied that an increase in WS caused a decrease in ductility and penetration, while increase in flashing and fire points. Al-Haydari and Masued [53] investigated the mechanical properties of HMA produced with WS-modified bitumen and remarked that there is significant improvement in mechanical properties of performance of HMA. Vila-Cortavitarte et al. [54] aimed to investigate the changes in HMA while adding three different types of polystyrene wastes including that of including general-purpose polystyrene, high impact polystyrene, and polystyrene from hangers to asphalt concrete to substitute bitumen. Throughout the study, each sample was tested separately for comparison purposes, so that the addition of waste polystyrene was found to modify several mixture properties, which were found as an increase in voids content and a significant decrease in plastic deformations, whilst other characteristics remained stable. Moreover, a life cycle assessment was determined for comparison of their environmental performance with that of conventional HMA. The highlighted result was that substituting part of the bitumen by polymers might reduce the environmental impacts of asphalt mixtures, taking into account the expected increase in their lifecycle provided by the presence of plastics. Nciri et al. [55] analyzed the performance of HMA produced with WS-modified bitumen, and similar results were indicated by them as mentioned for previous study. Ramadan et al. [33] investigated the rheological properties of bitumen modified with different rates of WS. They reported that WS modification improved bitumen rheological properties, especially rutting resistance, on basis of stiffness characteristics of itself. Mahida et al. [39] investigated the potential use of the PS waste in base bitumen with different proportions between 0.5% and 2.0% by weight of bitumen and characterized the modified bitumen and HMA properties through some conventional, rheological tests, and Marshall stability tests, respectively. The test results indicated that the PS-modified bitumen and HMA produced with the modified bitumen satisfied the requirements and showed significant improvement as compared to the ones manufacture with conventional binder.

Motivation and scope

The studies that introduced briefly as seen above give important insights into the effect of WS addition on bitumen properties. The available studies mostly focused on the changes in bitumen physical properties and the HMA characteristic, but rarely focused on the rheological properties of the WS-modified bitumen properties, especially based on both the short- and long-term aging cases. This is only the one case that motivate the author to establish this study. However, the main scientific gap that was determined from the earlier studies was that the absence of any studies on investigation of the compatibility between the two materials. As mentioned before, the studied materials are in the same origin, but having different characteristic. Moreover, there is the absence of any studies on determination proper contribution rate of WS in bitumen providing long-term stability during storage at high temperature, since it is expected that the two different materials show certain differences in physical, chemical, and mechanical properties [56–60]. In order to fill this gap thought as an important gap, the current study was established.

In the scope the study, investigations were constructed on 70/100 penetration grade base bitumen modified within different rates ranging from 1 to 5% by weight of bitumen with 1% increment. Some basic physical tests, known also conventional tests including penetration, softening and rotational viscometer and rheological tests including dynamic shear rheometer (DSR) and bending beam rheometer (BBR) were implemented on each studied samples. Aging processes required in rheological assessment under Superior Performing Asphalt Pavements (SuperPAVE) grading system were provided by rolling thin film oven (RTFO) and pressure aging vessel (PAV) to gather short- and long-term ageing cases, respectively. Compatibility between the bitumen and WS with each other following modification done in different rates was analyzed with storage stability test. The evaluation for the compatibility analysis was done on basis of two specified test, softening point and penetration test.

Materials

In the scope of this study, the bitumen sample with 70/100 penetration grade bitumen was supplied from Kırıkkale Refinery, Turkey. The basic properties of bitumen including penetration [61], softening point [62], ductility [63] flashing point [64], and viscosity [65] were determined with a series of test, and Table 1 presents the test results. The WS samples were supplied from waste containers, and some physical and chemical properties of WS are presented in Table 2.

To distinguish the sample results with each other in the figures and/or tables, it is worth to describe an abbreviation code for modified bitumen samples throughout the study. The samples codes were identified with the following system.

- BB: Base bitumen;
- WS-X: Waste Styrofoam modified bitumen;
- BBS: Short-term aged base bitumen;

Table 1 Fundamental properties of bitumen samples

Tests	Standard	Unit	Results
Penetration	EN 1426	dmm	74
Softening point	EN 1427	°C	44
Ductility at 10 °C	EN 13,589	cm	76
Flashing point	ISO EN 22,592	°C	305
Viscosity at 135 °C	ASTM D4402	cP	563.3
Viscosity at 165 °C			160.0

Table 2 Fundamental properties of WS

Order	Physical parameters	Unit	Results	Chemicals	Unit	Results
1	Molecular weight	g/mol	~ 300,000	Carbon	wt.%	94.64
2	Density	Kg/m^3	12.1	Hydrogen	wt.%	5.06
3	Thermal conductivity	W/mK	0.033	Nitrogen	wt.%	0.51
4	Flexural strength	N/cm^2	24	Sulfur	wt.%	0.01
5	Compressive strength	N/cm^2	10	Oxygen	wt.%	0.29

- BBS-XS: Short-term aged waste Styrofoam modified bitumen;
- BBL: Long-term aged base bitumen;
- BBS-XL Long-term aged waste Styrofoam modified bitumen,

where X is the rate of waste styrofoam in percentage numerated as 1, 2, 3, 4, and 5.

Experimental processes

The test methods used for determination of some basic physical properties of bitumen were determined by penetration, softening point, viscosity at 135 °C and 165 °C. DSR based test was conducted on each base and modified samples in case of unaged, short-, and long-term aging, while BBR based test was implemented on long-term aged samples residue. Storage stability test, which is an important method to evaluation compatibility between the modifier and bitumen, was performed on each unaged modified bitumen samples. The test methods mentioned in the scope of this study are presented in brief in this section.

Physical test methods

Penetration test

The test is applied on the bitumen samples to determine bitumen consistency. The test is done under a certain load (generally, 100-g) and temperature (25 °C) by utilizing a specific needle for 5 s. In this study, EN 1426 standard [61] was followed to conduct the test on samples.

Softening point test

The test is performed on bitumen samples to identify heating temperature making bitumen flow without sacrificing its chemical structure. The test apparatus consists of two certain sized rings, weighted steel balls, magnetic heater to provide elevated and homogeneous temperature condition, and a graded temperature. EN 1427 [62] was followed to apply the test throughout the current study.

Viscosity test

The test is conducted on the bitumen samples to determine the visco-elastic properties, where it is viscous at high temperature, while elastic at low temperature. The test system consists of rotational viscometer, measuring geometry, temperature-controlled chamber, sample chamber, temperature controller, balance, and platinum resistance thermometer. Brookfield rotational viscometer apparatus-based test following ASTM 4402 standard [65] was implemented on the samples under two specific temperatures (135 °C and 165 °C).

Rheological test methods

Dynamic shear rheometer (DSR) test

DSR is a method required in SuperPAVE grading system and utilized to identify the visco-elastic properties of bituminous materials under different temperature, constant or variable load and frequency. The test system consists of (1) chamber to make a stable ambient condition for testing (2) stable plates and (3) testing geometry with 8 mm and 25 mm, (4) specific software to start measuring and control device. It is possible to analyze short-term and long-term aged bitumen beside unaged form with DSR. The test gives some parameters called complex shear modulus (G*) and phase angle (δ°), which are the two identify various properties such as rutting and fatigue resistance. Rutting resistance can be analyzed with $G^*/\mathrm{Sin}\ (\delta^o)$ with DSR test applied on unaged and short-term aged bitumen, while $G^*.\mathrm{Sin}\ (\delta^o)$ values referred to fatigue resistance can be determined with applying the test on long-term aged samples. The limit values specified in SuperPAVE grading system for rutting are 1 kPa for unaged case, while 2.2 kPa for short-term aged samples. On the other hand, 5000 kPa is the limit value for samples in long-term aged form. Phase angle refers to the time lag between responses with applied force and gives visco-elastic properties of the samples. The scale of phase angle values is between 0° and 90°. Accordingly, the sample is identified elastic as its phase angle approaches to 0°, while it is determined viscous as its phase angle approaches to 90° [10, 70]. In the current study, the standard with EN 14,770 [71] was followed. The available testing temperatures for unaged and short-term aged case are 46–88 °C and 40–13 °C for long-term aged case throughout the scope of the current study. Considering the available temperature, the test had been continued for the tested samples until the limit failure value that specified for each aging case is reached.

Bending beam rheometer (BBR) test

BBR is implemented on long-term bitumen samples to identify their thermal cracking resistance and relaxation characteristics. BBR test system consists of (1) a fluid bath for conditioning the sample at desired temperature with the help of temperature controller system, (2) loading units and deflection measuring systems, which controlled by software. Creep stiffness (St) and m-value are the two parameters found from BBR tests indicated thermal cracking and relaxation characteristic of bitumen, respectively. The limit value for St specified in SuperPAVE grading system is 300 MPa at maximum and the limit value m-value is 0.300 at minimum. For better thermal resistance and relaxation characteristics, the samples must have higher St and m-value [10, 70, 72, 73]. BBR test was applied on samples throughout the current study according to EN 14,771 [71] under (-) 6, (-) 12, (-) 18, (-) 24 °C temperatures.

Aging

Aging occurs during the processes including heating bitumen, mixing it with aggregate mixture to produce HMA and transfering the HMA to construction site, and compaction of it on the site is called short-term aging. On the other hand, the aging of bitumen throughput the period from the pavement construction to the end of its service life is called long-term aging. It is possible to age bitumen samples in case of short and long-term in laboratory according to SuperPAVE grading system [75, 76].

To obtain the short-term aged bitumen sample, while occurring during mixing, transportation and compaction processes, rolling thin film oven (RTFO) test is used and implemented by following the EN 12,607–1 standard [77]. In this test method, certain amount of bitumen sample is poured in a specified open ended glasses and spreading bitumen through the glasses as a thin film is ensured by rotation of the holder plate at a constant speed. During the test, oven temperature is kept constant at 163 ˚C under specified rate of dry air that is blown into the sample through the open ending of glasses during rolling.

To obtain the long-term aged bitumen sample that refers the condition of bitumen sample at the end of service life, pressure aging vessel (PAV) test is used and implemented according to EN 14,769 standard [78]. The test can be carried out at 90, 100, 110 °C under 2.1 kPa pressure for 20 h. It is worth to indicate that produced short-term aged samples is the test samples being used to obtain long-term aging sample. Throughout the scope of this study, 110 °C was used for aging conditioning.

Storage stability test method

Modified bitumen is a kind of composite material, which bring two different materials together throughout a modification process. Compatibility is important issue for composite materials and it is crucial to provide a sample show homogenous characteristic and performance. If there is no any or poor compatibility between the samples, then the samples may separate from each other due to their physical, chemical, micro-structural properties, especially during storage at certain temperatures. Therefore, providing the desired performance in composite materials, specifically in modified bitumen would not be possible due to non-uniformity [56, 57, 59, 60, 79].

Throughout this study, a test known as storage stability or tube test was performed on modified bitumen samples according to EN 13,399 standard [80] to identify the compatibility between WS and bitumen. The test system consists of (1) test tubes, (2) bitumen oven, (3) defreeze, (4) knife, (5) smooth plate. The principle of this test on basis of filling the tube with modified bitumen, storage the bitumen filled tubes at high temperature at vertical position in oven, freezing the tube after conditioning, and testing the sample taken from top and bottom part of the tube. In the scope of this study, the test methods used for determine the characteristic of the samples taken from top and bottom was softening point, which is recommended in Highway Technical Specification (HTS) of Turkey in which the difference limit is ± 5 °C. The second was is that penetration test which is also recommended in HTS as the difference limit between the penetration of top and bottom edge samples is ± 9 dmm [81].

Bitumen modification procedure

The following bitumen modification procedure including the particle size and method of WS preparation and mixing processes of the WS within bitumen sample was specified for the current study in the light of earlier studies [33, 49, 66–69].

Initially, WS samples are collected from waste storage area. Because WS samples are in different and big size, it is needed to break them in small sizes, approximately, 1–2 cm particles. The broken WS samples are stored in a bag and weighted for the studied rates ranging from 1 to 5% with 1% increment by weight of bitumen. During size reduction and storage of WS, the bitumen is heated at 145 °C for one and half hour. Subsequently, 500 g of heated bitumen transferred to a metal box. The box filled with bitumen is placed on a heater works at 170 °C until the temperature of bitumen sample reaches and stabilizes at 170 °C. Then, mixing phase is started for WS and bitumen with a propeller mixer that works at 200 revolutions per minute (rpm). The weight for the specified contribution rate of WS samples is introduced in bitumen while the mixer works. After all WS samples are introduced and coated with bitumen, the mixer is worked at 1000 rpm for 30 min for being soften and penetrate the WS throughout the bitumen sample. WS and bitumen mixture was stirred at 1000 rpm for the next 60 min to melt WS in bitumen. One more stirring was done at 100 rpm for approximately 30 min to make the WS-modified bitumen homogenous before testing the samples.

Table 3 Test results for samples in unaged, short- and long-term aged form

Test methods	BB	WS-1	WS-2	WS-3	WS-4	WS-5
Penetration (dmm)	74.0 ± 0.7	70.6 ± 1.2	64.7 ± 0.2	56.4 ± 2.3	50.0 ± 0.6	48.0 ± 1.1
Softening point (°C)	44.0 ± 0.5	45.5 ± 1.0	50.9 ± 1.1	54.5 ± 1.7	57.6 ± 0.7	60.4 ± 1.0
Viscosity at 135 °C (cP)	563.3 ± 6.7	607.5 ± 9.7	624.1 ± 4.7	753.3 ± 8.7	841.1 ± 9.7	897.0 ± 5.1
Viscosity at 165 °C (cP)	160.0 ± 4.7	169.8 ± 3.3	173.7 ± 1.2	201.8 ± 8.1	214.9 ± 1.7	223.3 ± 0.7
Test methods	BBS	WS-1S	WS-2S	WS-3S	WS-4S	WS-5S
Penetration (dmm)	65.0 ± 1.2	62.6 ± 1.5	60.7 ± 1.9	53.4 ± 1.3	47.0 ± 1.0	44.0 ± 1.5
Softening point (°C)	48.0 ± 1.0	49.5 ± 1.0	54.0 ± 1.1	58.2 ± 1.7	60.6 ± 0.4	62.9 ± 1.0
Viscosity at 135 °C (cP)	675.6 ± 9.4	708.2 ± 5.7	748.1 ± 6.0	890.5 ± 8.7	978.8 ± 6.7	1197.0 ± 9.1
Viscosity at 165 °C (cP)	208.0 ± 3.0	236.9 ± 3.9	299.5 ± 5.2	301.8 ± 8.1	349.0 ± 1.7	393.3 ± 6.7
Test methods	BBL	WS-1L	WS-2L	WS-3L	WS-4L	WS-5L
Penetration (dmm)	35.0 ± 0.8	34.6 ± 0.3	31.7 ± 1.0	27.4 ± 1.4	24.0 ± 1.0	23.0 ± 0.5
Softening point (°C)	58.0 ± 1.0	60.5 ± 1.0	63.0 ± 1.1	67.2 ± 1.7	72.6 ± 0.4	73.5 ± 1.0
Viscosity at 135 °C (cP)	1255.0 ± 4.4	1608.2 ± 7.0	1748.1 ± 4.0	1860.5 ± 6.7	2078.8 ± 9.7	2197.0 ± 4.0
Viscosity at 165 °C (cP)	358.0 ± 0.9	406.9 ± 6.9	429.5 ± 2.2	451.8 ± 1.1	489.0 ± 1.0	501.3 ± 1.7

Results and discussion

Physical test results

Penetration, softening point and viscosity tests were conducted on each unaged, short- and long-term aged bitumen samples to examine the changes in physical properties of bitumen. The test results are presented in Table 3 for unaged, short- and long-term aged samples.

The data presented in Table 3 supported the output of earlier studies, which focused on the investigation of the effect of introducing plastic-based synthetics polymer to the base bitumen for modification purpose [82–86]. As seen in the table, increase in WS contribution rate causes significant decrease in penetration grade, increase in softening point, and viscosity. The findings revealed for unaged one can be seen similar to the test results of short- and long-term aged samples. However, the values of the test result in higher than that of found for the unaged samples because of the fact that aging makes the bitumen stiffer [87]. These results provide a foresight about the in the rheological properties of the bituminous binder.

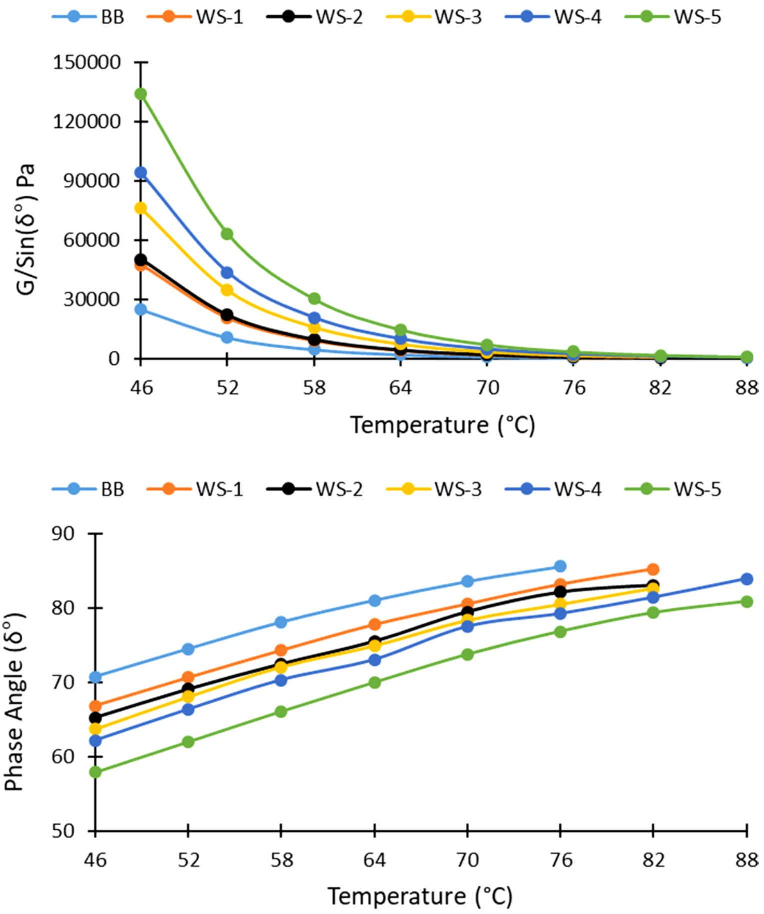


Fig. 1 DSR test results of unaged bitumen samples

Rheological test results

As mentioned before, there are two basic testing method in SuperPAVE grading system that are DSR and BBR. In respect of the system, the results of DSR test implemented on base and modified bitumen samples in unaged condition were presented in (Fig. 1) and while short-term aged form in Fig. 2. On the other hand, DSR test result for long-term aged bitumen case is given in Fig. 4.

The results of DSR test for unaged and short-term aged modified bitumen presented in Figs. 1 and 2 showed that increase in the rate of WS increases the failure temperatures of the samples. WS-modified bitumen samples showed better performance against rutting that is one of common distress observed on road surface, especially under higher elevated temperatures [45, 83]. Phase angle other than DSR test parameter is an indicator that shows the visco-elasticity properties of bitumen samples under tested temperature [75, 85] and showed that both

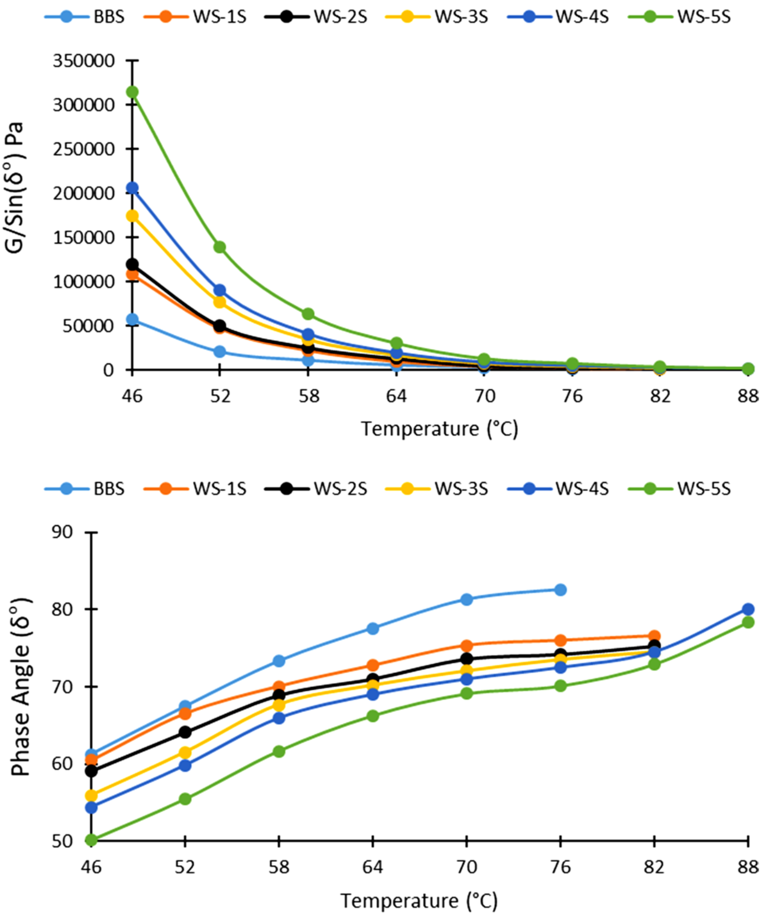


Fig. 2 DSR test results of short-term aged bitumen samples

increase in rate of WS in bitumen modification and aging make a significant contribution to elasticity properties. Moreover, it is worth to indicate that the test results given in Figs. 1 and 2 are compatible with each other while analyzing on basis of SuperPAVE grading system, where the characteristics of unaged and short-term aged bitumen samples are expected to be the same. DSR results of long-term aged samples given in Fig. 3 showed that WS modification increases the fatigue resistance performance, significantly. Similar to un-aged and short-term aged cases, phase angle decreases with both aging and increase in contribution of WS rate. The results given in Fig. 3 also indicated that the WS-modified samples show better fatigue resistance of bitumen samples than the long-term aged form of base bitumen. Similar to the DSR test results of unaged and short-term aged samples, values of phase angles complied with the SuperPAVE grading system. To make clear the failure and grading temperatures for all aging forms of WS-modified bitumen samples, Table 4 is presented.

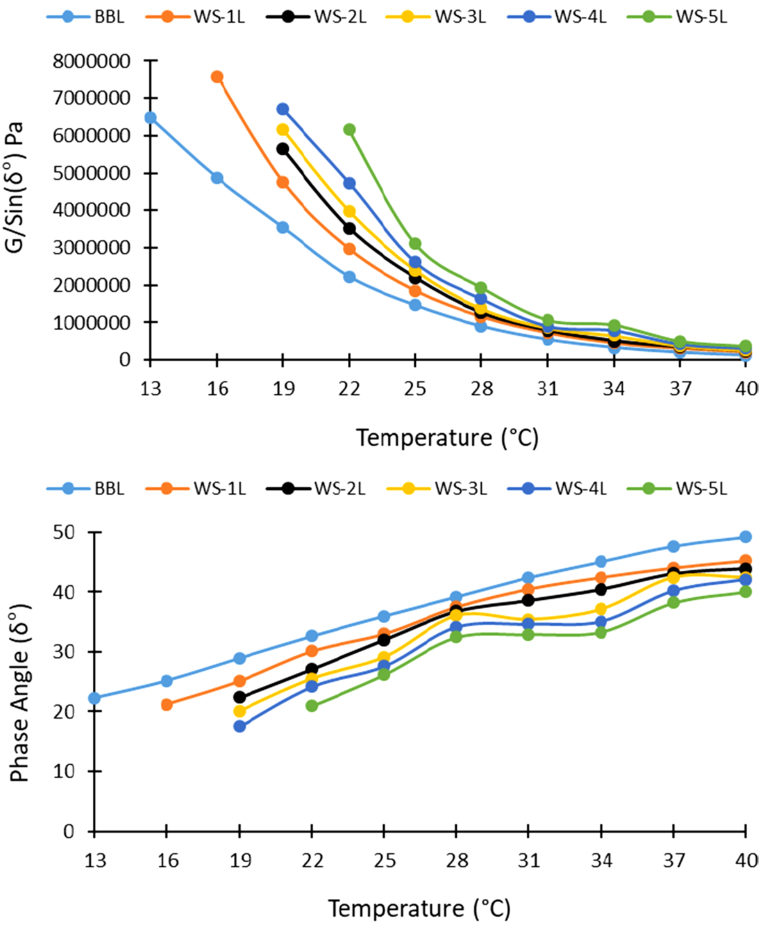


Fig. 3 DSR test results of long-term aged form samples

Table 4 Failure and grading temperatures for base and WS-modified bitumen

Aging Case	Parameters	BB	WS-1	WS-2	WS-3	WS-4	WS-5
Unaged	Failure temperature (°C)	76	82	82	82	88	88
	Grading temperature (°C)	70	76	76	76	82	82
Aging case	Parameters	BBS	WS-1S	WS-2S	WS-3S	WS-4S	WS-5S
Short-term	Failure temperature (°C)	76	82	82	82	88	88
	Grading Temperature (°C)	70	76	76	76	82	82
Aging case	Parameters	BBL	WS-1L	WS-2L	WS-3L	WS-4L	WS-5L
Long-term	Failure temperature (°C)	13	16	19	19	19	22
	Grading temperature (°C)	16	19	22	22	22	25

The data given in Table 4 indicated the failure and grading temperatures according to SuperPAVE grading system. The failure temperatures refer to the testing temperatures where the related complex modulus reaches the limit values that are 1.0 kPa, 2.2 kPa, and 5000 kPa, for unaged, short-term aged and long-term aged cases, respectively. On the other hand, grading temperatures refer to the testing temperatures below the failure one for unaged and short-term aged, while above the failure one as testing done for long-term aged samples. In this regard, grading temperature for base bitumen is 70 °C, while that of WS-modified bitumen coded with WS-1, WS-2, and WS-3 is 76 °C and the rest modified bitumen are 82 °C. On the other hand, the grading temperatures found for long-term aged samples are not used in SuperPAVE grading system, but it is used to proof the characteristic of the samples according to the system in the light of tests applied on unaged and short-term aged samples. Therefore, it can be indicated from Table 4 that the grading temperature of base bitumen is 16 °C, while that of modified bitumen with 1% and 2% of WS is 19 °C. The grading temperature of the samples with code of WS-3 and WS-4 is 22 °C and the last one, WS-5, is 25 °C.

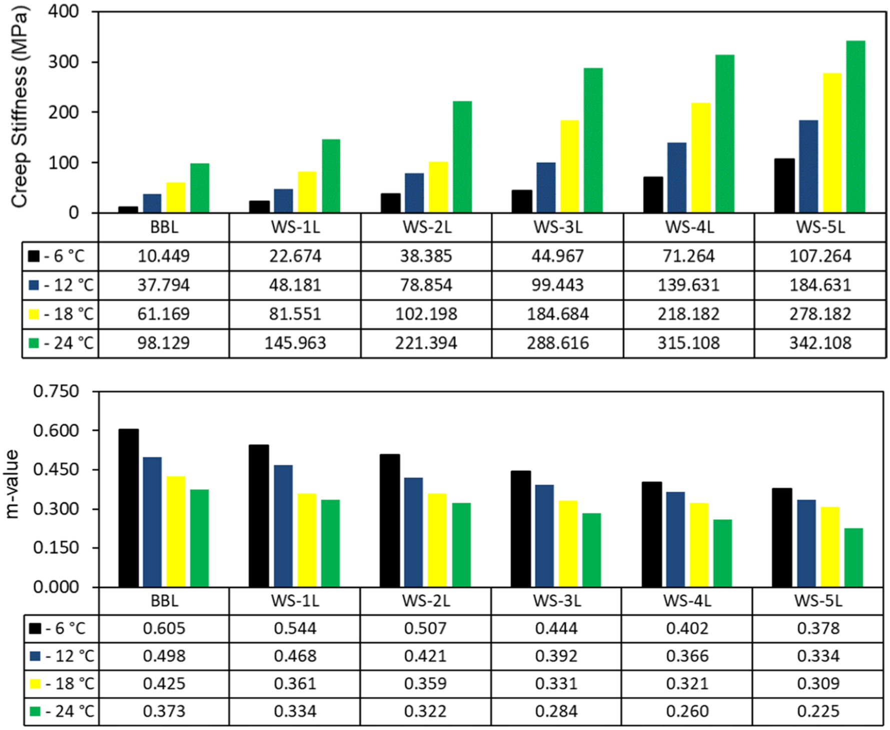
Conducting the BBR test on bitumen samples gives performance of bitumen samples by means of cracking resistance occurs at low temperatures. In this regard, BBR test was conducted on residue of long-term aged bitumen samples at four different test temperatures ranging between − 6 and − 24 °C by − 6 °C decrements. The BBR results based on the two test parameters, creep stiffness and m-value are presented in Fig. 4.

Figure 4 indicated that thermal cracking resistance of bitumen samples increases with an increase in WS contribution rate. The temperature for test results that met the minimum and maximum limits for creep stiffness and m-value parameters was determined lower temperature grade of the bitumen according to the SuperPAVE grading system. For bitumen samples with WS-3L, -4L and -5L codes exceed the creep stiffness value, but do not reach the minimum m-value at − 24 °C. However, all WS-modified bitumen met the limit value of the two BBR test parameters until at − 6, − 12, and − 18 °C. Therefore, the low temperature grades of for all bitumen samples can be determined as − 18 °C.

Storage stability analysis results

The compatibility between the composite materials such as modified bitumen is vitally important to provide a homogeneous or uniform mixture that met desired properties. To examine the compatibility between the two materials, bitumen and WS, one common test known as storage stability test was performed on modified bitumen samples with at least two repetitions. The principle of storage stability test is conditioning the test samples in vertical position at high temperatures [56, 79, 88]. Following to conditioning, softening point and penetration tests were conducted on the test samples taken from top and bottom part that recommended in HTS of Turkey [81]. Table 5 presents the result of tests.

Table 5 indicated that bitumen and WS are compatibly as the waste is used in certain rate, where it is also mentioned in numerous study dealt with modified bitumen



	BBL	WS-1L	WS-2L	WS-3L	WS-4L	WS-5L
⬛ - 6 °C	10.449	22.674	38.385	44.967	71.264	107.264
🟦 - 12 °C	37.794	48.181	78.854	99.443	139.631	184.631
🟨 - 18 °C	61.169	81.551	102.198	184.684	218.182	278.182
🟩 - 24 °C	98.129	145.963	221.394	288.616	315.108	342.108

	BBL	WS-1L	WS-2L	WS-3L	WS-4L	WS-5L
⬛ - 6 °C	0.605	0.544	0.507	0.444	0.402	0.378
🟦 - 12 °C	0.498	0.468	0.421	0.392	0.366	0.334
🟨 - 18 °C	0.425	0.361	0.359	0.331	0.321	0.309
🟩 - 24 °C	0.373	0.334	0.322	0.284	0.260	0.225

Fig. 4 BBR test based creep stiffness and m-value results

Table 5 Storage stability test result based on softening point and penetration

Samples	WS-1	WS-2	WS-3	WS-4	WS-5
Softening point of bottom edge (°C)	47.0 ± 0.5	52.0 ± 3.5	58.0 ± 2.5	62.0 ± 0.5	66.0 ± 1.5
Softening point of top edge (°C)	46.0 ± 1.0	48.5 ± 1.2	50.0 ± 1.7	51.0 ± 0.7	54.0 ± 0.5
Differences (°C)	1.0	3.5	8.0	11.0	12.0
Limitation (°C)	± 5	± 5	± 5	± 5	± 5
Penetration of bottom edge (dmm)	76 ± 1.4	72 ± 2.0	70 ± 1.0	64 ± 3.7	62 ± 3.9
Penetration of top edge (dmm)	78 ± 1.0	77 ± 1.2	79 ± 1.4	84.0 ± 1.3	88 ± 2.1
Differences (dmm)	2.0	5.0	9.0	11.0	16.0
Limitation (dmm)	± 9	± 9	± 9	± 9	± 9

done with different additives [57, 70, 79]. Modified bitumen codded with WS-1 and WS-2 were shown compatible as analyzing done with softening point. However, the penetration tests applied on the sample top and bottom edge of the test tube indicated that WS-3 also exhibits compatibility considering HTS requirements, which meant that different test methods give different compatibility evaluations, accordingly. The result also proofed that the non-compatible modification causes occurrence of different types bitumen as seen on the analyses done with penetration index in which bitumen sample with code of WS-4 and WS-5 gathered from top and bottom part of the tube can be classified in different bitumen classes on the basis of penetration grades.

Summary and conclusion

In this study, WS with 1% to 5% by weight of bitumen with 1% increment was added to base bitumen with 70/100 penetration grade for the purpose of modification. Numerous physical tests including penetration, softening point, viscosity and rheological tests including DSR and BBR were conducted on the samples in the case of unaged, short- and long-term aged form. To identify the compatibility between the waste and the bitumen used in the current study, storage stability test was performed on each modified bitumen samples in case of unaged form.

The followings can be highlighted based on the test results and analyses. WS modification changes physical and rheological properties of bitumen, significantly. Penetration decreases; softening point and viscosity of bitumen increase, while the rate of WS increases. WS modification improves rutting resistance and thermal cracking resistance of bitumen, whereas reducing fatigue resistance performance with an increase in the rate of WS. WS-modified bitumen is capable for storage as the contribution rate up to 2% as analyzed with softening point, and up to 3% as examined with penetration test. This result also showed the importance of test method after high-temperature storage.

Overall, this study showed that using WS as a kind of synthetic plastic that hazardous unless they disposed properly in safe way to the environment and living health can be possible within bitumen throughout a certain modification processes. Using the waste in this perspective can eliminate following disposing the waste by burning that gives serious harm to the atmosphere as a result of emerging greenhouse gas. Therefore, both green and sustainable production of bitumen by means of providing certain environmental and economic benefits throughout safer recycling of the plastic-origin waste and improving some characteristic of bitumen that enhance a long-lasting and sustainable construction of pavement.

Recommendation for future studies

The current study has focused on the use of WS as modifier in bitumen. The analyses were done on the basis of physical and rheological properties and storage stability analysis. The scope of the study can be expanded with some additional research, which are not taken in the scope of the current study. For example, performance of WS modification can be studied throughout different bitumen types, either in origin or in grade on basis of chemical because of the fact that only one type of bitumen performance was evaluated in the current study. Chemical and image-processing-based analyses can be done for better understanding the mechanism of modification.

Although there are too much investigations done on HMA performance, this task can be studied in deep after effective WS modification that may be provide an optimization analyses.

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