JOURNAL OF INNOVATIVE TRANSPORTATION

Treatment of hazardous waste engine oil as bitumen modifier for sustainable hot mix asphalt pavement

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Highlights

- Waste engine oil rejuvenates aged bitumen
- Optimum bitumen content is decreased
- Self-healing property of the bitumen is improved by softening the bitumen

Abstract

Engine oil is compulsory for vehicle operations and should be replaced with new one in specific periods of time or travel distance. Therefore, lots of waste engine oil (WEO) which are very hazardous to the environment is produced every year. Treatment of this waste is very difficult because of the heavy metals in it. In this paper, the usability of WEO in the hot mix asphalt for colder regions is investigated. Softening point and penetration tests have been conducted to WEO modified bitumen to see the change in rheological properties. In addition, Marshall Stability and indirect tensile strength tests have been performed on hot mix asphalt produced with WEO modified bitumen. WEO increases the penetration value while decreasing softening point of the bitumen. Stability results are all above the specification limit, and only specimens compacted with 3% WEO modified bitumen rate ensures the flow and TSR values. Because of the paper, WEO could be used in hot mix asphalt for colder regions and the damages giving to the environment could be decreased.

Information

Received: 13.05.2020

Received in revised: 30.06.2020

Accepted: 30.06.2020

Keywords: *hazardous; waste engine oil; self-healing; bitumen; modification*

1. Introduction

Engine oil is used for creating a slippery layer between the working parts of the automobile engine to prevent abrasion on them. It also cleans the working parts of the engine. Therefore, every automobile needs engine oil by running. However, after a period, engine oil becomes useless and should be replaced. Because of this replacement, nearly 24×10^6 tonnes of waste engine oil (WEO) are obtained each year [1], and the amount is increasing.

WEO is a high-volume hazardous mineral oil which is difficult to treat because of the heavy metals contained within [2]. WEO is an eco-toxic material and causes permanent ecological damage when thrown indiscriminately to nature. WEO causes water, soil and air pollution as well as damaging human health.

There are some methods for eliminating the WEO such as recycling it using solvents [3] or regeneration it by extraction [4-7]. However, they all are tiring methods. It may make more sense to use the WEO directly to eliminate.

One method for using the WEO directly is to use it in the Hot Mix Asphalt (HMA) as bitumen modifier. Especially when it is considered as approximately 5% by weight of the HMA is bitumen, lots of WEO could be reused. Therefore, damage given to the environment will be reduced greatly by using WEO as a bitumen modifier. WEO usage as rejuvenator material for recycled bitumen would save both cost and environment. Usability of WEO

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into HMA may be a suitable option to protect the environment from hazardous waste materials.

There are many studies [8-13] about adding waste cooking oil into the bitumen. Overall results of this studies, waste cooking oil can rejuvenate the aged bitumen. In a suggestion of these results, WEO could be a useful material for modifying bitumen. DeDene and You [14] have studied WEO in two different rates modifying the HMA and performed FT-IR (Fourier Transform Infrared Spectroscopy) and rutting tests. They suggest using WEO as a rejuvenator material in reclaimed asphalt pavement. However, they warned about using not too much WEO. Therefore, this paper demonstrates the rheological properties and strength values of the WEO modified bitumen.

In this study, WEO has been collected from an automobile repair shop which is used about $15x10^3$ km. Collected WEO is mixed with bitumen as 1%, 3%, and 5% by weight of bitumen. For mixing the bitumen with the WEO, propeller mixer is used. Modified bitumen have been tested with penetration and softening point tests for each rate. In addition to the penetration and softening point tests, the effect of WEO to the optimum binder content (OBC) have been discovered by using volumetric mix design procedure. Therefore, specimens have been compacted using Superpave Gyratory Compactor (SGC). At last, the effect of WEO to the HMA is obtained using Marshall Stability and tensile strength ratio tests. A major goal of this study is to the evaluation of WEO in HMA to achieve a green and sustainable solution. Some minor goals are; reducing the bitumen content used in HMA, increasing the self-healing ability of the HMA and decreasing the workability temperature of the bitumen.

After the introduction section of this paper, aggregate and bitumen are explained in the materials section. After that, the procedure for modifying bitumen with WEO, testing of penetration and softening points, and strength tests which are conducted on the specimens are explained in the method section which is followed by the results and discussion. In the conclusion section, it is put forth of the usability of waste engine oil as a binder modifier. Paragraph: use this for the first paragraph in a section, or to continue after an extract.

2. Materials

2.1. Aggregate

Although WEO is a bitumen modifier, HMA samples should be produced and tested to determine the usability of the WEO modified bitumen. A simple mixture of limestone aggregate is used. Properties of the limestone aggregate are listed in Table 1. Maximum aggregate size is selected as 19 mm in accordance with wearing course specification. Gradation used in this study is shown in Figure 1.

Table 1. Properties of limestone ($CaCO_3$) aggregate used in the tests

Sieve Diameter	Property	Standard	Value
4.75 – 0.075 mm	Specific Gravity (g/cm3)	ASTM C 127-88	2.750
	Saturated Specific Gravity		2.652
	Water Absorption (%)		0.130
25 – 4.75 mm	Specific Gravity (g/cm3)	ASTM C 128 88	2.660
	Saturated Specific Gravity		2.428
	Water Absorption (%)		2.800
	Abrasion Loss (%)	ASTM C 131	20.38

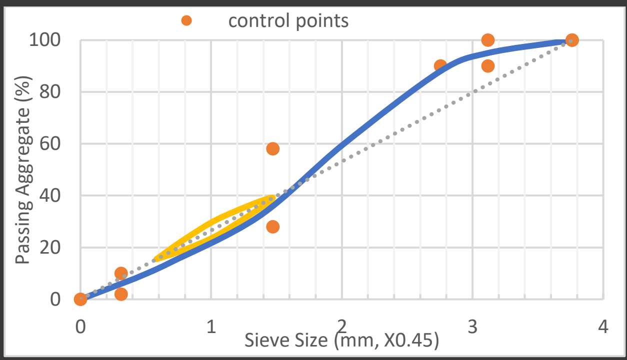

Figure 1. Gradation of the aggregates used in the study

2.2. Binder

50/70 penetration bitumen was supplied from Isparta Municipality as a binder for this study. Rheological properties of the neat bitumen are given in Table 2.

Table 2 Non-modified binder characteristics

Binder Characteristic Test	Average value	Standard
Penetration (25 ºC, 0.1 mm)	57.2	ASTM D5
Flash Point	180ºC	ASTM D92
Combustion Point	230 ºC	ASTM D92
Softening Point	51.1°C	ASTM D36
Ductility (@5 cm/min)	>100 cm	ASTM D113
Specific Gravity (g/cm3)	0.995	ASTM D70

OBC for neat bitumen is determined by preparing HMA samples at four different binder contents (3.5%, 4%, 4.5% and 5%). Samples were compacted using Superpave Gyratory Compactor (SGC) in accordance with EN 12697-31. Results are shown in Figure 2.

As seen from Figure 2, 4.5% binder content is giving the 4% air void, specification value. In addition, obtained voids in mineral aggregate (VMA) value should provide minimum specification limit (14%) for wearing course, which is 14.2% for 4.5% binder content. Voids filled with asphalt (VFA) should be between the specification limit values (65 – 75% interval) which are obtained 73.4%. So, selected 4.5% binder content provides all the specification limits and used as the OBC.

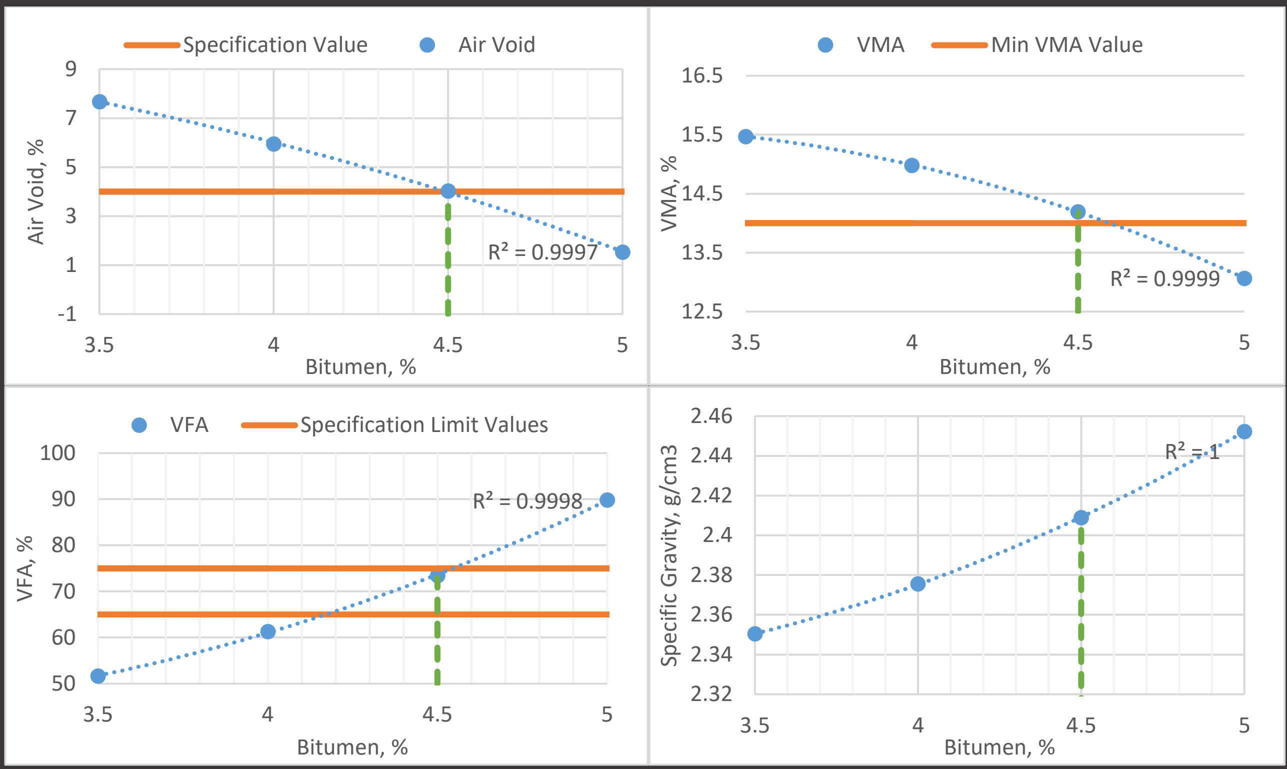

Figure 2. Volumetric mix design for non-modified bitumen

3. Method

3.1. Binder modification

Bitumen is modified with WEO using an adjustable 1.5-liter blender ($0 \leq {}^0C \leq 200$; $0 \leq rpm \leq 8000$). Bitumen is heated to 160°C and added certain rate (1, 3 and 5%) of WEO in the vessel. Mixing process was carried out at 4000 rpm for an hour. Afterwards the, bitumen tests (penetration and softening point) are undertaken on the WEO modified bitumen.

3.2. Penetration test

AASHTO T49 standard is used for determining the penetration value of the bitumen. 25°C conditioned bitumen is taken and placed under a needle with a 100 g constant load. Then, the needle with the load has been applied to the bitumen for five seconds. The penetration depth of the needle is measured. The depth of the penetration in 0.1 mm unit is recorded as penetration value of the bitumen. When the penetration value is high, then it means that the bitumen is soft and could be used in cold regions and vice versa. Bitumen behaviour against temperature change could be interpretable using the Penetration Index (PI) value of the bitumen which can be calculated as Equation 1.

$$PI=\frac{20(1-25A)}{1+50A} \quad (1)$$

$$A=\frac{\log V_P-\log 800}{25-V_{SP}} \quad (2)$$

Where PI is the penetration index, V_P is the penetration value at 25°C, and V_{SP} is the softening point of the bitumen.

3.3. Softening point test

The test was undertaken in accordance with AASHTO T53 standard for determining the softening points of the bitumen. Two rings are filled with the bitumen and the rings are placed in a fluid bath. Afterwards, the temperature of the fluid bath began to increase by heating. The temperature is recorded when the bitumen-filled ring no longer carries the 3.5 g steel ball and the ball falls 2.54 cm. Average temperature value recorded for the two rings is the softening point of the bitumen.

3.4. Indirect tensile strength

AASHTO T283 test procedure is used to obtain the Indirect Tensile (IDT) Strength. Compacted specimens were dry cured at the 40°C oven for 72 hours. Then, half of the specimens are loaded with the rate of 50.8mm/min until failure. Results are recorded as IDTU (unconditioned) strengths. Rest of the specimens are placed into a 25°C water bath for 24 hours and vacuum saturated to achieve a saturation level of 55 – 80% (Equation 3).

$$SL=\frac{(m_{Surf.Dry}-m_a)}{(V_a*V_s)}*10000 \quad (3)$$

$$V_a=\frac{(G_{max}-G_{bulk})}{G_{max}} \quad (4)$$

$$V_s=m_{Surf.Dry}-m_w \quad (5)$$

$$G_{bulk}=\frac{m_a}{V_s} \tag{6}$$

Where; SL is saturation level (%),$m_{Surf.Dry}$ is saturated surface dry weight (g), m_a is weight in air (g), V_a is air voids (%),V_s is volume of the specimen, G_{max} is theoretical gravity, G_{bulk} is bulk specific gravity and m_w is the weight of the specimen in water.

Saturated specimens are placed into freeze cabin at -18°C for 16 hours. Frozen specimens are thawed in a water bath at 60°C for 24 hours. Finally, specimens are placed for two hours into a 25°C water bath and then loaded till failure. The failure load values are recorded as IDTC (conditioned) strengths (Equation 7). IDTC to IDTU ratio is the Tensile Strength Ratio (TSR) (Equation 8). TSR is used to determine the moisture susceptibility. A minimum TSR value of 80% is recommended [15].

$$IDT=\frac{2P}{\pi dh} \tag{7}$$

$$TSR=\frac{IDT_C}{IDT_U}*100 \tag{8}$$

Where; IDT is the indirect tensile strength, P is the max load, d is the diameter of the specimens, h is the height of the specimens. IDT_C is the average strength value of the conditioned specimens and IDT_U is the average strength value of the unconditioned specimens.

3.5. Marshall stability

Marshall Stability test has been performed on the SGC compacted specimens to determine the stability change. Mixtures for each WEO rates have been prepared and compacted with SGC till 4% air void. Compacted specimens are soaked in a water bath at 25°C for 24 hours. Afterwards, they placed in a 60°C water bath for 30 minutes and loaded with Marshall Stability test machine at a speed of 50.8 ± 2 mm/min. The results are recorded as the stability value of the specimen.

4. Results and Discussion

Neat bitumen is modified using WEO with three rates (1, 3 and 5% by weight). WEO modified bitumen's change on softening point and penetration value is shown in Figure 3.

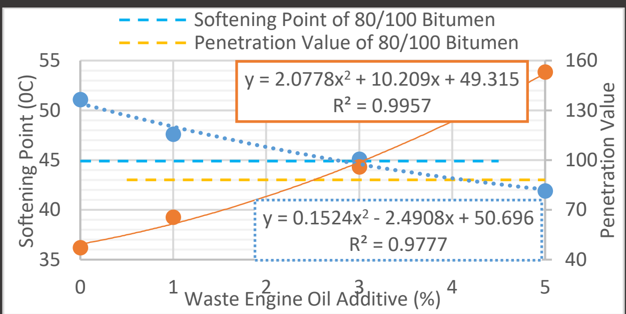

Figure 3. Change in the softening points and penetration values

Table 3 WEO modified binder properties

Property	Binder			
	Reference	1% WEO	3% WEO	5% WEO
Penetration, @25°C, , 0.1 mm	57.2	65,6	96	153.1
Softening Point, °C	51.1	47.6	45.1	41.9
Penetration Index	-1.057	-1.186	-0.883	-0.398

Figure 3 and Table 3 shows the change of penetration value, softening point and penetration index. The increase of the WEO additive in the bitumen increases the penetration value and decreases the softening point value. In addition, a simple softening point and penetration test is performed on an 80/100 bitumen. As a result, ~3% of WEO additive is close to 80/100 bitumen's softening point and penetration value. So, WEO could be used as a rejuvenator material as well as using a high-performance grade bitumen in colder regions. The decrease in the softening point allows more workability at lower temperatures.

WEO modified bitumen is used as a binder material in HMA to investigate the usability of the WEO. Therefore, Ø101.6 mm specimens are compacted and tested in accordance with AASHTO T283. Firstly, OBC is determined according to volumetric mix design procedure. 125 gyration numbers are selected to compact the specimens and they are compacted with four different binder rates. Change of the air voids, voids in mineral aggregates, voids filled with asphalt and specific gravity are shown in Figures 4, 5, 6 and 7, respectively.

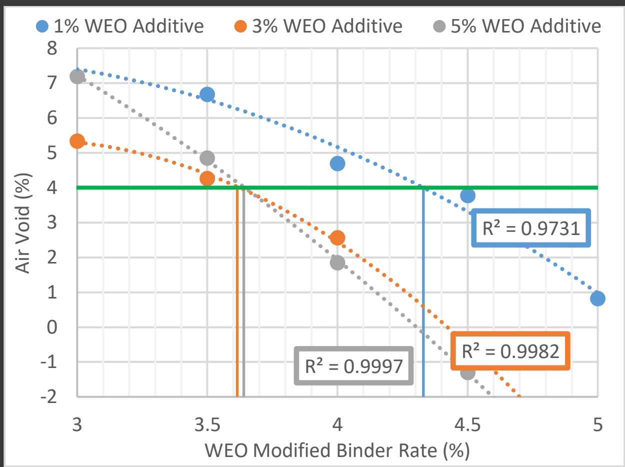

Figure 4. Binder rates versus air voids

Seen in Figure 4, binder rates that are giving the 4% air voids are the optimum binder rates and should provide minimum VMA specification limit, which is 14% for wearing course (Figure 5), and VFA values should be in the specification interval, which is 65 – 75% (Figure 6). Figure 7 shows the change in the specific gravity of the compacted specimens. Each rate is compacted in four different binder rates. However, specimens with 5% binder content that modified using 3 and 5% WEO had much more binder than it can hold in. So, excessing binder overflow out from the mould by compacting. Whence, after 125 gyrations (Ndesign), air void of the specimen goes below zero. Therefore, by obtaining the OBC for 3 and 5% WEO modified bitumen, specimens are compacted with 3, 3.5, 4, and 4.5% binder contents. Obtained OBCs are shown in Figure 8.

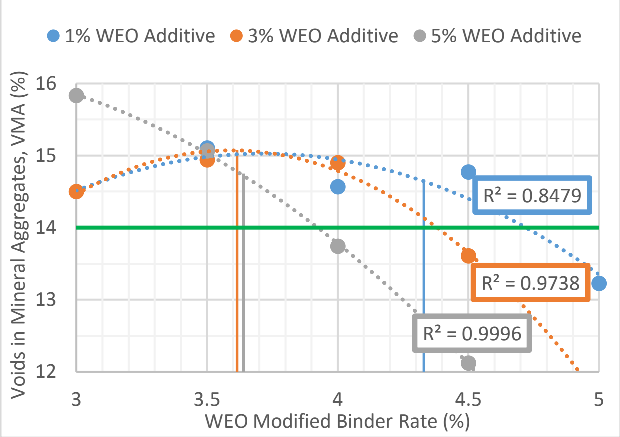

Figure 5. Binder rates versus VMA

Increase on the amount of the WEO added into the bitumen, decreases the OBC. Determined OBCs for neat, 1, 3 and 5% WEO added bitumen were 4.5, 4.33, 3.615 and 3.4% by weight of aggregates, respectively. The decrease on the OBC provides economic benefits as well as green solutions. In addition, using WEO in the bitumen decreases the needed bitumen content and so, the amount of the petroleum product decreases. At last, specimens should provide minimum TSR values for each determined OBC. IDT strengths and TSR values are shown in Figure 9.

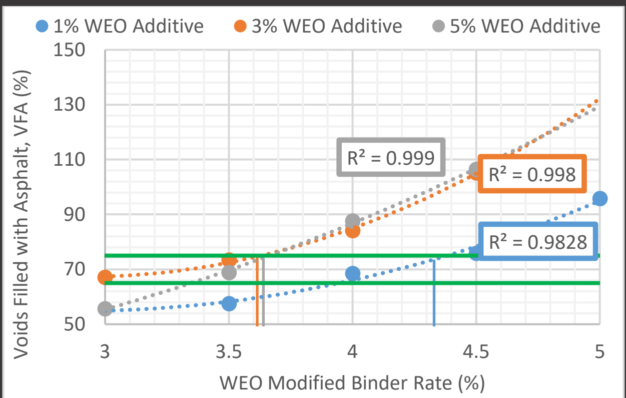

Figure 6. Binder rates versus VFA

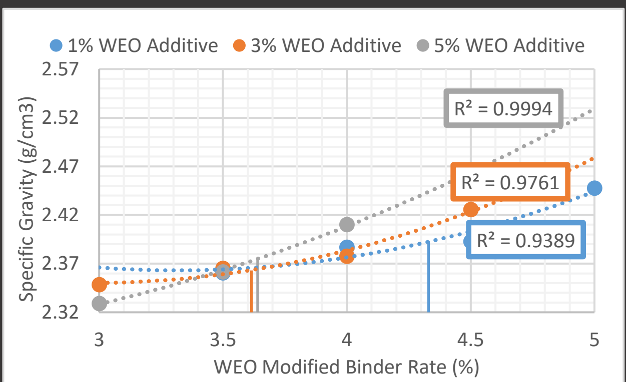

Figure 7. Binder rates versus specific gravity

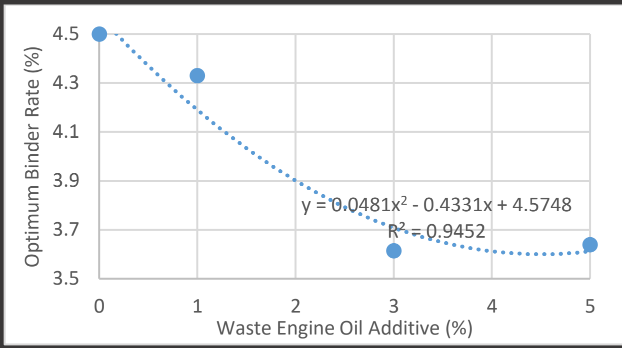

Figure 8. Change of OBC

IDT strength values for unconditioned specimens are decreasing by the increase of the WEO additive. However, the IDT strengths for conditioned specimens are increasing, although they are below the reference specimen's IDT strength. TSR values of the specimens which are compacted with 3 and 5% WEO modified bitumen, are above the minimum TSR value. Specimens compacted with SGC have been loaded with the Marshall tester to determine the stability and flow results. Test results are shown in Figure 10. According to the Marshall Stability test results, stability value has been decreased by modifying the bitumen with WEO. However, they all are above the minimum Marshall Stability value. Flow results should be between 2 and 4 mm where 1 and 3% WEO modified bitumen ensures the specification. When the IDT strength, TSR value, Marshall Stability and flow are considered together, 3%WEO modified bitumen could be used.

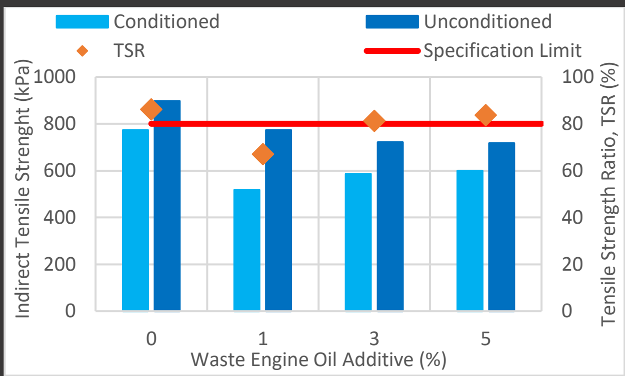

Figure 9. Indirect tensile strength and TSR values of specimens

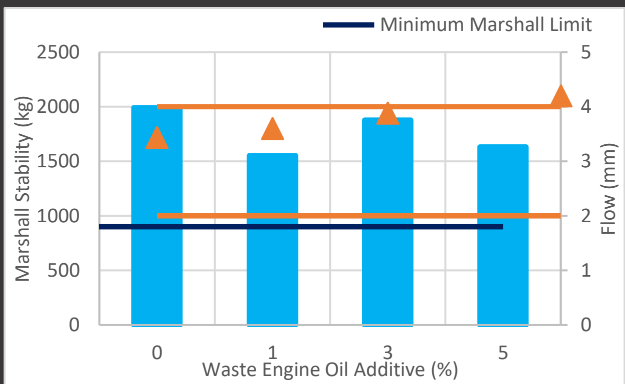

Figure 10. Marshall Stability and flow values of specimens

Pavements could be repaired over time by resting because of the thermoplastic behaviour. However, it is almost impossible under repeated traffic loads. But, the healing process could be speeded up by heating the pavement. Although it is a solution, heating causes bitumen to age and bituminous mixture can swell by overheating [16]. It can be though that by adding WEO into the bitumen decreases the self-healing temperature according to the values in Table 3. A non-standard test is conducted for testing the self-healing property of WEO added specimens. Specimens that are loaded to obtain the unconditioned IDT strength are left at ambient temperature for 72 hours. After 24 hours in the 60°C water bath, they are placed in a water bath at 25°C for two hours. Afterwards, they loaded again until failure. Results are shown in Figure 11.

Seen in Figure 11, the gradient of the first loading's trend line is 59.346. Therefore, it is expected that IDT strength values obtained at second loading should have a trend line with a gradient close to 59,346. However, the gradient value is 26.093. Therefore, it can be accepted that adding WEO into the bitumen has decreased the self-healing temperature of the specimen. In addition to the strength values, healing ratios can be seen in Figure 11. Healing ratio is calculated by dividing the strength value of the second loading to the first loading. 1% WEO modified bitumen heals itself by 65.07%. Increase on the WEO additive decreases the healing ratio of the specimens. The reason of this could be explained as increasing the WEO additive decreases the temperature for self-healing overmuch. Therefore, the binder in the specimen flows more than to fill the small cracks.

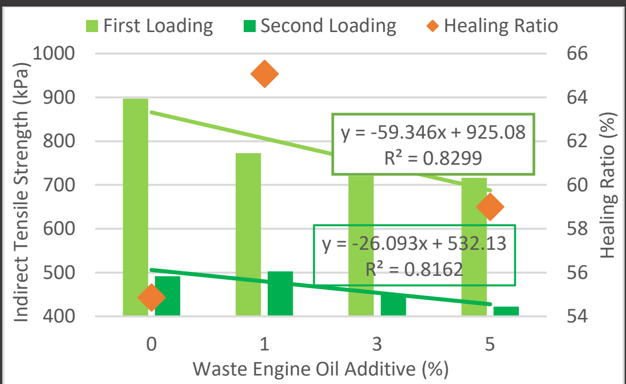

Figure 11. Change in the IDT strength after heating the specimens

5. CONCLUSION

Evaluation of hazardous waste engine oil is studied in this paper by determining the impact of WEO to the rheological properties of the bitumen and the physical properties of the mixture. Following conclusions can be drawn from this study:

- WEO could be used as a rejuvenator material for the aged bitumen.
- OBC was decreased by using WEO as bitumen modifier. So, economic gains (less bitumen) and green solutions (reusing of hazardous waste) are achieved in this paper.
- Decreasing the OBC decreases the amount of bitumen which is a petroleum product and hazardous to the environment.
- WEO modified high-performance grade bitumen could be used in colder regions.
- Adding WEO into the bitumen decreases the Marshall Stability and Indirect Tensile Strength values. However, all the specimens Marshall Stability value is above the specification limit.
- Adding WEO into the bitumen increases the flow of the mixture, and increases the TSR value. Therefore, 3% WEO added bitumen ensures both, flow and TSR specifications.
- WEO added bitumen's softening point is lower. Therefore, the mixture is able to heal itself faster at lower temperatures. In this way, WEO improves the self-healing feature of the bitumen.

Declaration of Interest Statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author Contribution Statement

E.Eriskin: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Draft writing – **S. Karahancer:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Draft writing – **S. Terzi:** Conceptualization, Data curation, Supervision, Validation, Review&Editing – **M. Saltan:** Conceptualization, Data curation, Supervision, Validation, Review&Editing

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