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Temperature sensitivity and performance evaluation of asphalt cement incorporating different types of waste polymers

Mahmoud Enieb[a*], Ahmed Salama Eltwati[b], Mohammed Abbas Al-Jumaili[c]

[a]*Department of Civil Engineering, Assiut University, Assiut, Egypt*
[b]*Department of Roads and Airports Engineering, Bright Star University, Brega, Libya*
[c]*Department of Civil Engineering, University of Kufa, Iraq*

Highlights

- Temperature susceptibility of Asphalt cements modified with CR and rPET was investigated
- The Temperature susceptibility was investigated by using PI, PVN, VTS, and AE methods
- CR and rPET decreased the temperature susceptibility
- CR and rPET increased the high temperature performance
- Correlation between the methods used to evaluate the temperature sensitivity

CR and rPET improved the rheological characteristics

Abstract

There is significant evidence that utilizing polymers improves asphalt cement characteristics, preserve the environment, and increases industrial-economic benefits. Consequently, the use of such modifier in asphalt cements via sustainable technology is strongly encouraged. The major goal of this research is to study the effect of modified asphalt cement with crumb rubber (CR) (10%, 15%, and 20% CR) and recycled polyethylene terephthalate (rPET) (1.5%, and 2.5% rPET) on the physical and rheological characteristics of asphalt cements. Asphalt cement experiments such as softening point, penetration, and rotational viscosity (RV), were performed on both the virgin and modified asphalt cements. The effect of CR and rPET on the temperature sensitivity of the asphalt cement was also evaluated by checking the penetration index (PI), penetration viscosity number (PVN), viscosity-temperature sensitivity (VTS), activation energy flow methods (AE) of all the modified asphalt cements. The rutting index (G*/sin δ) was calculated using Bari and Witczak model. The findings revealed that the addition of CR and rPET in the asphalt cement reduced the temperature sensitivity and enhanced the rheological characteristics of the asphalt cements. Moreover, incorporating the CR and rPET into virgin asphalt cements increased the high temperature performance of all percentage of CR and 2.5% WP modified asphalt. There was a considerable correlation between temperature sensitivity methods; PI, PVN, VTS, and AE. Finally, virgin asphalt modified with CR is better than rPET.

Information

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1. Introduction

Asphalt cements are viscoelastic materials, which are a tough elastic at temperatures that are low and a viscous liquid at high temperatures. Pavement performance is intimately related to the viscoelastic characteristics of asphalt cements and is gradually deteriorated when there is a heavy traffic volume and high-temperatures. In general, the loading period and temperature have a negative effect on the properties of asphalt cements [1, 2]. Hence, it is necessary to characterize asphalt cements with the aim of estimating the influences of temperature and stress on important engineering parameters. The behavior of asphalt pavements exhibits extreme sensitivity to temperature, including permanent high temperature deformation, service temperature fatigue, and thermal cracking due to low temperature [3, 4]. Temperature sensitivity is a significant factor in terms of rheological characteristics of asphalt cements. The term "temperature susceptibility" refers to a variation in the consistency of the asphalt cement s as a function of temperature. However, asphalt cements that have been modified to enhance the characteristics and function of the asphalt mixture is a viable approach to overcome the

*Corresponding author: ***m.enieb@aun.edu.eg*** (M. Enieb, +201002878440)

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problems of asphalt cements arising from their tendency to degrade performance against temperature.

Polymer modifications are a common technology to improve the quality of asphalt cements, which have an effect on asphalt pavement permeant deformation and thermal cracking. It is commonly recognized that polymer additives tend to enhance the characteristics of the asphalt cements considerably [5-8]. Polymers, for example, enhance cohesion, elasticity, and temperature sensitivity of asphalt cements, improve durability, low temperature thermal cracking, and high temperatures rutting in asphalt concretes concretes [9-13]. The polymers that are utilized as asphalt cement modifiers comprise three groups of plastomers, elastomer, and reactivity, depending to their composition and chemical properties. Although polymer modifiers reduce asphalt cements' thermal sensitivity, each kind of polymer has a different effect on the characteristics of asphalt cements [14]. Reactive and plastomer polymers generally raise stiffness and rutting resistance, while elastomer polymers enhance the elastic characteristics (fatigue resistance) of bitumen asphalt cements [15, 16]. Polyethylene, ethylene-butyl acrylate (EBA), and ethylene-vinyl acetate (EVA) copolymers are the most commonly used plastomers in the manufacturing of asphalt mixes, whereas styrene-butadiene natural rubber (SBR) is the most commonly used elastomer in the pavement industry.

Rubber and elastomer materials have been widely used for a long time as asphalt cement's modifiers and have received considerable attention from asphalt scientists due to their suitable properties, which have the ability to enhance various aspects of the asphalt cements and mixtures [17-20]. Furthermore, as a result of the environmental demand to reuse waste products, the utilization of rubber materials in asphalt mixtures offers alternative or more engineering application than recovered scrap tires. Elastomer's polymer additives such as styrene-butadiene rubber (SBR) and reclaimed polymers for instance crumb rubber (CR) have been applied to improve the temperature sensitivity of asphalt cements [21-24]. The combination of SBR with an asphalt cement results in the formation of a Split-phase block copolymer that absorbs oil and swells up to 9 times its original volume [25]. This leads to a significant variation in the characteristics of the original asphalt cement. The rheological behavior of asphalt cements containing SBR and CR has been evaluated by several studies [26-31]. They found that the inclusion of SBR and CR increased the fatigue life of the base asphalt cements. Furthermore, the performance of asphalt pavements such as rutting properties, resilient modulus, and tensile strength, were improved.

The global use of plastics is increasing substantially above the recycling rate, and the need for recycled materials is developing. The use of waste materials from recycled plastics in asphalt mixtures is being recognized as a practical approach to producing polymer modified asphalt to replace chemically pure virgin polymers and to provide environmental and economic benefits [32, 33]. As a result of the demand for recycling with the support of several governments, studies on recycled plastics in asphalt have increased dramatically in recent years. Joohari and Giustozzi, [34] investigated the commercial plastomers i.e., ethylene vinyl acetate (EVA), low density polyethylene (LDPE) and linear low-density polyethylene (LLDPE) as asphalt cements' modifiers. It was found that modification of asphalt cements enhanced stiffness at high temperatures and increased elasticity at moderate temperature. It was also shown that the incorporation of the plastomer into the asphalt cements led to an increase in stiffness and elastic behaviors at high temperatures and viscosity at low-temperatures. Bensaada et al., [35] found that modifying the asphalt cement with 3% waste plastics increased the softening point and decreased penetration. Furthermore, at superior temperatures, the rheological properties of asphalt cements were enhanced, resulting in a decrease in kinetic sensitivity and an enhancement in rutting resistance.

2. Objectives

The purpose of this study was to investigate how modifiers i.e., CR derived from scrap tires and recycled polyethylene terephthalate (rPET) produced from waste plastic cups (WP) affect the characteristics and temperature sensitivity of asphalt cements. To accomplish this, the rheological and physical characteristics of CR and WP modified- asphalt cements were assessed via the softening point test (SP), penetration test (Pen), and rotational viscometer (RV). Temperature susceptibility of the modified asphalt cements was measured using various methods in this study, including penetration index (PI), penetration viscosity number (PVN), viscosity-temperature susceptibility (VTS), activation energy flow methods (AE), rutting index ($G^*/\sin\delta$) for unaged asphalt cement using Bari and Witczak models [36].

3. Materials

The important steps that have been undertaken in this study are shown in Figure 1. Base asphalt cement was used, which was supplied from a nearby petroleum refinery and had PG 64-16. Table 1 represents the characteristics of the base asphalt cement utilized in this research. In this work, shredded waste plastic water cup (WP) and crumb tire rubber (CR) were utilized as asphalt cement modifications to improve the temperature susceptibility of asphalt cements, as shown in Figure 2. The WP was extracted from the waste plastic cup with particle size ranging from 2- to 5-mm length and 0.4-mm width, sourced from a cup-making company. The main constitute of WP is rPET polymers and Table 2 reveals their physical properties. On the other side, the CR in fine particles forming with a maximum particle size of 300 µm (passing sieve No. 50), was derived from scrap tires. Table 3 illustrates the properties of the CR.

Several samples were prepared to investigate the quality of modified asphalt cements in terms of temperature susceptibility. The first group of samples was made from modified base asphalt cement with CR in various amounts; 10%, 15%, and 20% by the weight of asphalt cement. The other group of samples was rPET incorporated to the base asphalt cement with percentages of 1.5 % and 2.5 %, by weight of the asphalt cement. All modified asphalt cements were made with high-speed shear blender (5000 r/minute) for one hour and the modification was constantly stirred at a temperature of 180 °C for 20 minutes at 1000 r/minutes to reduced bubbles [2].

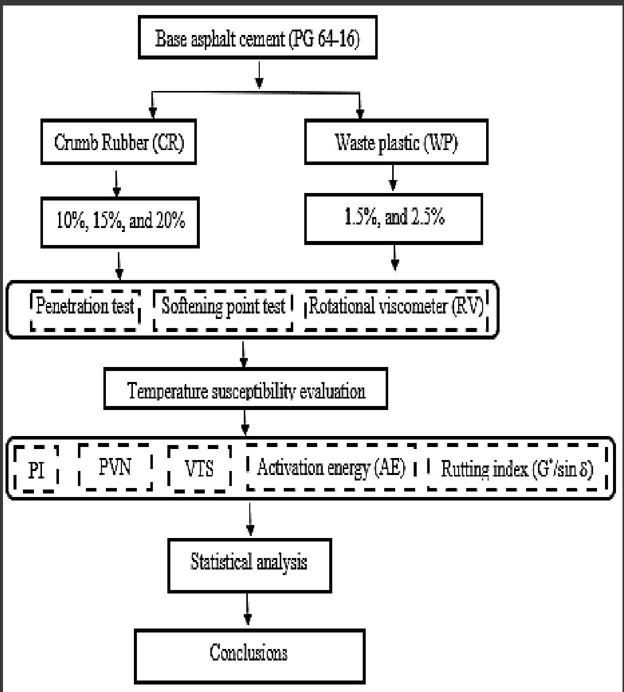

Figure 1. Experimental flowchart

Table 1. Base asphalt cement properties (PG 64-16).

Property	Value	Standards
RV @135 °C, cP	814	ASTM D 4402
RV @150 °C, cP	275	-
RV @165 °C, cP	150	-
Penetration @25°C, 5s, (0.1 mm)	46	ASTM D5
Softening point (°C)	52	ASTM D 36
Flash point (°C)	305	ASTM D 92
Specific gravity	1.13	ASTM D 70
Penetration indicator (PI)	-0.91	-
Penetration viscosity number (PVN)	-0.59	-

Table 2. Characteristics of waste plastic (WP).

Properties	Values
Density, g/cm^3	0.91
Tensile-strength, MPa	8.7
Tensile-elongation (%)	355
Melting temperature (°C)	109
Flexural modulus (MPa)	7.6

Table 3. Properties of crumb rubber (CR).

Property	Value	Standards
Specific gravity	0.88	ASTM D6270-98
Void ratio, e	1.5-2.5 (uncompacted) 1.2-0.9 (compacted)	-
Young's modulus, E, kPa	1240-5173	ASTM D6270-98
Poisson's ratio, (µ)	0.5	-
Capacity of water absorption (%)	2-4	-
Density (g/cm3)	1.3	-


(a) (b)

Figure.2. Materials used in this study, (a) crumb rubber (b) shredded plastic water cup.

4. Methodology

Several experimental tests i.e., the Pen, SP, and RV, were conducted in the laboratory to study rheological and physical characteristics of virgin and modified asphalt cements. ASTM-D36 [37] was used for the SP testing. The ring and ball device was employed to measure the softening point of asphalt cements which is explained as the temperature at which the asphalt cement must be heated for different road applications. Further, the penetration test at 25 °C was performed according to ASTM-D5 [38] standards, for consistency of asphalt cements measurement. The RV tester has been utilized to measure the viscosity of asphalt cements in the production and construction high temperature. RV testing ensures that the asphalt cement is a suitable temperature for mixing and compaction. According to the ASTM-D4402 [39] specification, the viscosity of the asphalt cement shall be less than 3000 MPa at 135°C.

5. Methods Used for Temperature Sensitivity Evaluation

Temperature sensitivity is a significant rheological feature of asphalt cements which is related to the final deformation performance. Temperature susceptibility is described as a parameter for determining how quickly the temperature changes in the asphalt cement properties. Recently, several different methods have been used to assess the temperature sensitivity of pure and modified asphalt cements. In this study, the methods of PI, VTS, and flow activation energy (AE) were utilized to evaluate the asphalt cement's performance in terms of their susceptibility to temperatures ranging from low to high temperatures.

5.1. Penetration index (PI) method

The PI method evaluates the temperature sensitivity of asphalt cements using data from penetration and SP tests. The PI can be utilized to quickly determine the temperature sensitivity of asphalt cements even if it is sometimes unsuitable with polymer modified asphalt cements. The Handbook of Shell Bitumen [40] provides a traditional method for calculating PI, as illustrated by the equation below

$$PI=\frac{1950-500.0\times \log\ (Pen)-20\times S\ P}{50.0\times \log\ (Pen)\ -S\ P-120.0} \quad (1)$$

Where;

Pen = penetration @ 25°C,

S P = temperature of softening point.

Higher PI values are the better performance in terms of temperature sensitivity of asphalt cements. Asphalt cements with an IP smaller than two for instance are extremely sensitive to temperature. It has been found that asphalt mixtures made of asphalt cements with low PI values are more susceptible to rutting and cracking at low temperatures [41, 42].

5.2. Penetration viscosity number (PVN) method

The PVN method is applied to estimate the temperature susceptibility of asphalt cements using the findings of penetration and viscosity tests. PVN was determined using the formula [43]:

$$PVN= 1.50\times\left(\frac{4.2580-0.79670\times \log\ (Pen)-\log\ (RV)}{0.79510-0.18580\times \log\ (Pen)}\right) \quad (2)$$

Where;

Pen = penetration @ 25°C in deci-millimeters,

RV = viscosity @ 135°C in centistokes.

Asphalt cements usually have PVN values ranging from +0.5 to +2.0 [43]. The asphalt cement temperature sensitivity is higher with declining in the PVN value.

5.3. Viscosity-temperature susceptibility (VTS) method

The VTS process has been commonly utilized to estimate the susceptibility of an asphalt cement to temperatures. The following equation is usually used to calculate VTS [44]

$$\text{Log}\ [\text{Log}\ (\eta)] = VTS \times \text{Log}\ (T)+A \quad (3)$$

Where;

η = viscosity in centipoise,

T = temperature of asphalt cement in degrees Rankine (R°),

A = intercept,

VTS = slope.

5.4. Activation energy of flow (AE) method

Viscosity may also be used to determine the fluid's shear resistance to a stream. As the temperature rises, the thermal energy of the particles increases, decreasing the flow resistance and reducing the viscosity of the liquid. The AE, which acts as a boundary to viscous flow, must be achieved before flow can occur [45]. Equation (4), sometimes described as the "Arrhenius" formula, can be applied to predict the temperature-viscosity relationship with asphalt cements [46].

$$\ln \eta = \frac{E_f}{R\,T} + \ln (A) \quad (4)$$

Where;

η = viscosity of asphalt cement in Pascal second, Pa.s

A = regression constant,

Ef = activation energy, kJ/mol

T = temperature in degree Kelvin,°K

R = universal constant of gas equal to 8.314 J/mol/degree Kelvin

5.5. Predict δ and G* using Witczak models for base and modified asphalt cements

Phase-angle (δ) and shear complex modulus (G*) are the two important parameters of Superpave determining viscoelastic behavior and finding performance grade (PG) of an asphalt cement. Bari and Witczak developed a model to predict with a high level of correlation (R^2 = 0.99) to calculate G* and δ at a given frequency and temperature according to the viscosity-temperature relationship as shown in Equation (3). This equation has been modified to account for loading frequency (fs = 1.59 Hz)) to find δ in degrees and G* in Pa.

$$\text{Log}\left(\text{Log}\ \eta_{fs,t}\right) = A' + VTS'\ \text{Log}\left(T\right) \quad (5)$$

$$A' = A\left(0.96990 \times f_s^{0.0257}\right) \quad (6)$$

$$VTS' = VTS\left(0.96680 \times f_s^{0.0575}\right) \quad (7)$$

$$\delta = \begin{bmatrix} 90.0 + \left(-7.3146 - 2.6162\ VTS'\right)\log\left(f_s \times \eta_{fs,t}\right) \\ +\left(0.1124 + 0.2029.\ VTS'\right) \times \left(\log\left(f_s \times \eta_{fs,t}\right)\right)^2 \end{bmatrix} \quad (8)$$

$$G^* = 0.0051 f_s \times \eta_{fs,t} \times \left(\sin\delta\right)^{7.1542 - 0.4929 f_s + 0.0211 f_s^2} \quad (9)$$

Where;

$\eta_{fs,t}$ is rotational viscosity as a function of f_s, in cP,

A' is modified A,

VTS' is modified VTS

6. Results and Discussion

6.1. Influence of CR and WP on the Physical Characteristics of Asphalt cements

Table 4 demonstrates the influence of CR and WP additions on the physical characteristics of asphalt cements as measured by softening point (S. P.) and penetration tests. From the table, adding the CR and WP led to reduce and increase the penetration and S. P. of the modified asphalt cements, respectively. This pattern was maintained as the contents of the additives increased.

Table 4. The softening point and penetration for base and

Asphalt cement type	Penetration,5s, @25˚C (0.1 mm)	Softening point (˚C)
Base	46	52
Base+10%CR	40	59
Base+15%CR	37	63
Base+20%CR	31	66
Base+1.5%WP	41	58
Base+2.5%WP	34	62

Figure 3 displays the influence of CR and WP on the RV of base and modified asphalt cements at different temperatures. Viscosity was determined at temperatures between 135 °C and 165°C for all specimens in this investigation. However, according to Figure 3, the RV of the asphalt cement raised with the increasing the content of the additive. The findings also indicated that the RV at 135 °C of the 20% CR-modified asphalt cement was about 2.5 times greater than the 1.5% and 2.5% WP-modified asphalt cements.

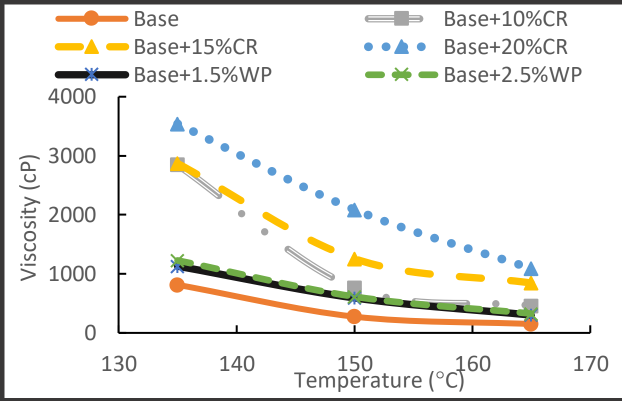

Figure. 3. Rotational viscosity of modified asphalt cements.

6.2. Effect of WP and CR on the Temperature Susceptibility of Asphalt cements

6.2.1. Results of PI method

Figure 4 illustrates the effect of incorporating crumb rubber and waste plastic on the penetration index (PI) of the reference and modified asphalt cements based on the penetration and softening point values. It was clear that the addition of waste plastics and crumb rubber enhanced the resistance to temperature susceptibility. This trend continued with the increase in the quantity of additives. Several previous studies showed the same results of this study [47, 48]. The PI values for modified asphalt cements were within the acceptable range from -1.0 to +1.0. Comparing CR with WP, the base asphalt cement (PG 64-16) with 20% had the maximum, while the base asphalt cement with 1.5% contained the minimum PI, respectively, indicating that CR-modified asphalt cements were less temperature susceptible than WP-modified asphalt cements. However, all the modified asphalt cements were shown to be less sensitive to changes in temperature compared to the base asphalt cement

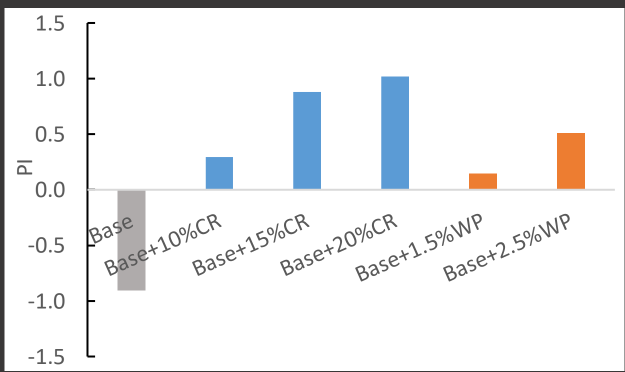

Figure 4. Results of PI for base and modified asphalt cements with CR and WP.

6.2.2. Results of PVN method

The Penetration viscosity number (PVN) of the base and modified asphalt cement with CR and WP are shown in Figure 5. It was seen that increasing the contents of CR and WP led to increase the VPN values, however, this was not always the case; for example, at 15% CR, there was a slight decrease in PVN. The figure also showed that all PVN values of asphalt cement specimens were in the +1.0 and -1.0 ranges. Typical PVN values for paving asphalt cements are in ranges of -0.5 to +2.0 and lower PVN values indicate higher temperature sensitivity, as said by Roberts, Kandhal [43]. Therefore, it can be concluded that the asphalt cement incorporating CR and WP had a lower susceptibility to the temperature than the base asphalt cement

6.2.3. Results of VTS method

Viscosity temperature sensitivity (VTS) was calculated to assess the temperature susceptibility at mixing and compaction temperatures (135, 150 and 165°C). An increase in VTS values means that the asphalt cement is more sensitive to change with temperatures [44]. Figures 6 and 7 show the VTS values for the modified asphalt cements with various contents of CR and WP. As can be seen, increasing CR and WP contents contributed to lower the VTS values of asphalt cements. The Base+20%CR provided the lowest value for the VTS, while the base asphalt cement exhibited the highest value. Therefore, the inclusion of CR and WP reduced the sensitivity of the modified asphalt cements to temperature variation.

6.2.4. Results of AE method

Figures 8 and 9 show the influence of CR and WP additives on the activation energy of the modified asphalt cement, and it was revealed that they were typically in the range of 58-70 kJ/mol and 84 kJ/mol for base asphalt cement. This results were consistent with findings of previous studies [46, 49]. It was also found that the asphalt cement containing CR and WP had a lower activation energy than the base asphalt cement, which means that the modified asphalt cements are less sensitive to change in temperature. This is due to the lower asphaltene content in the modified asphalt cement [50]. It was clear that as the CR percentages increased, the values of activation energy were reduced, indicating that asphalt cements with a greater concentration of CR were therefore less sensitive to the change in temperature. Conversely, increasing the WP content led to an increase in the activation energy.

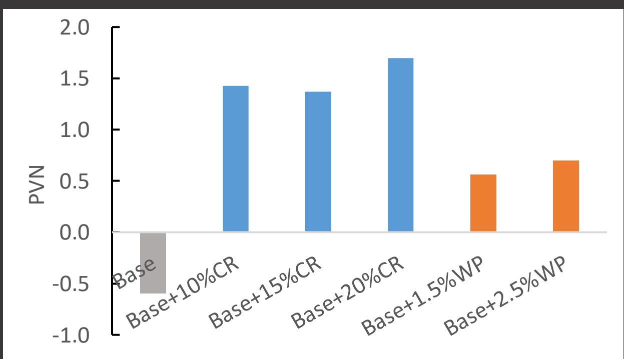

Figure 5. Results of PVN for the base and modified asphalt cements.

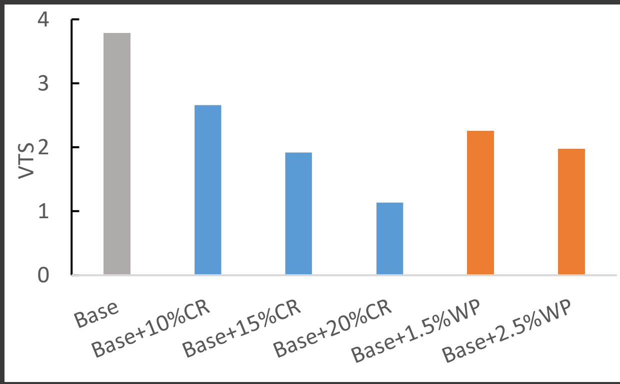

Figure 6. VTS results for modified and base asphalt cements @ 135, 150, and 165°C.

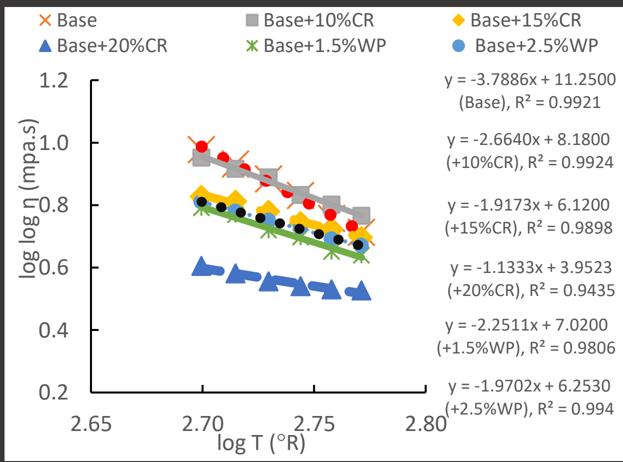

Figure 7. Viscosity-temperature relationship for the modified and base asphalt cements.

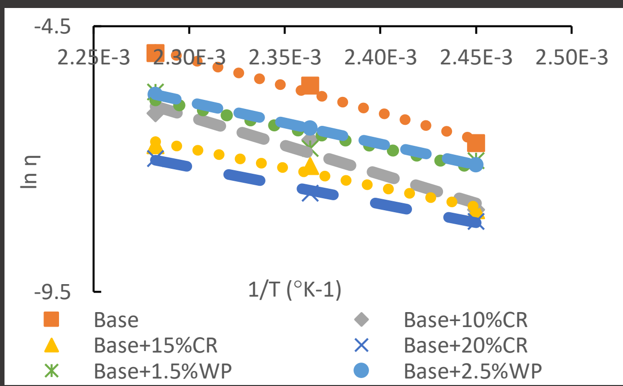

Figure 8. Results of RV test for the modified and base asphalt cements.

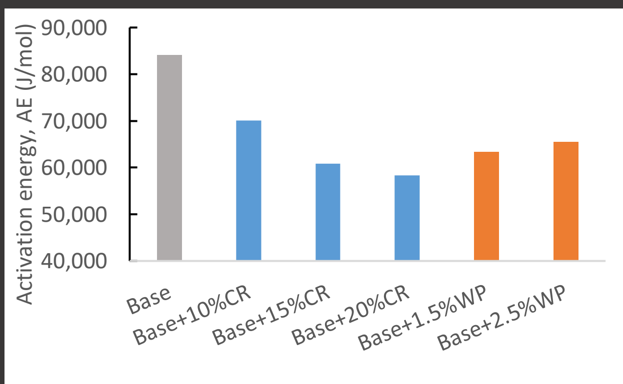

Figure 9. Results of AE for the modified and base asphalt cements.

Table 5. Values of A and VTS for the base and modified asphalt cements

Asphalt cement types	Base	Base+ 10% CR	Base + 15% CR	Base + 20% CR	Base + 1.5% WP	Base + 2.5% WP
VTS	-3.79	-2.66	-1.92	-1.13	-2.25	-1.97
A	11.25	8.18	6.12	3.95	7.02	6.25

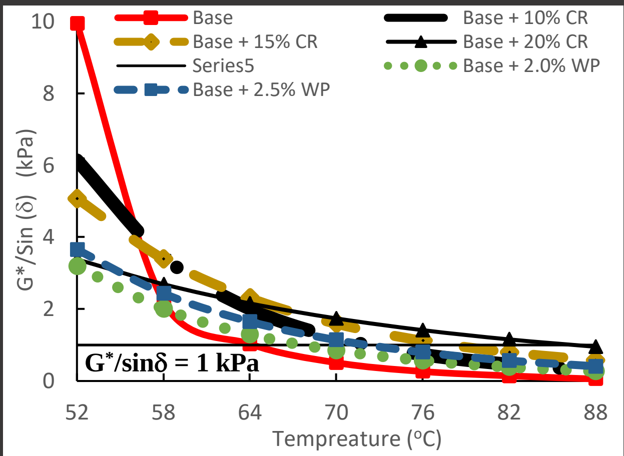

Figure 10. Results of performance grade at high temperature of base and modified asphalt cements.

6.3. Effect of WP and CR on the high-temperature performance grade

From the results of Figure 6 and Equation 3, VTS is the slope of the regression and A is the regression intercept of the linear logarithmic model of the relationship of temperature and viscosity shown in the following table for different asphalt cements. According to Bari and Witczak model with values of A and VTS from Table 5, Figure 10 is drawn from the range (52-88) °C.

Figure 10 shows the influences of WP and CR on the high temperature characteristics of asphalt cements. G* / Sin (δ) values for unaged asphalt cement must be ≥ 1.0 kPa as per Superpave requirements to help avoid rutting failure. The base asphalt cement mixed with CR and WP increased the G* / Sin (δ) as seen in Figure 10. This means that the rutting resistance of modified asphalt cement was higher than the base asphalt cement. In addition, it can be observed that, with higher percentages of CR and WP, one can see that the pattern was still present. As can be seen, adding a CR of 20%, 15%, and 10% to the base asphalt cement caused to upgrade the PG64-16 to PG82-xx, PG76-xx, and PG70-xx, respectively. A similar trend can be seen with WP modified asphalt cements, but with less significance; the base asphalt cement of PG 64-16 was affected by high temperature and 1.5%WP and 2.5% modified asphalt cements have upgraded to PG 70-xx (with one-grade increase). Mirzaiyan, Ameri [25] also studied the effect of using elastomer polymer modifier on high-temperature-performance grading-modified asphalt cements, and their results support the findings of this study.

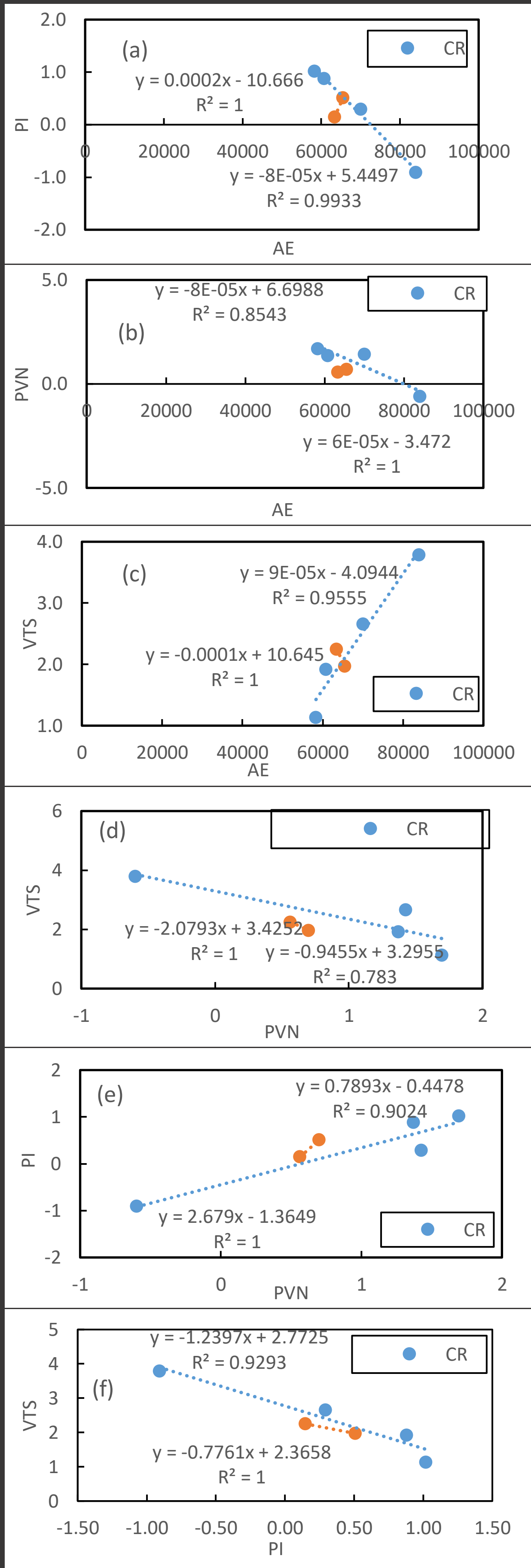

Figure 11. Correction between temperature susceptibility methods, (a) PI vs AE, (b) PVN vs AE, (c) VTS vs AE, (d) VTS vs PVN, (e) PI vs PVN, (f) VTS vs PI.

6.4. Correlation between the methods of temperature susceptibility

This study used a variety of approaches to test the temperature susceptibility of modified asphalt cements, including PI, PVN, VTS, and AE methods. These methods showed different results and interpretations for temperature susceptibility; therefore, it is useful to conduct a statistical analysis to determine if there is a relationship between these methods. The correlation coefficient (r) was used for the degree and strength of the correlation. The value of r coefficient is in the range of -1.0 and +1.0 where the value is always absolute. The r coefficient of 0 suggests that there is no connection between the variables being examined. The stronger the present correlation, regardless of direction, the closer the r coefficient approaches1, suggesting a more linear relationship between the variables. The closer the coefficient r towards ±1, direction regardless, the stronger the correlation revealing a more linear relationship between the variables. Table 6 and Figure 11 show the correlations between temperature susceptibility methods; PI, PVN, VTS, and AE. The results showed that there was a significant correction among all methods, with the r coefficient for all methods approaching ±1.0, regardless of the waste polymer modifier types.

Table 6. Correlation coefficient of different methods of temperature susceptibility evaluation.

	AE	PVN	PI	VTS
AE	1			
PVN	-0.83	1		
PI	-0.95	0.92	1	
VTS	0.96	-0.82	-0.95	1

7. Conclusion

The following conclusion can be reached based on the experimental and theoretical findings of this study:

- The asphalt cement modified with CR and WP increased the softening point while penetration was reduced.
- The rotational viscosity of the modified asphalt cement was improved with increasing the additive content and was still less than 3000 cP at 135 °C according to Superpave requirements. Also, the viscosity at 135 °C for the 20% CR modified asphalt cement was two and a half times greater than that of the 2.5% WP modified asphalt cement.
- The penetration index of 20% CR-modified asphalt cement was higher than 2.5% WP, which indicated that CR-modified asphalt cements were less sensitive to temperature than WP-modified asphalt cements.
- The penetration viscosity number (PVN) of CR-modified asphalt cements was higher than WP-modified asphalt cements. This shows that the CR-modified asphalt cement was less susceptible to temperature than WP-modified asphalt cement.
- The viscosity-to-temperature sensitivity (VTS) of asphalt cement modified with 20% CR is less than all percentage of WP-modified asphalt cements in absolute terms.
- The 15% and 20% CR modified asphalt cement had lower activation energy values than 1.5% and 2.5% WP-modified asphalt cements. This means that the CR-modified asphalt cement was less susceptible to temperature changes than the WP-modified asphalt cement.
- 20% CR-modified asphalt cement upgrade performance from PG64-xx to PG82-xx, while 2.5% WP-modified asphalt cement and base asphalt cement have upgraded by one grade increment.
- There was a strong correlation coefficient among all methods of analysis. In conclusion, the CR-modified asphalt cement was better to the WP-modified asphalt cement

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

M. Enieb: Conceptualization, Data Curation, Formal analysis, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing - Original Draft, Writing - Review & Editing – **A. S. Eltwati:** Conceptualization, Data Curation, Formal analysis, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing - Original Draft, Writing - Review & Editing – **M. A. Al-Jumaili:** Conceptualization, Data Curation, Formal analysis, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization.

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Investigation of wetting and hydrophobic properties of bitumen modified with different vegetable oils

Sercan Serin[a,*], Sümeyye Elif Demirezer[b]

[a]*Department of Civil Engineering, Faculty of Engineering, Osmaniye Korkut Ata University, Osmaniye, Turkey*
[b]*Department of Civil Engineering, Institute of Natural Sciences, Düzce University, Düzce, Turkey*

Highlights

- Bitumen modified with different vegetable oils.
- Physical, mechanical and hydrophobic properties of bitumen were determined.
- Hydrophobic properties of bitumen can be improved with vegetable oils.
- Vegetable oils cause serious changes in the physical and mechanical properties of bitumen.

Abstract

In this study, the effects of oils obtained from vegetable products on the physical, mechanical and hydrophobic properties of bitumen were investigated. Within the scope of the study, six different vegetable oils were used for bitumen modification: hemp oil, flax seed oil, laurel ghee, centaury oil, castor oil, pine turpentine oil. These are 100% pure vegetable oils, obtained by using cold press method. The bitumen was modified by adding vegetable oils to bitumen with the proportions of 3%, 5% and 7%. Including the reference group, 19 sample groups were formed with six different vegetable oils by using three different mixing ratios. The physical and mechanical properties of the prepared bitumen samples were determined, according to their contact angles their sensitivity to water, surface wetting and hydrophobic properties were determined by using the IMAGEJ program. As a conclusion of the results of the studies, it has been introduced that different vegetable oils cause serious changes in the physical and mechanical properties of bitumen, and in addition, bitumen modified with vegetable oils can make a significant contribution to removal of water from the road surface which is a major problem for traffic safety.

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1. Introduction

In this study, in order to eliminate the damage caused by water and moisture on bitumen, the change in the hydrophobic property of bitumen as a result of modification with different vegetable oils has been investigated.

Bitumen is a chemical having a high boiling point that contains hydrocarbons in its structure. Bitumen is used as a binder for the aggregates in asphalt mixture to hold together. Its road surface properties are known to play an important role in traffic safety. As a result of the technology supply and greater demand from road users, surface properties of roads are becoming increasingly significant in the construction and maintenance of roads for comfort and safety [1].

Bituminous coatings provide good driving comfort to drivers by means of their smooth surface feature. Roads with smooth surfaces would also reduce the risk of accidents in rainy weather. Because the water film thickness is related to mean texture depth of pavement surface. There is consensus among many researchers about the effect of the surface properties of the coating on accident risks [2-4].

Moisture damage at the interfaces of bitumen-aggregate in the binder has been studied by various researchers [5, 6]. In these studies, moisture damage behavior in asphalt pavement was investigated to measure the adhesion strength of the asphalt binder. Lately, the surface energy of bitumen and aggregate has been empirically associated with moisture-related damage of asphalt concrete [6].

*Corresponding author: sercanserin@osmaniye.edu.tr (S. Serin, +90 328 8271000-3621)

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Moisture damage can be defined as loss of strength and durability in asphalt mixes due to moisture. Moisture damage occurs due to loss of bonding between asphalt cement and fine and coarse aggregate. On the other hand, the effect of repetitive loads causes the pavement to become more sensitive to moisture [5].

For reasons such as eliminating the negative effects mentioned above, and on the other hand, to develop sufficient elastic properties with improved resistance to permanent deformation, to prevent cracks, to provide bitumen the necessary rigidity at high temperatures, to provide flexibility at low temperatures, to provide bitumen a high storage stability and resistance to thermal deformations, it is seen that bitumen has been modified using various additives [7].

In this study, in order to eliminate the damage caused by water and moisture on bitumen, the change in the hydrophobic property of bitumen as a result of modification with different vegetable oils has been investigated.

2. Hydrophobic and Hydrophilic Property

As a result of the effect of the potential energies of liquids, the molecules remaining in the interior are less dense than the molecules on the surface of the liquid, so that surface tension occurs on the surfaces of liquids. Thus, liquid substances form different contact angles with solid surfaces. If contact angles are greater than 90 ° C, it is hydrophobic, if less than 90 ° C it is hydrophilic (Figure 1). It is defined as superhydrophobic if greater than 140 ° C, and superhydrophilic if closer to 0 ° C [8].

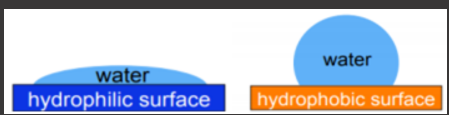

Figure 1. Hydrophilic and hydrophobic surface, respectively [9].

The term surface contact angle, first discovered by Thomas Young in 1805, is one of the methods used in determining the non-wetting state of solids, their surface energy properties, liquid-solid interface and solid surface energy at minimum equilibrium distance [10].

The expression of contact angle (θ) depending on surface and interface energies, also known as Young's Equation, is shown below [11].

YsgCosα=Ykg-Yks (1)

In this equilibrium;

Ysg: Surface tension (energy) of the liquid (mJ/m²)

Yks: Energy of the solid - liquid interface (mJ/m²),

Ykg: Energy of the solid surface (mJ/m²)

A modal representation of the parameters used in the equation is presented in Figure 2 below.

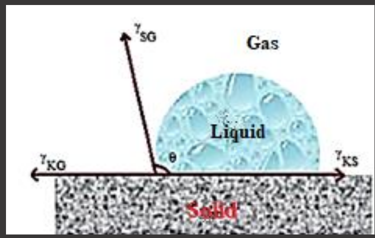

Figure 2. Representation of contact angle of a water drop with solid surface [12].

Materials with altered hydrophobic or hydrophilic properties by improving their performance with various additives are found in many sectors on production of products [10-22]. In addition, this issue has been widely discussed in scientific studies in different areas such as soil improvement, coating of materials, enhancing hydrophobic properties to concrete and cement-based materials, and reducing the effect of corrosion in reinforcement steel [8, 11, 23-28].

In the study conducted by Lal et al. [29], wetting and drying of a hydrophobic macroporous setting such as porous asphalt (PA) was investigated under different environmental loads. Three different types of porous asphalt with different pore sizes were sealed on all surfaces except the upper one, and they were tested by pouring water droplets on them.

In 2018, Zakerzadeh et al. aimed to measure the contact angle of the material sprayed to the surface, in the presence of various hydrophobic coatings with a certain weight percentage. In asphalt samples, the contact angle measured with 8 different hydrophobic materials was investigated. On average, they increased the contact angle of the asphalt surfaces from 75 to 156, making the surface of the asphalt pavement superhydrophobic [30].

Gao et al. [31] prepared samples of super hydrophobic asphalt concrete by using modified hydrophobic materials and nanomaterials in their study. Anti-icing and de-icing performance of superhydrophobic asphalt concrete has been investigated on different designs. Simulation test and theoretical analysis were used together in the study, and it was compared with conventional asphalt concrete. The researchers examined the anti-ice properties of the samples prepared by using contact angle and surface energy.

Nahvi et al. [32], in their study, optimized the superhydrophobicity and slip resistance of hydrophobic coatings on asphalt concrete surfaces. It has been tried to make asphalt concrete superhydrophobic by using different spraying times and various dosages of chemicals. In order to determine the superhydrophobicity and shear resistance of coated asphalt concrete, water contact angle and friction coefficient were measured at the micro-tissue.

Han et al. [33] aimed to obtain a hydrophobic emulsified asphalt coating on asphalt pavement by adding a hydrophobic agent to the emulsified asphalt in their research. Factors affecting the hydrophobic property, such as the roughness of the hydrophobic material, the dosage and the joining method were taken into account. Anti-ice property (ice-repellency) of the prepared samples was characterized by the contact angle.

Han et al. [34] have made a research to overcome the shortcomings in durability of hydrophobic emulsified asphalt pavement caused by poor slip resistance performance and poor wear resistance. In the study, hydrophobic emulsified asphalt modified with waterborne epoxy resin was used. The wet track abrasion test and load wheel test were performed to evaluate the optimal asphalt content of the micro surfacing mixture.

Dalhat et al. [35] used recycled low and high density Poly-Ethylene (rLDPE and rHDPE) to transform the asphalt surface from hydrophobic to Super Hydrophobic. Asphalt surfaces have been modified using different curing times. Then, the roughness and water contact angle of the prepared samples were analyzed.

In this study, it was aimed to modify the pure bitumen used on asphalt roads with different vegetable oils. Thus, the change in wetting and hydrophobic properties of bitumen was investigated. In the literature search, there is no study found where vegetable oils are used to improve the hydrophobic properties of bituminous materials. In this context, six different vegetable oils obtained by cold press were used for bitumen modification, and the change in surface contact angle was compared with the reference sample. On the other hand, the changes in the physical and mechanical properties of the modified bitumen were also comparatively studied.

3. Material

3.1. Bitumen

The bitumen B 50/70 used in the study was obtained from the asphalt production facility used in urban road construction. Basic physical experiments were carried out on bitumen before it was modified. The results of the experimental studies are presented in a table below (Table 1).

3.2. Bitumen modification with vegetable oils

Six different vegetable oils were used in the study to modify bitumen. These are 100% pure vegetable oils, obtained by using cold press method. Six different oil types were chosen for the study: Flax seed oil, laurel seed oil, hemp seed oil, centaury oil, castor oil, pine turpentine oil. Especially cold pressed vegetable oils were preferred in the study, since they were obtained only by mechanical method without heat treatment. On the other hand, while the vegetable oils used in the study were preferred, the plants that are widely produced in our country or that are aimed to be expanded were taken into consideration.

Table 1. Basic physical properties of bitumen.

Tests	Specification Limits	Test Results
Ductility (cm)	> 100	> 100
Nicholson test (%)	> 50	> 50
Softing Point (˚C)	-	47.70
Penetration (1/10 mm)	-	62.80
Bitumen Class	-	B50/70
Specıfıc Gravıty (gr/cm^3)	-	0.99

Within the scope of the study, different ratios were used to determine to what extent the vegetable oils changed the water and moisture sensitivity of bitumen. In this process, bitumen was modified by adding each vegetable oil in three different proportions (3%, 5%, 7%). Thus, modified bitumen with six different oils having three different contents has been developed. In addition, after the reference bitumen sample is included, a total of 19 different groups were formed in the study. The abbreviations for the formed groups are presented in Table 2. Abbreviations of the modified bitumen by adding vegetable oils to pure bitumen in different proportions are shown in Figure 3.

Table 2. Coding the mixing ratios.

	% Content	Coding
Reference Bitumen Sample (RBS)	-	RBS
Hemp Seed Oil (HSO)	3	HSO3
	5	HSO5
	7	HSO7
Flax Seed Oil (FSO)	3	FSO3
	5	FSO5
	7	FSO7
Laurel Seed Oil (LSO)	3	LSO3
	5	LSO5
	7	LSO7
Centaury Oil (CEO)	3	CEO3
	5	CEO5
	7	CEO7
Castor Oil (CAO)	3	CAO3
	5	CAO5
	7	CAO7
Pine Turpentine Oil (PTO)	3	PTO3
	5	PTO5
	7	PTO7

4. Method

In this study, an image analysis program called IMAGEJ was used to determine the sensitivity of modified bitumen to water and to reveal their hydrophobic properties. This program is very practical, and it gives fast results. The photos of the drop were taken to measure the contact angle of the water drop on the bituminous mixture with the solid surface, so that the drop was fixed and perpendicular to the surface. These photos transferred to the IMAGEJ program. The contact angle for 19 samples was analyzed one by one under the Contact Angle tab. Thus, it was revealed how differently the prepared mixtures react to water. In Figure 4, the picture of the contact angle determination of the samples is presented.

Figure 3. Samples prepared by adding different proportions of vegetable oil.

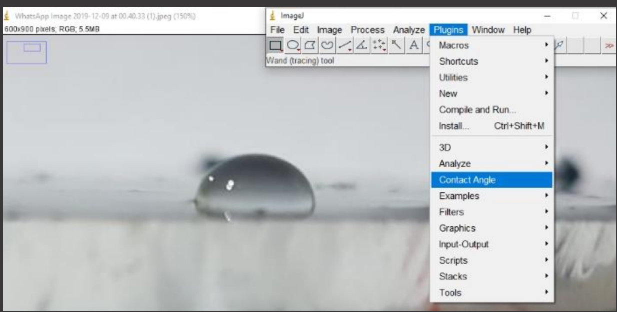

Figure 4. Contact angle analysis done by IMAGEJ program interface.

5. Research Findings

5.1. Physical tests on modified bitumen

Some experiments have been carried out to determine the changes in the physical and mechanical properties of bitumen after vegetable oils added in different proportions to bitumen. The results were examined in detail (Table 3).

According to the results of softening point test, the softening value of our reference samples was determined as 47.70 ° C. In the mixture with FSO, CAO and LSO additives, when the effects were examined according to the varying ratio of the vegetable oils in the mixture, it was observed that the softening point increases along with the increase in the ratio of vegetable oil. On the contrary, in other groups (HSO, CEO, PTO), it was observed that the softening points of the bitumen decreased with the increase in the oil content.

When the effects were examined according to the varying ratio of the vegetable oils in the mixture, in all groups, it was determined that as the rate of vegetable oil in the bitumen is increased, the penetration value increases. This shows that the oils in the mixture increase the processability of the mixture.

The specific gravity values of all groups except FSO and LSO increased along with the increase in the oil content. This result is thought to be directly related to the specific weight of the oils added in the mixture.

Also the ductility and Nicholson stripping test results were examined for all groups, it is determined that all groups meet the specification limits.

Table 3. The physical test results of modified bitumen.

Vegetable Oil	V. Oil Content (%)	Softening Point (˚C)	Penetration (1/10 mm)	Specific Gravity (gr/cm^3)	Ductility (cm)	Nicholson test (%)
RBS	0	47.70	62.80	0.99		
	3	51.10	63.70	1.21		
HSO	5	50.50	76.60	1.23		
	7	48.75	107.00	1.25		
	3	45.60	82.00	1.35		
FSO	5	47.75	91.30	1.27		
	7	53.00	100.00	1.19		
	3	48.75	67.60	1.27		
LSO	5	55.00	85.70	1.22		
	7	55.50	93.30	1.18	> 100	> 50
	3	53.15	63.30	1.12		
CEO	5	51.25	72.00	1.21		
	7	48.05	84.30	1.25		
	3	50.25	61.00	1.22		
CAO	5	50.30	66.60	1.41		
	7	53.50	93.30	1.5		
	3	56.50	72.70	1.21		
PTO	5	53.25	123.30	1.32		
	7	49.00	144.60	1.35		

5.2. EDX analysis of modified bitumen

EDX point or area analysis; It gives the element distribution of selected area on the sample surface in percentage. By applying high voltage and high pA, the concentration of X-rays is increased, by absorbing from the 200 nm surface of the sample, it gives results.

The results of electron-dispersed X-ray spectrometer analysis of 19 samples are given in Table 4. The information about the chemical composition of the mixtures was obtained by EDX analysis. In Figure 5, the change of EDX analysis values within the same group is presented. The change that occurred with the increase in the amount of oil in the FSO group was compared with the reference sample. As a result of EDX analysis, it is observed that the structures peaking at carbon (C), oxygen (O) and sulfur (S) elements. In the reference sample, it was observed that the majority of the composition (86.8%) was carbon, which is followed by 10.55% oxygen and 2.64% sulfur. When the FSO groups are examined, it was observed that the 3% of flax seed oil added to the mixture reduces the amount of carbon and sulfur and increases the amount of oxygen in the modified bitumen. With the increase of flaxseed oil content, it was observed that there was an increase in the amount of carbon and sulfur in both solution groups with 5% and 7% of oil content in modified bitumen, whereas the amount of oxygen decreased.

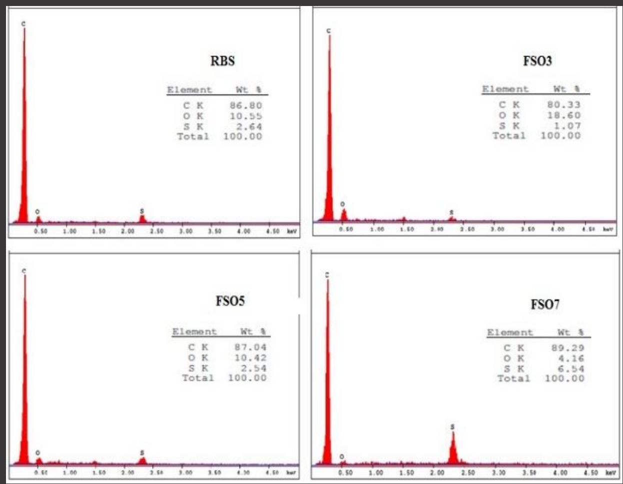

Figure 5. The change of the values of EDX analysis within the same group.

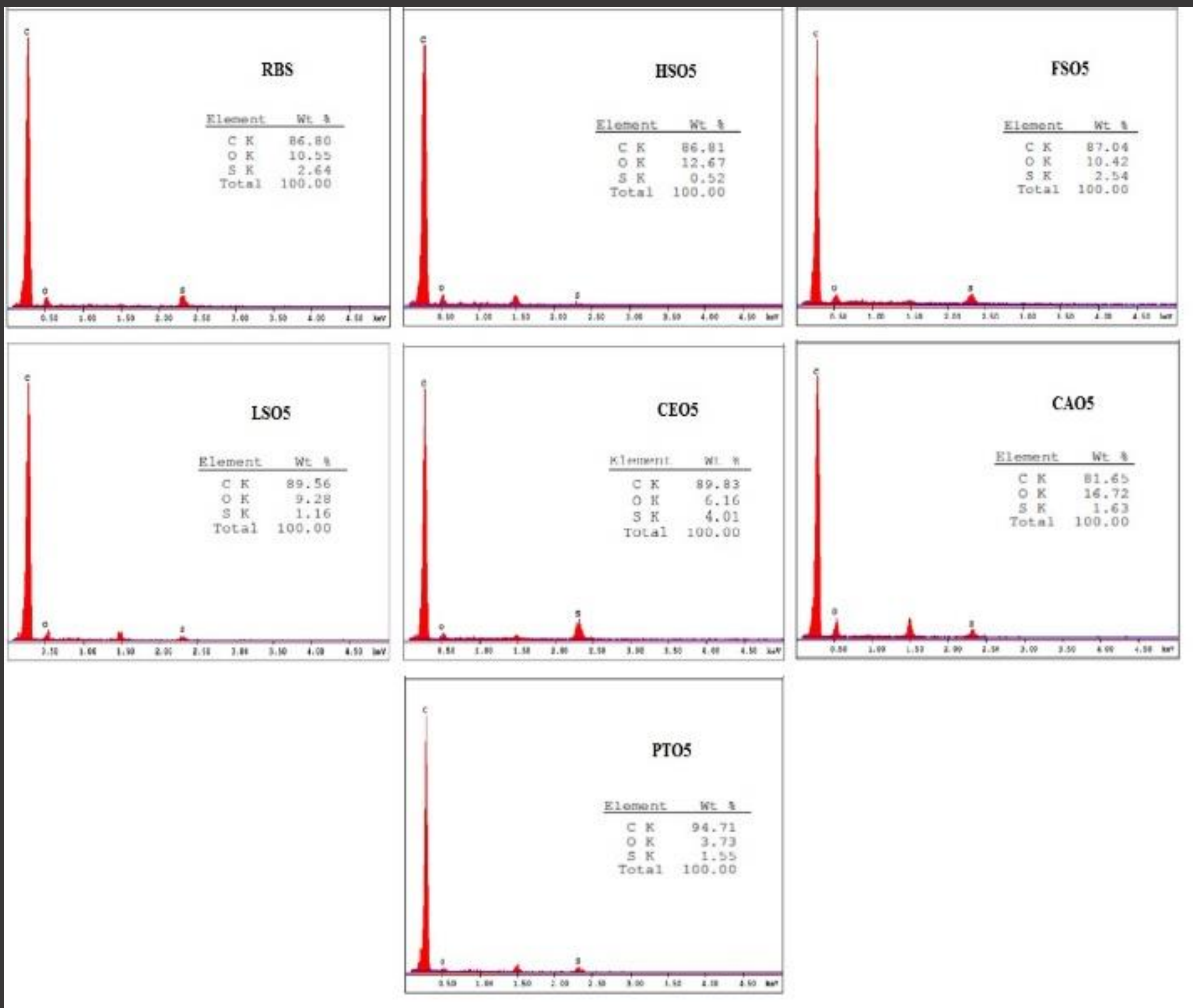

Figure 6. Change of the values of EDX analysis within different groups.

In Figure 6, the changes that occur when different vegetable oils are added to bitumen at the same ratio have been examined. It has been determined that the carbon content of the HSO group was close to the reference sample, while its sulfur value decreased, and oxygen value increased. It has been determined that compared to the reference sample, carbon values increase, and oxygen values decrease in groups having 5% of oil FSO, LSO, CEO and PTO groups. In the CAO group having 5% of oil on the other hand, it has been determined that the carbon content is lower than the reference and the oxygen content increased. Except in CEO group in all groups, compared to the reference, a decrease in sulfur content was determined. The Aluminum peaks (Al) found in the analyzes were not included in the evaluation, since it is believed that the mixture samples were caused from the containers where they were stored.

The EDX results of the sample groups given above and of all other groups are presented in Table 4.

5.3. Hydrophobic properties of modified bitumen

19 different prepared samples were transferred to flat plates with a manner to have a flat surface. In order to determine the hydrophobicity and water sensitivity of the modified bitumen mixtures, a drop of water was dropped on the bitumen mixtures, which were poured into the container and completely hardened, and images were taken and analyzed (Figure 7).

The photographs were taken in a way that the drop was seen fixed and vertical on the surface to measure the contact angle between water drop on the bituminous mixture with the solid surface. They were transferred to the IMAGEJ program. The contact angle is analyzed one by one under Contact Angle tab for the 19 samples. Figure 8 shows the determination of the values of angles after the analysis made with IMAGEJ for the reference sample and different samples.

Table 4. The results of EDX analysis.

	Elements %		
Coding	C	O	S
RBS	86.80	10.55	2.64
HSO3	89.00	7.30	3.70
HSO5	86.81	12.67	0.52
HSO7	89.29	9.60	1.11
FSO3	80.33	18.6	1.07
FSO5	87.04	10.42	2.54
FSO7	89.29	4.16	6.54
LSO3	93.13	2.84	4.03
LSO5	89.56	9.28	1.16
LSO7	87.76	11.39	0.86
CEO3	91.74	7.23	1.02
CEO5	89.83	6.16	4.01
CEO7	92.66	2.42	4.93
CAO3	91.09	5.86	3.05
CAO5	81.65	16.72	1.63
CAO7	86.43	9.57	4.00
PTO3	91.82	6.88	1.30
PTO5	94.71	3.73	1.55
PTO7	91.63	2.52	5.85

Figure 7. Position of the water drop on the bituminous mixture.

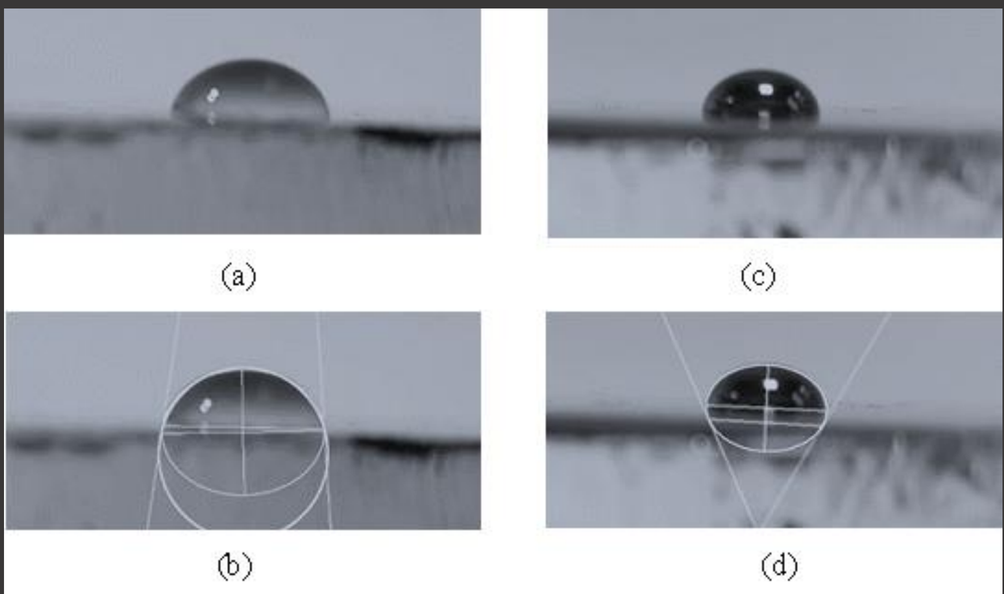

Figure 8. Image of water drop on bitumen surface before and after the analysis (a) Reference sample, (b) Reference sample after the analysis, (c) CEO3 sample, (d) CEO3 sample after the analysis.

Table 5. The results of contact angle analysis of all samples.

	Angle	Length	Theta C	Uncertainty	Theta Left	Theta Right	Theta E	Radius	Contact Angle
RBS	178.91	264.05	107.80	0.50	97.60	94.70	96.20	138.70	72.20
HSO3	177.43	89.09	98.90	0.30	97.00	97.30	97.20	45.10	81.10
HSO5	-178.41	108.04	94.80	0.50	80.60	92.50	86.60	54.22	85.20
HSO7	178.94	108.02	107.50	0.80	101.80	101.40	101.60	56.61	72.50
FSO3	-179.54	124.00	96.90	0.40	83.60	87.20	85.40	62.45	83.10
FSO5	-179.56	130.00	94.00	0.70	77.70	79.10	78.40	65.17	86.00
FSO7	-178.99	113.02	90.00	1.10	74.40	75.40	74.90	56.56	90.00
LSO3	-179.53	123.00	93.30	0.70	86.00	84.90	85.40	61.63	86.70
LSO5	180.00	111.00	94.10	0.80	85.70	85.00	85.40	55.67	85.90
LSO7	180.00	129.00	99.70	0.60	88.40	90.40	89.40	65.42	80.30
CEO3	174.38	281.26	63.50	4.90	62.60	61.90	62.20	165.13	116.50
CEO5	177.84	106.08	94.30	0.50	85.50	86.00	85.80	53.20	85.70
CEO7	179.10	128.02	95.40	0.50	85.40	79.50	82.40	64.29	84.60
CAO3	179.54	125.00	91.40	1.00	80.10	76.90	78.50	62.59	88.60
CAO5	178.97	111.02	97.20	0.70	85.00	84.30	84.60	55.98	82.80
CAO7	180.00	103.00	94.40	0.50	86.80	84.30	85.60	52.14	85.60
PTO3	177.86	107.07	94.20	1.10	88.60	81.70	85.20	53.70	85.80
PTO5	179.55	126.00	98.60	0.40	89.10	89.70	89.40	63.76	81.40
PTO7	177.96	281.18	102.40	0.50	95.00	91.10	93.00	144.00	77.60

After modification of bitumen with all vegetable oils used in the study and the use of them in different proportions, the obtained values from contact angle analysis study are presented in Table 5.

When Figure 9 is examined, it has been observed that the approximate contact angle value of the reference sample, which is pure bitumen, is 72.2 °. When the samples modified by adding vegetable oil in different proportions are examined, it is observed that the contact angle value exceeds that of the reference sample in all mixtures. When the groups were examined, it was found that the highest change in contact angle were found in CEA groups. The highest contact angle was formed as 116.5 ° in the CEO3 group. The lowest contact angle value was formed as 72.50° in the sample groups modified with adding 7% hemp seed oil (HSO7). When each group was examined separately, it was observed that with the modification of bitumen with hemp seed oil, the highest contact angle value was found in the HSO5 group. After reaching ratio of 5% of additive, the contact angle also started to decrease gradually; however, in all three groups, the contact angle value didn't drop below that of reference sample. When the bitumen samples modified with flaxseed oil (FSO) were examined, it was observed that the contact angle value increased with the increase in the additive ratio. In FSO groups, the lowest contact angle value was reached in FSO3 samples with 83.10°, and the highest contact angle value was obtained in FSO7 samples with 90°. When the groups with laurel seed oil (LSO) were examined, it was observed that the contact angle value tended to decrease with the increase of the oil content ratio. The contact angle was 86.7° in the LSO3 group, whereas it was calculated as 80.30° in the LSO7 groups. When the bitumen groups (CEO) modified with centaury oil were examined, it was observed that the contact angle value decreased with the increase in the additive ratio. In this group, with 84.60°, the lowest contact angle value was reached in the CEO7 group. The lowest contact angle was 88.60 ° in bitumen groups, in which castor oil added (CAO), the lowest contact angle value was observed in the CAO5 group with 82.80°. In pine turpentine oil added groups (PTO), the contact angle values of modified bitumen tended to decrease with the increase the in additive ratio. While the average contact angle was 85.80° in the PTO3 group and 81.40° in the PTO5 group, it was 77.60° in the PTO7 group which is also the lowest contact value within the group. It is seen in Figure 9 that the CEO3 and FSO3 groups are above the hydrophobic minimum limit value of 90°.

6. Conclusions

Studies, besides determining the surface wetting, water sensitivity and hydrophobic properties of bitumen, the main binder material used in bituminous road construction, has showed what kind of differences will occur in physical and mechanical properties with the change of these features of bitumen. Considering the removal of water from the surface, which is an important traffic problem for highways, and the damage of water to the road, it offers very important results. Although it is known that the basic physical properties of the bituminous binders can be changed with different modified additives, together with the change in its sensitivity to water and its hydrophobic properties, this detailed information could not be found in the literature. In this context, this study provides the reader with an original information.

Bituminous binder was modified by using six different vegetable oils and the contact angle value expressing the sensitivity to water were found. In all studies, the water sensitivity of the bituminous binder, modified with vegetable oils, can be further reduced and thus hydrophobic properties can be achieved.

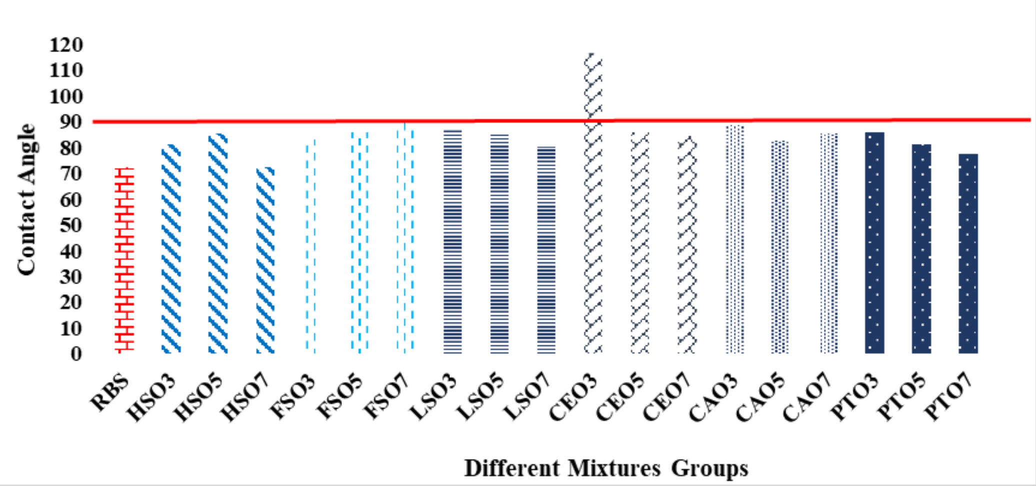

Figure 9. Contact angle changes of different groups.

When bitumen is evaluated considering basic physical properties, the softening point value of our reference sample was determined as 47.70 ° C according to the results of the softening point test. If the change that occurs with the increase in the ratio of vegetable oil content added to bitumen during modification considered, it is observed that the softening point increases along with the increase in the ratio of vegetable oil content in the mixtures having FSO, CAO and LSO additives. In HSO, CEO and PTO groups on the other hand, it was determined that the softening points of the bituminous binders decreased with the increase in the vegetable oil content. This shows that some vegetable oils increase the sensitivity of bitumen to heat, whereas others decrease it.

When penetration values, which is another basic physical property, are examined; it was determined that the average penetration value of the reference samples was 62.8 mm, whereas there were significant increases in the penetration values of all groups, with the addition of vegetable oil. It was observed that the highest increase in penetration value occurred in PTO7 group, whereas the lowest increase in penetration value was in CAO3 group. Penetration value is significant especially during the production of bituminous hot mixes for workability and flexibility of road coating. Increasing the penetration value makes bitumen become softer. This means an ease of processing for applications at very low temperatures and that cracking and breakage at low temperatures can be prevented.

When the reference and all other sample groups were examined, an elongation of +100 cm observed in all the ductility results and it was determined that they behaved ductile against rupture, that is, the characteristics expected from the binder in the coating layer in structures was ensured. It was determined that the peeling strength of all samples was greater than 50%. Thus, it can be stated that the adherence between aggregate and the binder is strong.

When the results of EDX analysis are examined, it was determined that vegetable oils, added in different proportions to the bituminous binder, caused occasionally increases and sometimes decreases in carbon, oxygen and sulfur contents compared to the reference sample.

When the sensitivity to water, surface wetting and hydrophobic properties of bitumen, which is the main scope and originality of the study, were examined, it was found that the sensitivity of bitumen to water can be reduced by adding vegetable oil. With the results of the analysis, it was determined that different vegetable oils added in different proportions, contribute to this characteristic of bitumen higher or lower levels. Studies have shown that bituminous binders modified with vegetable oils, contribute significantly to all physical, mechanical, and surface wetting properties. This way, significant data have been provided about reducing moisture damage, one of the biggest problems of roads, and eliminating the risk of accidents caused by surface defects.

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

S. Serin: Conceptualization, Data Curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization , Writing – Original Draft, Writing - Review & Editing – **S. E. Demirezer:** Data Curation, Formal analysis, Investigation, Methodology, Resources, Software, Validation, Visualization , Writing – Original Draft.

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Research Article

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Planning of airport pavement with artificial intelligence methods

Burak Kucukcapraz[a,*], Serdal Terzi[b]

[a]*Department of Civil Engineering, Engineering Faculty, Suleyman Demirel University, Isparta, Turkey*
[b]*Department of Civil Engineering, Engineering Faculty, Suleyman Demirel University, Isparta, Turkey*

Highlights

- Artificial intelligence can be used for pavement design
- High regression of 97% has been achieved
- ANFIS generate the pavement design faster

Abstract

Rigid pavements slab thicknesses are determined using readings from design curves where human, reading, and curve mistakes could commonly occur. In addition, readings from these design curves take precious time and need high attention and diligence. In this study, the ANFIS model is developed instead of the traditional curve reading method, which is more practical and timesaving. So, it could decrease the mistakes which are occurring from curve readings. For this purpose, it has produced a random data set. A slab thickness for each data in the set has been determined using design curve readings. Obtained slab thicknesses are used for training the ANFIS model and an alternative method has been obtained. The created model has predicted the slab thicknesses with a regression of 97.05% compared to the slab thicknesses obtained from curve readings.

Information

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Keywords: *Airport pavements, slab thickness, ANFIS, design curve, model*

1. Introduction

The developments in the aviation sector first gained momentum in and after the 1st World War. It provided war superiority, ensured the smooth and safe transportation of people, soldiers, and equipment in a short time, and continued to progress rapidly on the road opened. This mobility; Along with the emerging problems, research, development, and scientific activities, have increased rapidly. Research and development activities have not focused only on the development of the aircraft to be used. Improvements; flight runways, parking areas (hangars), maintenance and repair units, security systems, and units require the existence of a large facility, and the sustainability of these interconnected systems has also revealed the necessity of ensuring smooth, dynamic, and low-cost sustainability [1-3]. Today, air travel and the necessity of using these facilities are because of military needs, and the intensity of civil aviation is increasing [4]. There are publications in the literature about fuzzy logic applications in airports [5-12].

Gopalakrishnan et al. [13] used an adaptive neural fuzzy inference system (ANFIS) to recalculate the airport's flexible pavement layer modulus. They aimed to explore the feasibility of using ANFIS for the inverse analysis of multilayer aerodrome flexible pavements based on falling weight deflectometer (FWD) data. This approach is hybridized using a finite element structural model to calculate pavement responses with known properties of pavement materials subjected to FWD loading. The finite element model deals with the nonlinear and stress-dependent behaviour of the geomaterials used underlying the free pavement layers, resulting in modelling the responses and characterizing the suitable materials.

Kaur and Kaur [14] provided a design for weather conditions using the fuzzy logic method and the neuro-fuzzy method. Simulation results of both neuro-fuzzy management and fuzzy logic are compared to indicate the better one between the two. As a result of the study, neuro-fuzzy is superior to fuzzy logic because it provides adaptability and learning.

Charts are used to determine the layer thicknesses of airport rigid pavements. Unless the chart readings are done carefully, reading errors are made. For this reason,

*Corresponding author: *serdalterzi@sdu.edu.tr (S. Terzi, +90 246 211 1040)*

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it is aimed to investigate the usability of the ANFIS method, which is faster and minimizes errors, instead of the chart method.

2. Material and Method

2.1. Material

The readings from the layer thickness determination chart were used to make the airport runway pavement thickness design with the fuzzy logic method. The chart of layer thickness is given in Figure 1.

"K" ground module; represents the soil strength category and makes it easy to predict the possible pavement behaviour of the soil. Categorized as high strength, medium strength, low strength, deficient strength [15]. When the chart was analyzed, it was determined that the third-order parabola curves of the K coefficient curves and the aircraft weight curves were linear. The equations for the values of 50, 100, 200, 300, and 500 for the K coefficient are shown in Equations 1, 2, 3, 4, and 5, respectively. For these values, the x-axis is considered the unit axis.

$$y_{50}=-4.1667x^3+77.5x^2-568.33x+2020 \quad (1)$$

$$y_{100}=-6.6667x^3+100x^2-598.33x+1875 \quad (2)$$

$$y_{200}=-5x^3+70x^2-420x+1475 \quad (3)$$

$$y_{300}=-9.4167x^3+110.5x^2-529.38x+1502.5 \quad (4)$$

$$y_{500}=-7.8544x^3+85.69x^2-405.21x+1252.5 \quad (5)$$

The variable y in the above equations expresses the concrete strength of psi.

3. Method

3.1. Takagi-Sugeno Method

Takagi-Sugeno (T-S) method, which is a qualitative modelling method based on fuzzy logic [16], is a convenient method for engineering applications [17]. T-S method, which is a fuzzy logic modelling used in the analysis of nonlinear systems; used to deal with complex analysis and synthesis problems; It is standard modelling that can give average weighted values with the results of nonlinear systems and can also be studied with different linear system theories [18].

The most important advantages of this method are; have simple output functions that are functions of the inputs; It can be listed as reducing the processing load, high computational speed, and practicality of its use for systems that do not require sensitive results but are dynamically changing rapidly [19]. Figure 2 shows the association of membership levels from the blurring unit with the polynomial output membership functions in the Takagi-Sugeno inference method. In the Takagi-Sugeno inference method, polynomial functions are used for the output, as seen in Figure 2.

In Sugeno type fuzzy modelling; Output membership functions are grouped with different subheadings according to whether they are linear or fixed [22]

- Zero-order Sugeno fuzzy model (Output membership functions fixed)
- 1st order Sugeno fuzzy model (1st order line equation.

The mathematical calculation logic of the T-S fuzzy model is as follows [23];

For a nonlinear dynamic system (Equation 6)

$$\dot{x}=f(x,u), \qquad x\in X\subset R^n \text{ ve } u\in U\in R^r \quad (6)$$

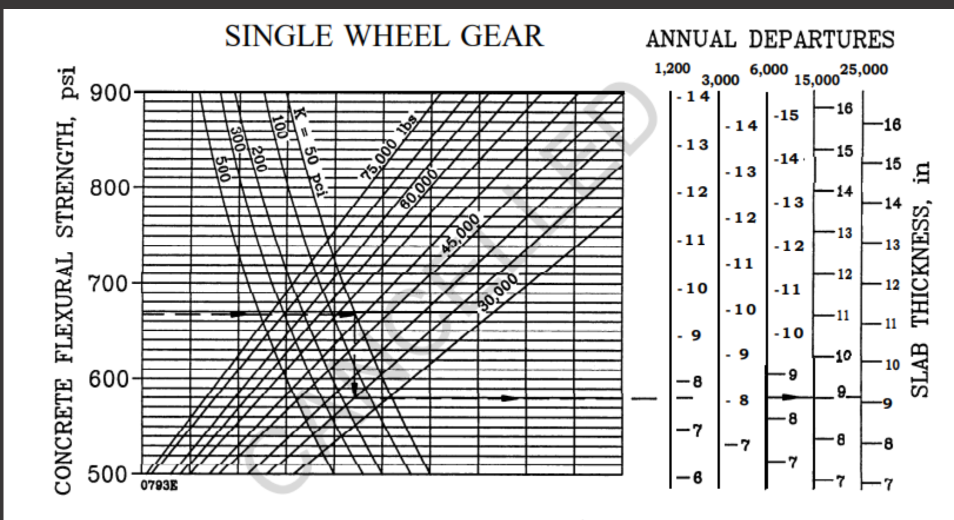

Figure 1. Rigid Pavement Design Curve [21]

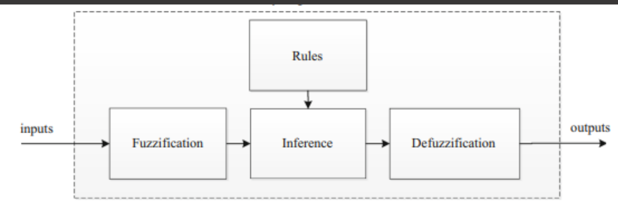

Figure 2. Basic elements of fuzzy logic [20]

A Takagi–Sugeno fuzzy model will approximate this system by properly interpolating it to local systems. Each local model contributes to the global model in a fuzzy subset of X x U. This fuzzy set; is defined by a membership function, leading to the Takagi-Sugeno fuzzy model (Equation 7).

$$\dot{x}= \sum_{i=1}^{N}(A_i x+ B_i u+d_i)\, w_i(x,u) \quad (7)$$

w_i:X x U→[0,1] (Equation 8), where the weighting functions are given by fuzzy inference;

$$w_i(x,u)=\frac{\mu_i(x,u)}{\sum_{j=1}^{N}\mu_j(x,u)} \quad (8)$$

Results and Discussion

This study, it is aimed to prevent undesirable situations that will occur as a result of situations such as loss of time, attention errors, and calculus errors that people will naturally experience while reading with a fuzzy logic model. In this context, readings were taken with high meticulousness and accuracy on the provided charts and ensured that they were correct. Random values were derived from doing readings, and readings were taken with these values. Then, using the reading values obtained with the same input data, a fuzzy logic model was developed. The main structure of the generated fuzzy logic model is shown in Figure 3. The model was established with five inputs and one output.

In creating the data set, 500 and 900 psi values, which are the chart limits for concrete strength, were taken as limit values, and 5793 random values were generated in EXCEL with the RAND command in this range. In addition, for the "K" coefficient, data production was carried out with the “RAND” commend and between 50 and 500 values. Then, ten different aircraft weights that will use the runway were selected as 13620, 15890, 18160, 20430, 22700, 24970, 27240, 29510, 31780, and 34050 kg. For this selection, each aircraft's weight took a value between 1 and 10, and 5793 integers between 1 and 10 were produced with the RAND command. The weight corresponding to the produced integer was used in the relevant combination. Finally, the method used in the estimation of aircraft weight was used for 1200, 3000, 6000, 15000 and 25000 years/number of aircraft take-offs, which can be read on the chart, each weight was given an integer from 1 to 5, respectively, and these five numbers were given with the RAND command. The integer is generated. The take-off value corresponding to the integer produced is the annual number of take-offs in the combination. In this way, 1449 values created differently were read over the chart, and layer thickness values were obtained. Random 80% of the values obtained in this way (1157) were used to train the Fuzzy Logic model, and the remaining 20% (292) was used for testing the created model. The main structure of the created model is shown in Figure 3.

Figure 3. The main structure of the Fuzzy Logic model

The model shown in Figure 3 has four inputs and one output. As ANFIS parameters, each input is of trimf type. The output membership function is determined as constant. In the fis formation, the effect range value was 0.5, the compression factor was 1.25, the acceptance rate was 0.5, and the rejection rate was 0.15. The hybrid method was used as the optimization method in the Train Fis type. Because of 1000 iterations, the error value was 0.55.

To establish a smooth relationship between all input data and output data on the created model, 243 rules were written. The relationship between the input and output parameters after the written rules is shown in Figure 4. To test the model after writing the rules, the test data set was entered on the query screen, and the results were compared with the actual values. Because of the comparison, an R^2 value of 97% was reached (Figure 5).

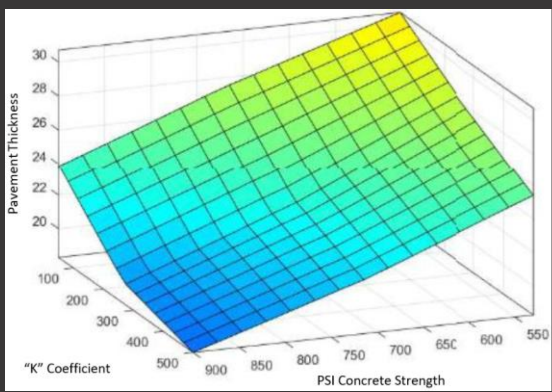

Figure 4. The change in the output value depending on the input data of the created model.

Because of the training, Figure 5 was obtained when the values obtained from the model were compared with the output parameter of the data set used for training the model. When Figure 5 is examined, it has been obtained that the data set used because of the model's training can represent the output values by 97.40%. Because of the examination, it can be said that the training was concluded successfully. After the values obtained because of the training were obtained with an accuracy of 97.77%, the model created was tested. The layer thicknesses obtained by the model because of the test data and the layer thicknesses obtained from the test inputs and the abacus were compared. Because of the comparison, Figure 6 was obtained. When Figure 6 is examined, it is seen that the layer thicknesses obtained from the test data of the model match the layer thicknesses read from the abacus with an accuracy of 97.05%. The model was developed because the test process can estimate layer thicknesses.

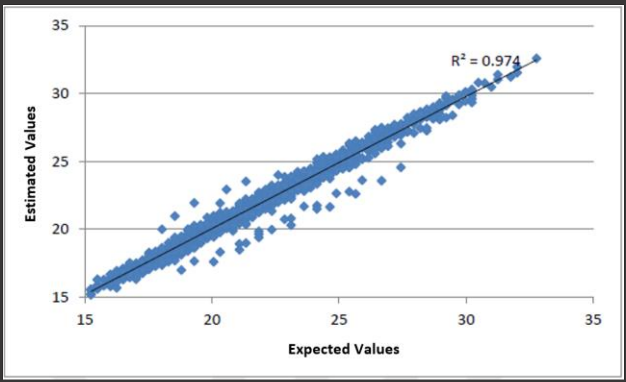

Figure 5. The relationship between the predicted and the education values read from the chart.

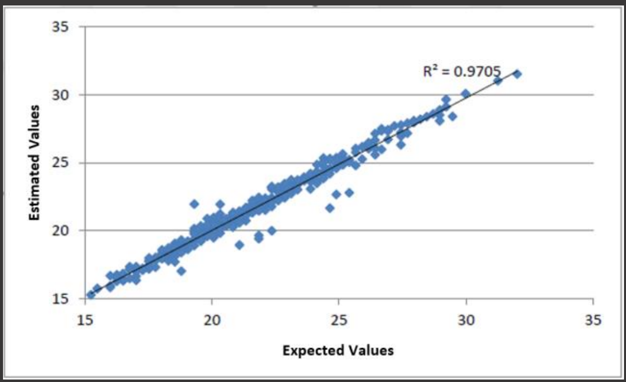

Figure 6. The relationship between the predicted and the test values read from the chart.

4. Conclusion

This study aimed to determine a more practical and fast rigid pavement layer thickness with the ANFIS model instead of determining the airport rigid pavement layer thickness with the traditional abacus method. In this way, the errors caused by the chart, reading errors, and human errors can be prevented. In addition, results can be achieved in a much faster and more practical way.

For this purpose, a random data set was created, and abacus readings were performed with high precision for each set. The obtained results were used to train the ANFIS model, producing an alternative solution instead of the abacus reading. The model obtained in this context could predict the layer thicknesses obtained because of the chart readings at a rate of 97.05%. This result shows the usability of the created model in determining the rigid pavement layer thicknesses of airports. Besides the high accuracy rate, losing time during abacus readings is significantly reduced.

The data analysis of the study was carried out only on the single wheel landing gear and considering the relevant results; In future studies, repeating the same study with double-wheel landing gear readings and results and extracting accuracy relationships with chart tables will be beneficial in minimizing time losses and human error factor in this area. Besides the method used in the experimental study process, the comparison of the results obtained by processing the same data with the Mamdani inference method and the results of the Sugeno inference method will both enrich the literature, and the difference between the accuracy factor between the two methods will be evaluated in terms of applicability.

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

B. Kucukcapraz: Formal analysis, Investigation, Software, Visualization, Writing – Original Draft – **S. Terzi**: Conceptualization, Funding acquisition, Software, Supervision, Writing – Review&Editing

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