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Sustainable Production of New-Graded Bitumen with Waste Styrofoam Modification

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Abstract: Styrofoam is a recyclable petroleum origin product. However, releasing it and/or its waste into nature causes permanent damage to environment and human health owing to toxic materials that it contains. This study was set out on sustainable recycling of waste styrofoam (WS). To recycle the waste, it is used as a modifier in bitumen. In this respect, three type of bitumen in different penetration grade, which are one used for modification the other two used for reference in optimization analysis and WS in five different rate ranging from 1% to 5% by weight of bitumen were utilized. Different conventional test methods were applied on each samples to identify the effect of WS rate on bitumen basic characteristics. Optimum rate of WS required to produce new grade bitumen was evaluated based on modification index found for all test results. The test results showed that WS modification changes the bitumen properties, significantly. It can be possible to produce new graded bitumen using certain rate of WS. Test method was found a critique factor, since optimum rate of WS considered based on modification index changes due to the test method. Overall, the recycling WS using as a modifier in bitumen can an alternative, energy efficient, economic, and eco-friendly method.

Keywords: Sustainability, recycling, waste, Styrofoam, bitumen, modification

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1. INTRODUCTION

Sustainability is a kind of institutional operating practices and physical development that meet the needs of users without compromising the ability of future generations to provide their own requirements with the waste of natural resources (Anonymous, 2019). Therefore, sustainable practices must enhance a health environment for all livings and support the economic activities (Hart, 1997; Norton, 1992; Sikdar, 2003). Economic activities that vital to meet the human being needs extensive amount of energy to be used, and therefore significant amount of greenhouse gas is emerged beside of waste generation (Tonelli et al., 2013). Greenhouse gases released into the air and the energy used by human and industrial facilities may be possible to be reduced using advance technology. But wastes arising from vital activities and increasing population remains constant (Singh et al., 2012; Tseng et al., 2018). Fortunately, the wastes can be recycled instead of natural resource and can be used for different purposes (LaGrega et al., 2010; Reed et al., 1995).

Wastes are valuable materials in today world and significant economic gains can be provided with their recovery. Moreover, certain benefits can be obtained by means of environmental, health and aesthetic aspects. Waste resources might be residential, industrial, commercial, institutional, constructional, clinical, agricultural etc. based. They might in the form of solid, liquid and gas (Awoyera and Adesina, 2020; Chung and Lo, 2003; Oliveira et al., 2008; Reed et al., 1995; Thomas and Rahman, 2006). In the scope of the study, one of waste generally in occurs in solid form is evaluated to its feasibility to be recycled as a bitumen modifier. The waste utilized in this paper is of styrofoam, which is also known as expanded polystyrene (EPS). It is oil-originated synthetic polymer such as plastic consisting of styrene monomers (Ramadan et al., 2020).

Pandemic of coronavirus disease 2019 (COVID-19) increases dramatically usage of styrofoam based materials. Not only being widely used in packing jobs but also used in building and construction works, marketing, and some domestic applications, significant amount of post-use waste is generated during the period (Dev and Sengupta, 2020). Styrofoam can be destroyed if it is exposed to extremely high temperatures. It is known that heating it with fire releases toxins such as carbon black and carbon monoxide, which are hazardous product and effect the human and the other livings health (LaGrega et al., 2010; Ramadan et al., 2020). The degradation of styrofoam material after usage is possible even if it is thrown into nature without any precautions. However, the time for degradation may be at least 500 years up to 4500 years (Awoyera and Adesina, 2020). Rapid rate in urbanization and technological development has increased the generation of waste material. It is possible to recycle such kind of wastes and make them valuable and versatile raw source for different engineering applications (Kaya and Kar, 2016; Grinnell, 1996; Nciri et al., 2020; Ngugi et al., 2017; Thakur et al., 2018).

Using waste styrofoam (WS) as a modifier in bitumen to improve their certain engineering properties has been a subject being attractive since the beginning of the 21st century with development polymer technology. However, the studies on this subject has been mostly restricted with comparisons of the effect of WS on bitumen characteristics including physical, and rheological ones beside of performance of hot mix asphalt produced bitumen with WS modification. Numerous examples from earlier studies are presented at the following to highlight in those manners.

Nassar et al. (2012) reported the effect of WS contribution on bitumen is significant in mechanical properties, particularly on viscosity. Baker et al. (2016) did an experimental study on physical properties of bitumen modified with WS three different rate from 5% to 15% with 5% increments by weight of bitumen. Researcher pointed out: decrease in ductility and penetration and increase flashing and fire points are significant. Al-Haydari and Masued (2017) investigated the potential benefits of WS usage in HMA properties. One of the results indicated by the authors is that adding WS into bitumen did not produce a modified bitumen. The other is introducing WS to bitumen and making a homogeneous mixture enhancing the mechanical performance of HMA. Nciri et al. (2020) investigated the potential usage of WS as modifier for hot mix asphalt (HMA) to produce flexible road pavements. The scope of the study is limited with the chemical and microscopic analysis. The authors found that WS addition increases the resin concentration in asphalt matrix, but does not affect the crystalline phase structure of asphalt. Microscopy base analysis shows asphalt and WS are compatible. Ramadan et al. (2020) investigate the mechanical properties of bitumen modified with different rate of WS. They reported that addition of WS into bitumen for modification purpose improve the stiffness of the bitumen. Moreover, there is significant improvement in high-temperature performance of bitumen modified with WS. This result associated with rutting resistance of the pavement produced using WS modified bitumen. Yıldız et al. (2021) investigated the usability of waste EPS foam in asphalt modification at the rate of 2%, 4%, 6%, and 8% by weight. The bitumen used in the study has 50/70 penetration grade and the conventional test methods were implemented for evaluation of the changes with modification, which were found significantly in certain contribution rate. They showed the feasibility of using EPS foam additive to be used in bitumen modification for hot regions, where low penetration is required.

1.1. Motivation and Objective

Together these studies provide important insights into the effect of WS addition on bitumen properties, but do not give extensive scientific understanding the effective or optimum rate of WS. According to the presented study, different contribution of WS rate change the grade of bitumen by means of either penetration or viscosity, in other words, new-graded bitumen was produced with WS modification. Although the changes in bitumen properties were determined with the available studies, there was not any study evaluating the optimum contribution rate of WS used for producing new bitumen, especially, according to test methods, bitumen type, modification processes (Vinodhkumar and Vinodhkumar, 2022, Porot, et al., 2021, Pérez-Lepe, et al. 2003). Therefore, it can be said that it is a little-known subject focused on the feasibility of usage for modification purpose and effect of it on bitumen properties. These cases indicate that there is a need to investigate the usage of WS in bitumen various perceptions.

In this respect, this study was established to investigate engineering properties WS modified bitumen based on penetration, softening point, flashing point, and viscosity test results and to make a comparison between the base and the WS modified ones. Determination the changes in temperature susceptibility compression and mixing temperature of bitumen modified with WS being used in hot mix asphalt, and the optimum rate of WS included in 100-150 penetration grade bitumen to reflect the properties of 70-100 and 50/70 on the basis of test methods in order for producing new graded bitumen are the other objectives.

2. MATERIAL AND METHOD

Three type of bitumen were used. These bitumen binders are in grade of 100/150, 70/100 and 50/70 penetration rate. All bitumen samples were supplied from Kırıkkale Refinery with deputy of Adana Bitumen Chief of General Directorate of Highways located in Republic of Turkey. The basic properties of bitumen are given in Table 1. The WS samples are supplied from waste collection and recycling containers located on the university campus. Some physical and chemical properties of WS are presented in the light of the study done by Nciri et al., 2020 (Table 2). It is worth to describe an acronym or abbreviation for each sample type used throughout the study for each bitumen form to distinguish the sample results from each other in figure or table bases. In this respect, Table 3 is prepared to notify the sample ID in which bitumen in 100/150 penetration grade is used for modification purpose, 70/100 and 50/70 penetrate grade are the reference ones used for optimization to determine the rate of WS that reflects the same characteristics for the modified bitumen for each case.

Table 1. Fundamental properties of bitumen samples

Tests	Unit	Standard	Test result of bitumen		
			A	B	C
Penetration	dmm	EN 1426	56	74	129
Softening Point	°C	EN 1427	47	44	39
Flashing Point	°C	ISO EN 2592	315	305	285
Ductility (25 °C)	cm	EN 12589	>108	102	58
Viscosity (135 °C)	cP	ASTM D4402	698.3	563.3	307.5
Viscosity (165 °C)			180.0	160.0	95.8

Where, A: PG:50/70, B: PG:70/100, C: PG:100/150

Table 2. Fundamental properties of WS

Chemical Parameter	**Unit (%)**	**Result**
Carbon	wt.	92.34
Hydrogen	wt.	6.93
Nitrogen	wt.	0.51
Sulfur	wt.	0.00
Oxygen	Wt.	0.22
Physical Parameter	**Unit**	**Result**
Molecular Weight	g/mol	~300,000
Density	Kg/m^3	17
Thermal Conductivity	W/ mK)	0.040
Flexural Strength	N/cm^2	24
Compressive Strength	N/cm^2	10

Table 3. Identification form for bitumen samples

Sample ID	Bitumen Composition	Form of Bitumen
BB	Base Bitumen	PG:100/150
CB-1	Base Bitumen	PG:50/70
CB-2	Base Bitumen	PG:70/100
WS-1	Base Bitumen + 1% WS	Waste Styrofoam Modified Bitumen
WS-2	Base Bitumen + 2% WS	
WS-3	Base Bitumen + 3% WS	
WS-4	Base Bitumen + 4% WS	
WS-5	Base Bitumen + 5% WS	

Where, PG is penetration grade

2.1. Production of WS Modified Bitumen

In order to prepare the WS modified bitumen, the recent literature linked with the polymer modification processes were analyzed (Gökalp, et al., 2019, Lin t. al. 2019, Anwar et al., 2020, Yıldız et al. 2021). In the light of the cited studies, production processes of WS modified bitumen were determined. The followed processes is presented step by step at bellow.

- 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, 2-3 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 of WS, the bitumen is heated at 140 °C for one and half hour. 500 gram of heated bitumen transferred to a metal box. The box with bitumen is located on a heater works at 170 °C for the next half hour.
- After the heat of the bitumen samples reaches to 170 °C, the prepared WS samples was placed one by one in a container filled with hot bitumen.
- Subsequently, mixing phase is started for WS and bitumen with a propeller mixer that works at 200 revolutions per minute (rpm). The weighted for the specified contribution rate WS samples are introduces in bitumen while the mixer works.
- After all WS samples are introduced and coated with bitumen and the mixer is worked at 1000 rpm for 30 minutes for soften and penetration of the WS throughout the bitumen sample.
- The last step for the mixing is that arrangement mixing the mixture at 100 rpm for 15 minutes to provide homogeneity of WS modified bitumen. The other reference base bitumen samples are also subjected to the same mixing processes to provide the same aging level for the modified ones.

2.2. Test and Analyzing Methods

Some basic properties of bitumen were planned to determine, and the test methods categorized as conventional were performed. These are penetration, softening point, flashing point, viscosity at 135 °C and 165 °C. To observe the effect of WS contribution rate on thermal susceptibility, penetration indexes for each bitumen sample are calculated with internationally accepted formulation. The test methods are briefly summarized at the following.

Penetration test: The test is applied on the bitumen samples to determine their consistency or hardness under a certain load, temperature by utilizing a specific needle for certain time. In this study, EN 1426 standard was followed to conduct the test on samples. The three test results are considered acceptable if the range of the results does not exceed the relevant value given in the standard. Finally, the arithmetic mean of the acceptable results is reported (Gökalp et al., 2019).

Softening point test: Similar to penetration test, this test method is also one of conventional test used mostly to determine the softening point of the bitumen. EN 1427 was followed to apply the test. If the difference between the two temperatures, that the bitumen samples fall down does not exceed 1 °C for softening points, the test results is taken as acceptable. Finally, the mean of the temperatures is expressed to the nearest 0.2 °C (Gökalp et al., 2019).

Viscosity: Bitumen is a visco-elastic material and its viscosity changes with heating. To make the bitumen workable in HMA production and application it on the field, bitumen should be heated, sufficiently. Viscosity test is used to determine the sufficient heat. Brookfield rotational viscometer test is implemented on the samples according to ASTM 4402 standard under two specific temperatures: 135 °C and 165 °C (Mirsepahi et. al, 2020) within the scope of the study.

Flashing Point: Bitumen has certain volatile component and this component evaporates as exposed a fire source.

Following to heating, flashing can occur, temporarily. The temperature at this point is called flashing point. The flashing point for each bitumen samples may change due to their origin, chemical composition and the additive used to modify them. In this regard, flashing point test is implemented on each samples according to EN 22592 standard (Yaşar, 2015)

Penetration index: Bitumen is a thermal susceptible construction material. Thermal activities effect bitumen state and therefore its physical and mechanical properties. To identify the level of sensitiveness of bitumen, penetration index is developed on basis of penetration and softening point test results. To determine the index value, the following equation is used.

$$PI = \frac{1952 - 500\log Pen - 20SP}{50\log Pen - SP - 120} \quad (1)$$

where,
PI refers to penetration index,
Pen refers to penetration value obtained at 25 °C, and
SP refers to softening point value.

As the bitumen PI index increases the thermal susceptibility is decreases. The range of PI value for the bitumen to be used in HMA production is (+) 2 and (-) 2. However, evaluation of the thermal susceptibility of bitumen with PI is made with (-) 2. PI values below the (-) 2 indicates that the bitumen more resistant to thermal activity than those above (-) 2 (Firoozifar, et al. 2011, Sengoz and Işıkyakar, 2008).

Modification index: Bitumen modification change the bitumen characteristics. To determine the change in properties and make a comparison between the modified and base bitumen, an index called modification index value is established in the light of the earlier studies (Gökalp and Uz, 2019, Gökalp, et al., 2019). The index value can be calculated with the following equation.

$$MI = \left(\frac{VR - VMi}{VR} \right) x100 \,) \quad (2)$$

Where,
MI refers to modification index,
VR refers to test results for reference bitumen, and
VM refers to test results for modified bitumen,
i WS rate indicator.

Optimization rate analysis: Modification index results are used to predict the optimum rate of WS for the new bitumen that stimulate the properties of reference bitumen used throughout the study. This analysis is done for all test methods studied in this paper, individually. As the modification index reaches to zero, the rate remarks it is considered as the optimum rate for the reference bitumen (Gökalp and Uz, 2019, Gökalp, et al., 2019). To do the analysis, best fit curve method is used. There are three main objectives to do this analysis. These are describing the trend of change in bitumen properties, predicting the rate of WS that provide studied reference bitumen, which are in 70/100 and 50/70 grade, and highlighting the effect of test methods on optimum rate.

3. RESULTS AND DISCUSSION

This section is presented in two parts. The first is test and analysis results and the second one is on the optimization analyses of WS contribution rates that reflect the 70/100 and 50/70 bitumen properties studied within this study.

3.1. Test and Analysis Results

The current study was established on evaluation of the effect of different rate of WS on the bitumen properties as being used modifier. To examine the change in bitumen properties, conventional test methods and thermal susceptibility analysis were performed. Table 4 indicates the results of test and analysis for each type of sample.

Table 4. Test and analysis results

Test Methods	Samples and Test Results							
	CB-1	**CB-2**	**BB**	**WS-1**	**WS-2**	**WS-3**	**WS-4**	**WS-5**
Penetration (dmm)	56.0	74.0	129.0	105.6	85.7	69.4	54.0	48.2
Softening Point (°C)	47.0	44.0	39.0	43.0	46.9	52.5	57.6	59.4
Flashing Point (°C)	315	305	285	290	310.0	320.0	329.0	335.0
Penetration Index	-1,72	-1,94	-2.17	-1.29	-0.67	0.24	0.73	0.82
Viscosity at 135 °C (cP)	698.3	563.3	307.5	337.5	424.1	703.3	791.1	1417.0
Viscosity at 165 °C (cP)	180.0	160.0	95.8	141.8	152.7	171.8	224.9	263.3

The data presented in Table 4 shows that the significant effect of addition of WS to the bitumen. Similar conclusions were highlighted in earlier studies done by Yıldız et al., 2021, Ramadan et al., 2020, Baker et al., 2016, Nassar et al., 2012. But, the level of changes are different due to material origin and/or test methods. Therefore, the general result in the current study and the earlier studies complied with each other. To indicate the results presented in Table 4, briefly, it can be indicated that bitumen penetration rate decreases, the softening point as the WS contribution rate increases. Moreover, flashing point of the bitumen also increases with increasing rate of WS and this case provides that the bitumen may be safer as heating against explosion caused by a source of flame. However, the change is lower than the other test results. On the other hand, the findings for PI results show that the WS modified bitumen exhibits better thermal susceptibility, because PI decreases while WS rate increases. Moreover, looking for the viscosity, as can be easily expected from penetration and softening point results, viscosity of the bitumen samples increases with WS modification.

It is possible to determine the temperature of the bitumen being used in HMA production in mixing and compaction phases with viscosity test. To evaluate it, the related standard, which is ASTM D4402 recommends mixing and compaction as the viscosity of bitumen matches 170±20 cP and 280±30 cP, respectively (Öner, 2018). This criterion make the bitumen and the HMA workable both in plant and in site. The compression and mixing temperature results gathered from viscosity test is presented in Table 5.

It can be seen from the data presented in Table 5 that the mixing and compression temperatures of bitumen increases with addition of the WS modified bitumen. Comparing with the base bitumen, BB, the increase in temperature is approximately 15 °C in mixing and 25 °C in compression as the WS rate is 5%.

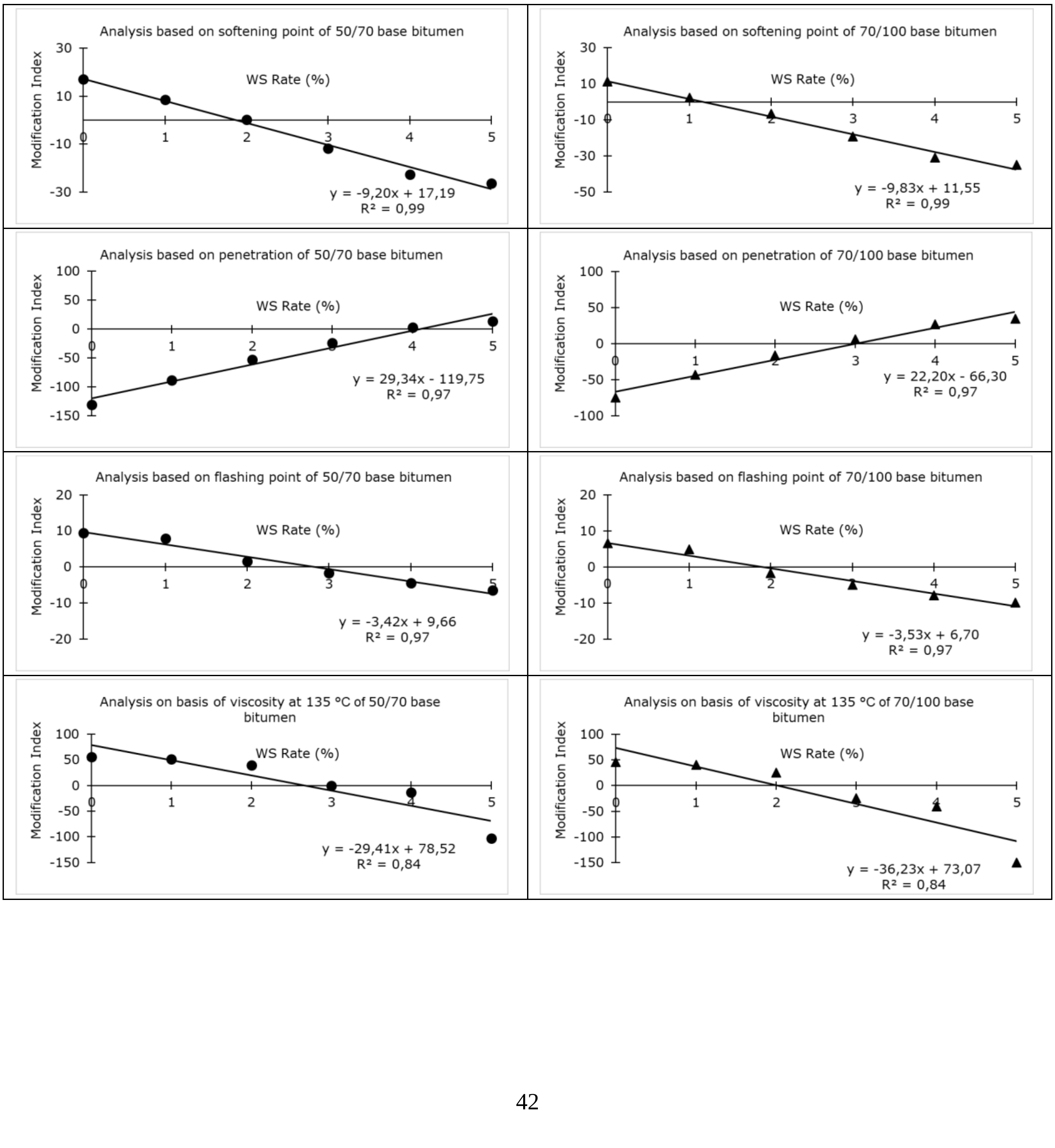
Table 5. Compression and mixing temperature results

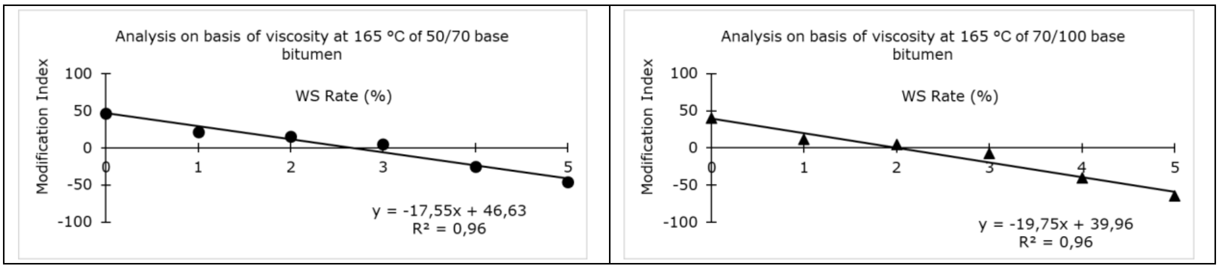
Temperature (°C)	Limits (cP)	Samples and Test Results							
		CB-1	CB-2	BB	WS-1	WS-2	WS-3	WS-4	WS-5
Mixing	170±20	167-164	166-163	157-152	164-158	165-161	166-164	169-167	168-167
Compression	280±30	161-157	158-153	143-135	148-139	154-148	161-157	164-161	165-164

Overall, all the results presented in Table 4 and Table 5 showed that modifying the base bitumen in 100/150 penetration grade with different rate changes significantly the studied properties of bitumen. The properties of modified bitumen approach to the reference bitumen in 70/100 and 50/70 penetration grades. This finding as mentioned before that is the motivation of the current research, which was rarely studied before for WS modified bitumen.

3.2. Optimization Analysis Results

The optimization analyses are established on best line analysis corresponding to the highest accuracy coefficients This case is done for the two, 70/100 and 50/70, grade bitumen. To start the analyses, best-fit line graphs in linear basement are given in Figure 1.





Where, x is WS rate and y is the referenced test or analysis results

Figure 1. Optimization analysis for 50/70 and 70/100 reference bitumen

It is obvious from the optimization analysis presented in Fig. 1 that there are high root square values that more than 0.95 except of the ones occurred for the viscosity at 135 °C found for the drawn best-fit line. As zero value of modification index gives optimum rate of WS that different WS rates are required for providing different bitumen in grade. As expected, optimization analysis corresponding to different test results gives different optimum WS rate. Similar results were found in recent studies used similar optimization approach (Gökalp and Uz, 2019, Uz and Gökalp, 2020, Gökalp and Uz, 2021) to determine optimum rate of additive to be used in modification of bitumen. To summary the optimum WS based on the test method for the two reference bitumen cases, Table 6 is presented.

Table 6. Optimum WS rate based on the test method for the reference bitumen samples

Test Methods	**Optimum WS rate (%)**		**Difference in rate between CB-1 and CB-2 (%)**
	CB-1	**CB-2**	
Penetration	4.08	2.99	26.7
Softening Point	1.87	1.17	37.4
Flashing Point	2.82	1.90	32.6
Viscosity at 135 °C	2.67	2.01	24.7
Viscosity at 165 °C	2.66	2.02	24.1

The results of optimum rate analysis presented in Table 6 indicate that higher rate of WS requires to make the studied bitumen in 100/150 penetration grade properties similar to CB-1 due to lower penetration grade and vice-versa. Moreover, it can be highlighted that the optimum rate of WS changes depend on the result of test method, which are different in numerous points. Looking for the differences between the optimum rate required to enhance properties of CB-1 and CB-2, the highest one is considered for softening point results as 37.4%, while the lowest one for viscosity at 165 °C as 24.1%. Similar conclusions were highlighted in numerous studies done by Gökalp and Uz, (2019), Uz and Gökalp,(2020), and Gökalp and Uz, (2021), which all investigate the subject on basis of both rheological and conventional test methods.

4. CONCLUSIONS

The studied waste material in the current study is that of styrofoam emerged mainly from packing and construction demolition activities. Although, great number of studies carried out on different waste to improve the bitumen characteristics, investigation done on the feasibility WS for use modifier in bitumen take limited place in the literature. Therefore, some uncertainties existed about the relation between the waste and bitumen. To make an original contribution to the current literature, an investigation on optimum contribution rate being used for producing new-grade bitumen in addition to highlight the effect of WS contribution on studied bitumen properties. Therefore, the current study is thought to be one of preliminary study, and the research methodology was stand on the conventional test to show main characteristics of bitumen. To achieve the aim, bitumen in 100/150 penetration graded bitumen was used to modify the bitumen with WS with 1% to 5% with 1% increment by weight of bitumen in rate. 70/100 and 50/70 penetration graded bitumen were used as reference that constructing the optimum rate analyses of WS as used in the studied bitumen. Best-fit line analysis is done for each test results to make optimization analysis. Consequently, it can highlighted that sustainable recovering of WS is reasonable with bitumen modification, WS modification improves the bitumen engineering characteristics, using certain rate of WS can change the grade of bitumen, different WS rate is required while optimization analysis done based on different test methods, higher WS rate is necessary for producing lower penetration graded bitumen.

Since it is a kind of preliminary study, some additional analyses are reqired to make a clear sense about the usage of WS in bitumen as modifier. Some are may be exemplified as following. Different bitumen types, either in origin or in grade should be studied since only one type of bitumen performance was evaluated in the current study. The effect of environment can be studied in detail due to the temperature-sensitivity characteristics of bitumen. Investigation should be expanded with the analysis based on rheological test methods to bring deep scientific understanding of the subject. Finally, the effect of WS modified bitumen on asphalt mixture performance, which is not included in this study should be investigated.

Ethics Committee Approval
N/A

Peer-review
Externally peer-reviewed.

Author Contributions
Conceptualization, Investigation, Material and Methodology, Supervision, Visualization, Writing-Original Draft, Writing-review & Editing: İ.G. Other: The author has read and agreed to the published version of manuscript.

Conflict of Interest
The authors have no conflicts of interest to declare.

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