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Prediction of Rheological Parameters of Asphalt Binders with Artificial Neural Networks

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Abstract: Recycling of industrial, agricultural etc. wastes is economically and environmentally important. In recent years, researchers was focused on the using wastes in structural materials. In this study, modified asphalt binders were obtained by adding 7 different ratios waste engine oil (2%, 4%, 6%, 8%, 10%, 12% and 14%), which released as a result of routine maintenance of automobiles, to the pure asphalt binder. Then, Dynamic Shear Rheometer (DSR) experiments were applied on pure and modified asphalt binders. The rheological properties of asphalt binders at different temperatures and frequencies (loading rates) were evaluated by performing the DSR Test at 4 different temperatures (40°C, 50°C, 60°C and 70°C) and 10 different frequencies (0.01-10Hz). Then, the obtained complex shear modulus and phase angle values were estimated with Artificial Neural Networks. The results showed that the addition of 2% waste mineral (engine) oil improved the elastic properties of the asphalt binder by increasing the complex shear modulus and decreasing the phase angle values. In addition, it was concluded that the rheological parameters of asphalt binders can be successfully obtained with Artificial Neural Networks, by estimating the results with low error rate and high accuracy.

Keywords: Waste Engine Oil, Recycling, Asphalt, Modification, Artificial Neural Networks

Introduction

Bitumen, which is used as a binder material in hot mix asphalts, is obtained by refining petroleum (Hunter et al., 2015). Bitumen, which has a very complex structure, ages due to effects such as traffic loads, climatic conditions, very high and very low temperatures, and loses its flexibility properties at the beginning of its service life over time (Yan et al., 2020; You et al., 2019). Pure bitumen may not provide the desired properties when used in the mixture. For this reason, additives are used to provide features such as temperature sensitivity, strength, flexibility at low temperatures. Polymer materials are most commonly preferred, and the bitumen to which polymer materials are added is called “Polymer Modified Bitumen (PMB)” (Paliukaite et al., 2016; Qian et al., 2018; Shadmani et al., 2018; Shan et al., 2019).

With the cost of the used additives and the increase in the amount of waste materials in the world day by day, the idea of using waste materials in engineering materials has emerged. For this purpose, various waste materials can be used as additives in bitumen and hot mix asphalts. The type of waste material used is very diverse, such as plastics materials, steel slags, polymers, vehicle tires, construction waste (Aldagari et al., 2021; Hake et al., 2020; Hu et al., 2018; Kamoto et al., 2020; Mashaan et al., 2021; Murugan et al., 2020; Padhan et al., 2013; Qian et al., 2018; Seyma Seyrek et al., 2020; Shadmani et al., 2018; Shruthi et al., 2020). In recent

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years, waste oils have also been used as additives or rejuvenators (Asli et al., 2012; Eriskin et al., 2017; Fernandes et al., 2018; Rahman et al., 2017; Zargar et al., 2012).

In this study, waste engine oil, which is produced as a result of periodic maintenance of vehicles, was used as an additive in bitumen binders, and its effect on the rheological parameters of bitumen was evaluated. For this purpose, modified bitumen samples containing waste motor oil in 7 different ratios (2%, 4%, 6%, 8%, 10%, 12% and 14%) were obtained, and then frequency sweep test was applied on these samples with a Dynamic Shear Rheometer device. Frequency sweep test was carried out at four different temperatures, 40°C, 50°C, 60°C and 70°C, and under ten different frequencies between 0.01-10Hz. Then, Artificial Neural Network (ANN) models were created and rheological parameters obtained from engine oil modified bitumen were estimated by ANN models.

Materials and Methods

The bitumen that used in the study (B50/70) was supplied from TÜPRAŞ Batman refinery. Waste engine oil (WEO) was obtained from a local auto repair shop. The compositions and physical properties of the waste motor oil used are given in Table 1, and the image of the oil is given in Figure 1.

Table 1. Compositions and physical properties of WEO

Items	Nitrogen (%)	Carbon (%)	Hydrogen (%)	Sulfur (%)	Flash Point (°C)	Density (g/cm^3)
WEO	-	83.18	13.91	0.408	210	0.8816

Figure 1. Image of waste engine oil

While obtaining modified bitumen, WEO, were added to the binder (2%, 4%, 6%, 8%, 10%, 12% and 14% by weight of the bitumen), then mixed in a mechanical mixer at a constant temperature of 180°C at 1000 rpm for 1 hour. The schematic representation of the modification process is given in Figure 2.

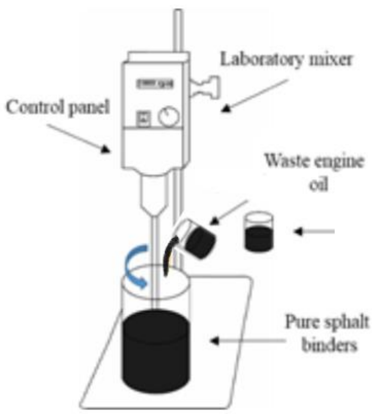

Figure 2. Schematic representation of the modification process

Traditional Binders Experiments

Penetration, softening point and flash point tests were carried out on modified bitumen samples. While the penetration test was applied according to the ASTM D5 standard, the softening point test was performed according to ASTM D36 and the flash point test was carried out according to ASTM D3143. The traditional binder test results of original and modified bitumen are presented in Table 2.

Table 2. Conventional binder test results of original and waste motor oil modified binders

Type of Binder	Penetration (mm^{-1})	Softening Point (°C)	Flash Point (°C)
Pure	62	53.3	245
2% WEO	64	53.25	242
4% WEO	69	52.2	240
6% WEO	77	51.1	238
8% WEO	88	49.6	232
10% WEO	105	48.15	228
12% WEO	121	46.95	224
14% WEO	136	44.65	217

Table 2 shows that the addition of WEO decreases the softening point values while increasing the penetration values of the original binders. With the addition of WEO, the flash point values decreased compared to the original binder. The use of WEO resulted in a softer behavior of original bitumen.

Dynamic Shear Rheometer (DSR)

The behavior of binders under load, strain and time is generally determined by DSR experiments. The DSR device is given in Figure 3. During the test, a bituminous binder sample is placed between two metal plates kept at constant temperature. One of the plates makes sinusoidal movements and the other is fixed. When torque is applied, the DSR motor goes from point A to point B, returns to point A and moves to point C. Then it reaches point A again. This process creates a single rotation and is repeated throughout the experiment (Fig. 4) (Yalçın, 2020).

Figure 3. Dynamic Shear Rheometer test device

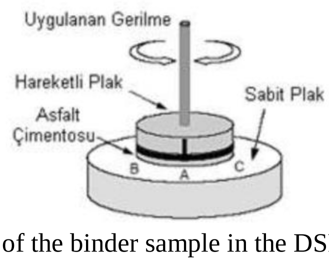

Figure 4. Movements of the binder sample in the DSR test (Yalçın, 2020).

As a result of DSR experiment, complex shear modulus and phase angle values were obtained. A high complex shear modulus means a high resistance to rutting. If high complex modulus values are obtained against low phase angle values, it is said that the bitumen binder behaves more elastically. A phase angle of 0° is considered to be completely elastic, while if this value is 90°, the material is considered completely viscous (Figure 5) (Yalçın, 2020).

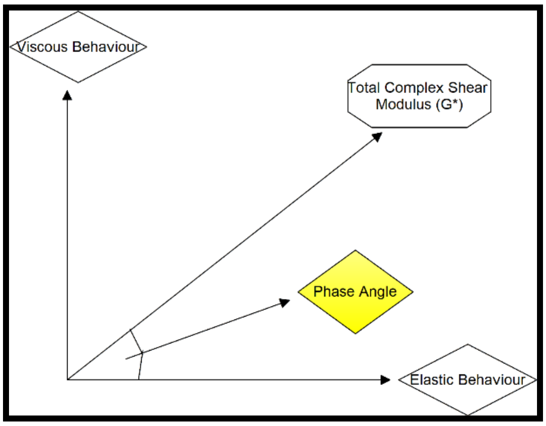

Figure 5. Representation of elastic and viscous behaviors according to DSR Experiment

In the study, sample geometry was chosen as 25mm diameter and 1mm height. Frequency sweep experiment was carried out on bitumen binders at 4 different temperatures (40°C, 50°C, 60°C and 70°C), 10 different frequencies (0.01Hz-10Hz).

Artificial Neural Network (ANN)

ANNs are an information processing process inspired by the human brain. It consists of many interconnected processing elements (neurons) that work in concert to solve specific problems. There are five parts in an ANN structure: inputs (X1,X2,X3…), weights (W1,W2,W3…), combining (addition) function, activation (transfer) function and output (Y). Inputs enter neurons with weights, pass through the coupling function and are transferred to the activation function (Graupe, 2013; Öztemel, 2008; Sönmez Çakir, 2019). Then the cell output values are calculated. The general structure of the ANN cell is presented in Figure 6.

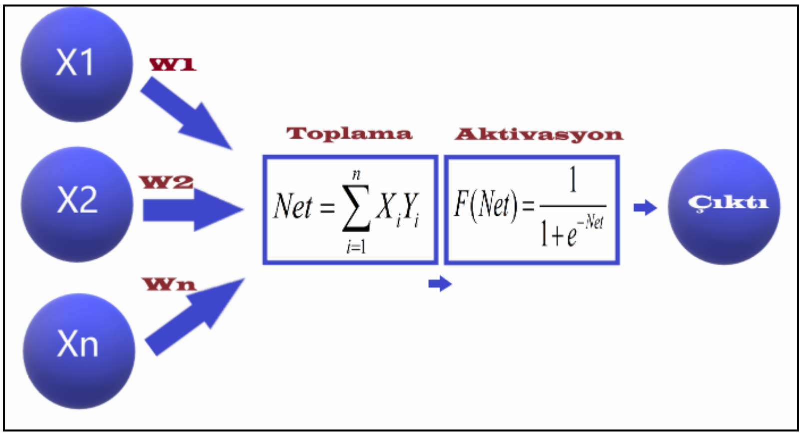

Figure 6. General structure of the ANN neuron

The artificial neural network models that created in the study were run in the MATLAB environment. Two models were created separately for the complex shear modulus and phase angle values, and a sigmoid feed-forward network structure was preferred for both models. The training algorithm is important in ANN analysis. The training algorithm to be used should be both fast and give high accuracy results with low error. For this reason, Levenberg-Marquardt back-propogation training algorithm was preferred for both models. After 70% of the data set was randomly selected for the training process, the remaining 30% was divided equally and selected for the validation (15%) and testing phases (15%). In order to determine the number of neurons in the hidden layer, different iterations and hidden layer numbers were tried to find the optimum value. The model that provides the lowest error rate with the highest accuracy should be preferred. In this study, 12 neurons were found suitable for both models.

The schematic representation of the artificial neural network model is given in Figure 7. In both models, temperature, frequency and waste engine oil content are defined as inputs. The output is the complex modulus and phase angle.

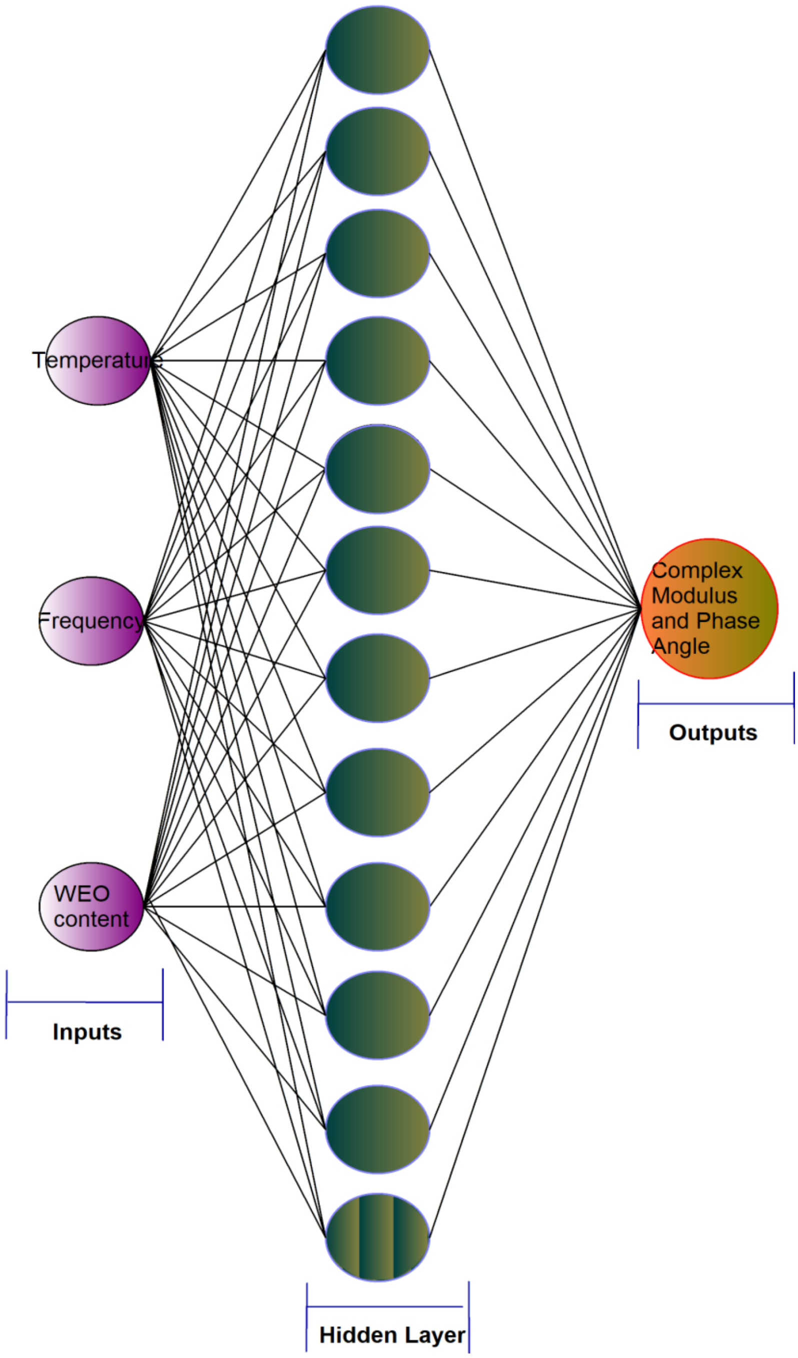

Figure 7. ANN Model

Results and Discussion

DSR Results

In the study, dynamic shear rheometer experiments were carried out on original and waste engine oil modified binders at 40°C, 50°C, 60°C and 70°C and at 10 different frequencies between 0.01 Hz and 10 Hz. The obtained complex modulus (G*) and phase angle curves are given in Figures 8 and 9.

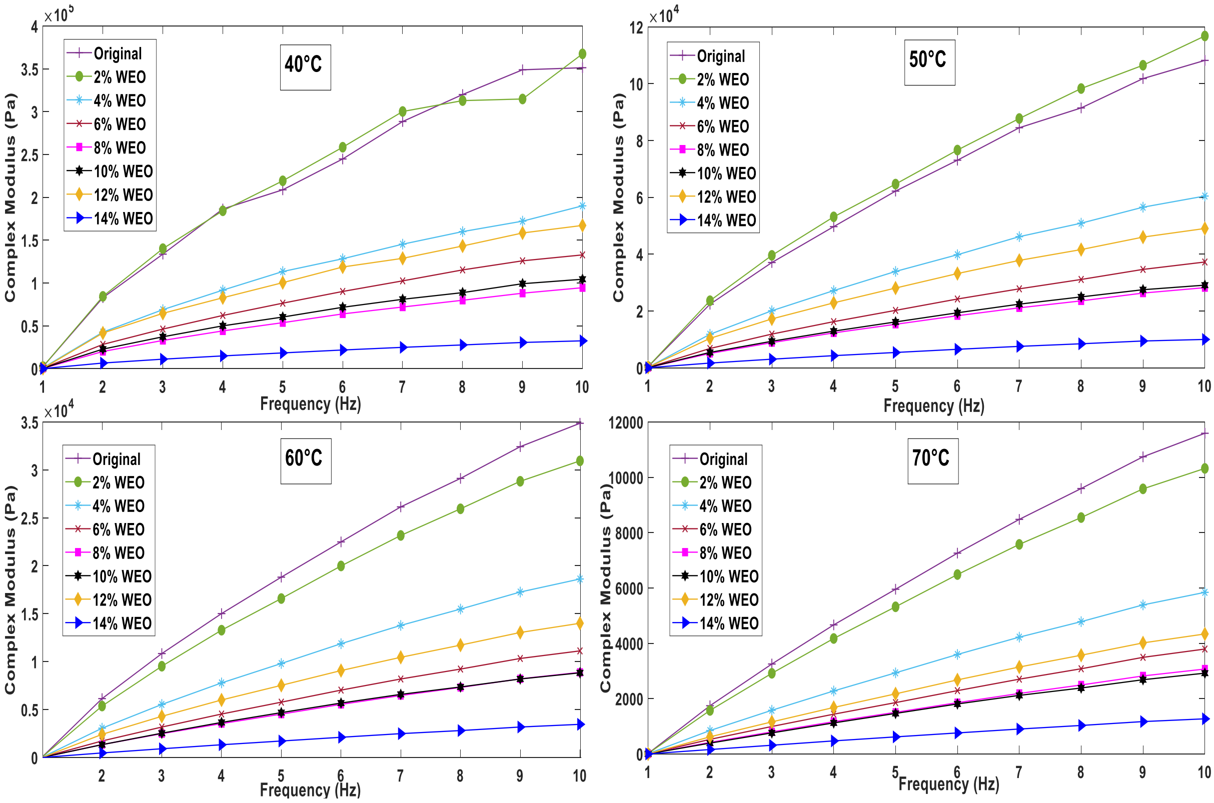

Figure 8. Complex module curves

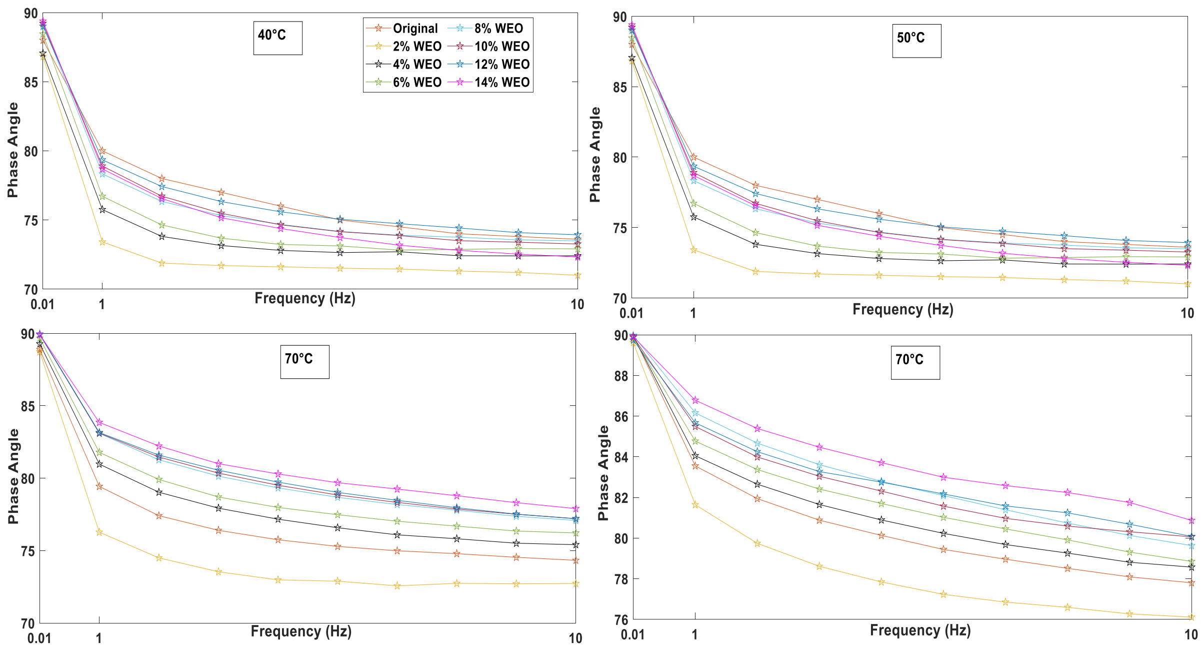

Figure 9. Phase angle curves

When Figure 8 is examined, the increase in the frequency, in other words, the loading speed, caused an increase in the complex module values. The complex modulus values of the binders generally decreased with the increase in the waste engine oil ratio. When the results corresponding to low frequency values are examined, the effect of adding engine oil is seen more clearly. However, the effect ratio decreased at higher frequencies. Original binders offered higher complex modulus values at each frequency.

Obtaining a high complex shear modulus against a low phase angle value is a measure of the elastic behavior of the bituminous binder. When Figure 9 is examined, it is seen that the phase angle values decrease as the frequency increases.

Artificial Neural Networks (ANN) Results

The regression graphs created to represent the relationship between the predicted data of both ANN models and the experimental data are given in Figure 10 for complex modulus values and Figure 10 for phase angle values.

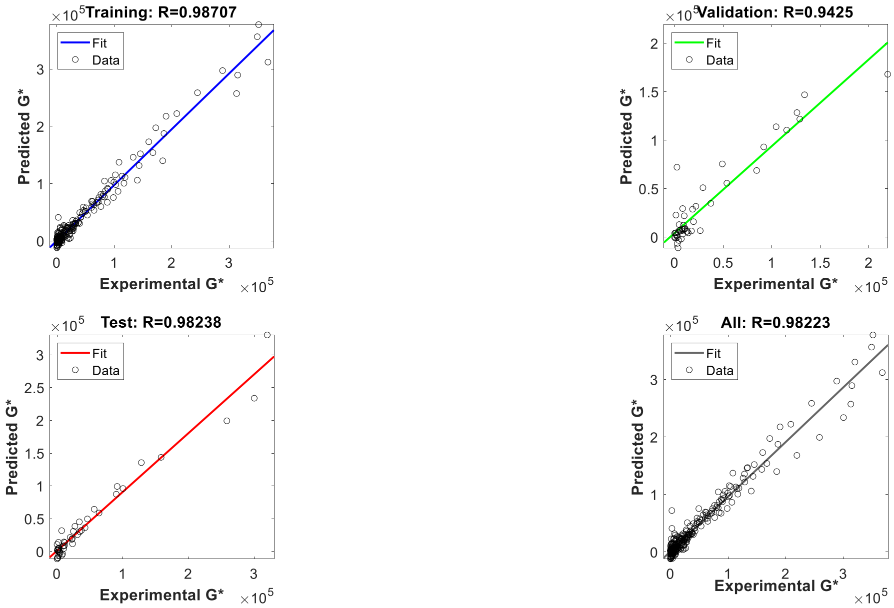

Figure 10. Relationship between experimental complex modulus data and ANN predicted data

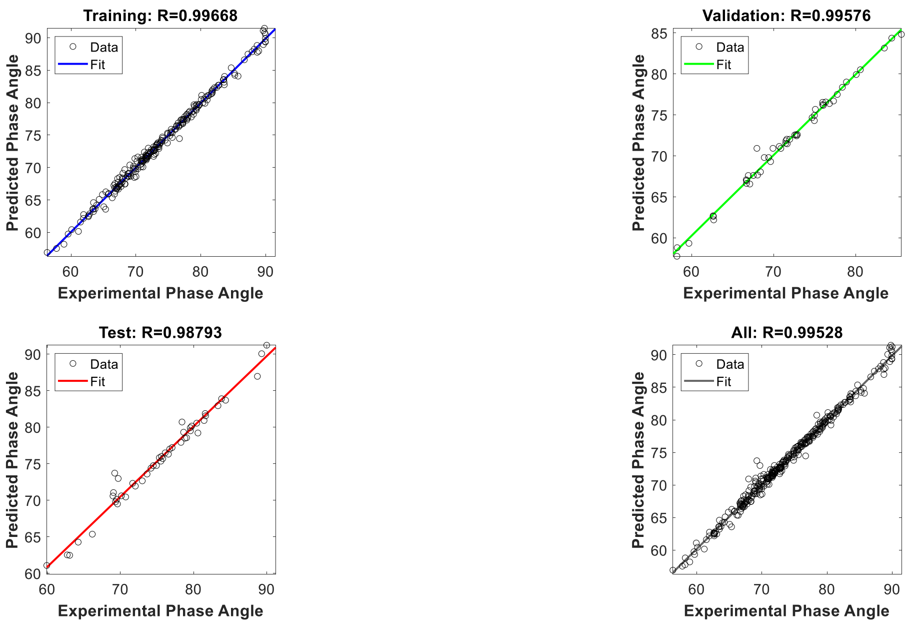

Figure 11. Relationship between experimental phase angle data and ANN predicted data

When Figures 10 and 11 are examined, it is clearly seen that both models provide high accuracy results. The correlation (R^2) between the data obtained as a result of the proposed models and the experimental data was found to be above 0.98 when evaluated overall for both models. Figure 12 was created to show how precisely the neural network model predicts output values. As the number of cycles increases, the error rate generally decreases. The training process is terminated when the error rate in the validation dataset starts to decrease so that the model is not subject to overfitting. The best performance corresponds to the number of cycles giving the lowest error rate. According to Figure 12, the error rate decreased rapidly as the network learned. When Figure 12 is examined, it is seen that the best verification performance is obtained in 25 cycles (epochs) for the complex module and 38 cycles for the phase angle. These results show that the properties of bituminous binders can be predicted by neural networks with low error rate and in a very short time.

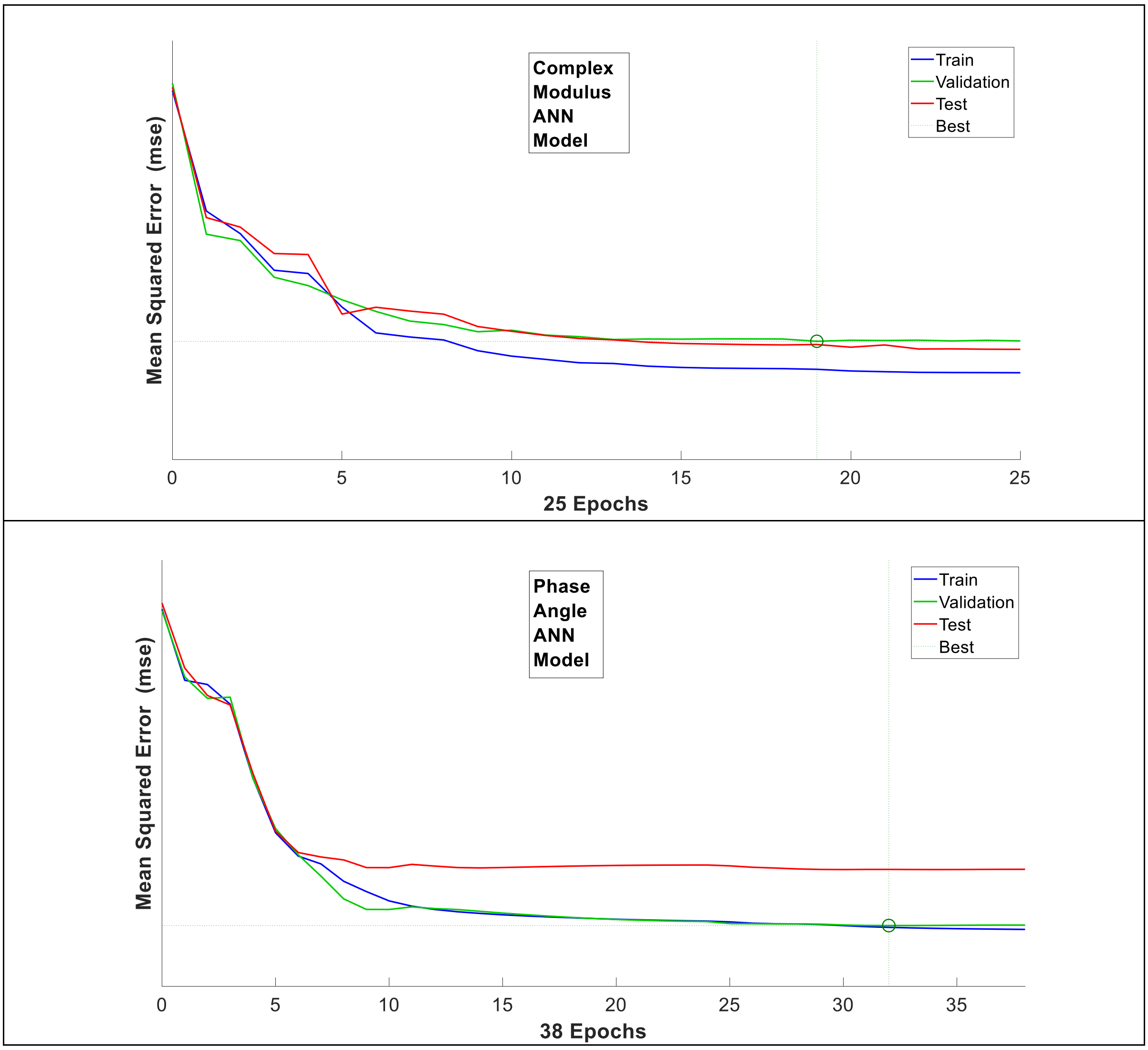

Figure 11. ANN performance plot, a) Complex modulus ANN model, b) Phase angle ANN model

Conclusions

In this study, 2%, 4%, 6%, 8%, 10%, 12% and 14% of waste engine oil that released as a result of the periodic maintenance of the vehicles were added to the original bitumen. Then, frequency sweep test was carried out on the modified bitumen samples with DSR device at four different temperatures (40, 50, 60 and 70°C) and under 10 different frequencies (0.01Hz-10Hz). The rheological parameters of the binders were estimated with the artificial neural network model and the two data sets (experimental versus predicted) were compared.

According to the results, it was determined that the complex modulus values generally decreased with the addition of waste engine oil and the increase in the additive ratio. Original binders offered higher complex modulus values at all frequencies and temperatures. This shows that the addition of waste engine oil weakens the resistance properties of bitumen against rutting and renders them weak against deformations. When the phase angle values were evaluated, the increase in the frequency values decreased the phase angle values. It is thought that the addition of waste engine oil can improve the elastic properties by increasing the phase angle values.

When the artificial neural network model results were evaluated, the ANN model created for both the complex module and the phase angle gave high accuracy results with low errors. In addition, the ANN model reached the result quickly with a small number of iterations. As a result, it has been determined that the rheological parameters of bituminous binders can be successfully predicted by ANN. Being able to predict the experiments in the laboratory with artificial intelligence methods will provide benefits in terms of both time and material.

Scientific Ethics Declaration

The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

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