

Research Article

Investigation of the Rheological Properties of Asphalt Binders Modified with Nanomaterial

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Abstract

This study examined the effects of the Aerosil 150 addition on the rheological characteristics of bituminous binders at various temperatures. In the study, a frequency sweep test was applied to determine the rheological properties of pure binders and binders with 2%, 4% and 6% Aerosil 150 additives. Unaged binders were subjected to the frequency sweep test using a Bohlin DSR rheometer at test temperatures ranging from 40°C to 80°C (increasing by 10°C). The results showed that adding Aerosil 150 additive to the pure binder raised the binder's complex modulus (G^) values while decreasing the phase angle (δ) values. At 40 °C 0.1 Hz frequency, 2%, 4% and 6% Aerosil 150 doped binders gave G^* values 1.52, 2.02 and 3 times higher than pure binder, respectively. The same ratio is 1.31, 1.54 and 1.99 times at 5 Hz frequency and 1.28, 1.47 and 1.82 times at 10 Hz frequency. At the same temperature, as the frequency value increases, the binders' complex modulus values approach each other. When the phase angle values at 40°C were examined, the 2%, 4%, and 6% Aerosil 150 modified binders, when compared to pure binder at 0.1 Hz frequency, yielded 2.75°C, 5.56°C, and 9.17°C lower phase angle values, respectively. This decrease is 3.19, 5.04 and 7.33 °C at 5 Hz frequency and 3.09, 4.84 and 6.76 °C at 10 Hz frequency. This shows that at various frequencies, the modified binder behaves more adaptably than the pure binder. The fact that the binder has a low δ value against a high G^* value indicates that it will exhibit more flexible behavior. It was discovered as a result that Aeresil 150 modified binders performed better in terms of rheological qualities than pure binders.*

Keywords: Modification, nanosilica, rheological properties

1. Introduction

Nanomaterials have a wide range of applications, and in recent years they have frequently been utilized to boost the effectiveness of asphalt binders or mixtures. The ability of nanomaterials to improve performance is based on chemical purity, large surface area, high tensile strength, high functional density and high absorption ability [1][2][3][4]. In general, nanotechnology is expected to benefit existing products in two ways: making them more cost-effective, durable and efficient, and creating entirely new products [5]. Nanosilica is reported to improve aging [6] and fatigue and rutting resistance [7]. It is also stated to affect the anti-stripping properties of asphalt binder [5].

According to studies in the literature, adding 1% to 2% of silica fume to asphalt cement causes a reduction in temperature sensitivity, penetration, ductility, softening point, and elastic stress recovery [8][9]. Nanosilica doping has been reported to provide high resistance to permanent deformations [10][11].

Researchers investigated the effect of 2-4-6% Nanosilica additives in polymer modified bitumen. According to their results, it was stated that the addition of nanosilica increased the complex modulus (G^*) values of polymer modified binders at low frequencies and high temperatures and thus provided better rutting resistance, whereas it increased fatigue resistance by decreasing G^* values at high frequencies and medium temperatures (lower than 40 C). It was also stated that 6% nanosilica ratio is the optimum percentage [12].

In the research examining the potential use of nanosilica as an additive for asphalt, the authors evaluated how temperature, strain rate and frequency affect viscosity. Using pure binder and nanosilica-treated asphalt binders, various rheological tests were conducted. According to reports, adding nanosilica increases the rutting resistance asphalt binders. Fatigue testing using the linear amplitude sweep test also reveals that adding nanosilica prevents microcrack nucleation, improving the asphalt binder's fatigue life. The major polymeric chains of the asphalt binder are protected by nanosilica particles, which may operate as a possible heating barrier, enhancing the asphalt's resilience to aging and exhibiting self-healing properties [13].

The study investigated the effect of SBS and nanosilica additives on the fatigue life of asphalt binder and mixtures. Linear amplitude scanning (LAS) test and four-point bending tests were performed to evaluate the fatigue life of asphalt binder. The results showed that using SBS and nonosilica together considerably extended the asphalt binder and mixture's fatigue life, and the testing findings indicated that 6% was the ideal amount

of nanosilica. Moreover, a strong link between the asphalt mixture's fatigue life and the asphalt binder was found [14].

The rheological characteristics of asphalt binders modified with the nanomaterial Aerosil 150 were examined in this work at five different temperatures between 40°C and 80°C (increasing by 10°C).

2. Materials and Methods

2.1. Materials

The study used B50/70 penetration grade binder that was acquired from Batman Petrol Refinery. Aerosil® 150 Hydrophilic Fumed silica additive from Evonik company was used as asphalt binder additive. Table 1 shows the physico-chemical properties of the additive used. Table 2 shows the pure and modified binders used in the study. Aerosil 150 modified binders were prepared with the mechanical mixer shown in Figure 1 by mixing at 170°C at 1000 rpm for 60 min.

Table 1: Physico-chemical properties

| Properties | Unit | Typical value |
|-------------------------------|-------------------|---------------|
| Specific surface area (BET) | m ² /g | 150±15 |
| Average primary particle size | nm | 14 |
| Tamped density | g/l | 50 |
| Moisture | % wt. | ≤ 1.5 |
| Ignition loss | % wt. | ≤ 1.0 |
| pH (in 4% dispersion) | | 3.7 - 4.7 |
| SiO ₂ - content | % wt. | ≥ 99.8 |

Table 2: Binder combination

| Additive | Binder types | | | |
|-----------------|--------------|-----|-----|-----|
| | 0 | 2 | 4 | 6 |
| Aerosil 150 (%) | 0 | 2 | 4 | 6 |
| Symbol | 0-0 | 0-2 | 0-4 | 0-6 |



Figure 1: Mechanical mixer

2.2. Method

2.2.1. Frequency sweep test

With a Bohlin DSR rheometer, the frequency sweep test was carried out on pure and Aerosil 150 modified binders between 40°C and 80°C (increasing by 10°C). The test was run with a 1 mm gap and a 25 mm parallel plate geometry. The frequency range for the test was between 0.1 and 10 Hz. In order to determine the viscoelastic behavior by extending the test frequency over a wider frequency range, the master curve curves were generated by the Arrhenius equation given below according to the time-temperature superposition principle (TTSP) at a reference temperature of 40 °C.

$$\log a_T = \frac{E_a}{R} \left(\frac{1}{T} - \frac{1}{T_{ref}} \right)$$

E_a is for the activation energy related to relaxation, R stands for the gas constant, T stands for the experimental temperature, T_{ref} stands for the reference temperature, and a_T stands for the shift factor.

To produce a master curve, the complex modulus and phase angle measurements made at various temperatures between 40°C and 80°C were horizontally shifted to the reference temperature of 40°C. In this method, a wide range of reduced frequencies are used to express the rheological characteristics suggested by complex modulus and phase angle. Values at low frequencies correspond to 80 °C temperature-sensitive

characteristics. The features of low temperature (such as 40°C) are represented by data at low frequencies, in contrast.

3. Result

Figure 2 shows the main curves of complex modulus values of neat and Aerosil 150 modified binders at master curve reference temperature. According to Figure 2, as the frequency values increased, the complex modulus values increased. As the ratio of Aerosil 150 additive increased, the increase in the complex modulus increased compared to the neat binder. At high temperatures (low frequency) the difference in complex modulus values of neat and Aerosil modified binders is higher. As the frequency increases (low temperature), it is seen that the complex modulus values approach each other. This shows that Aerosil modified binders will exhibit more flexible behavior at high temperatures. At 40°C 0.1 Hz frequency, 2%, 4% and 6% Aerosil 150 additives gave G^* values 1.52, 2.02 and 3 times higher than pure binder, respectively. The same ratio is 1.31, 1.54 and 1.99 times at 5 Hz frequency and 1.28, 1.47 and 1.82 times at 10 Hz frequency. This also shows that the temperature sensitivity of Aerosil 150 additive binders is less.

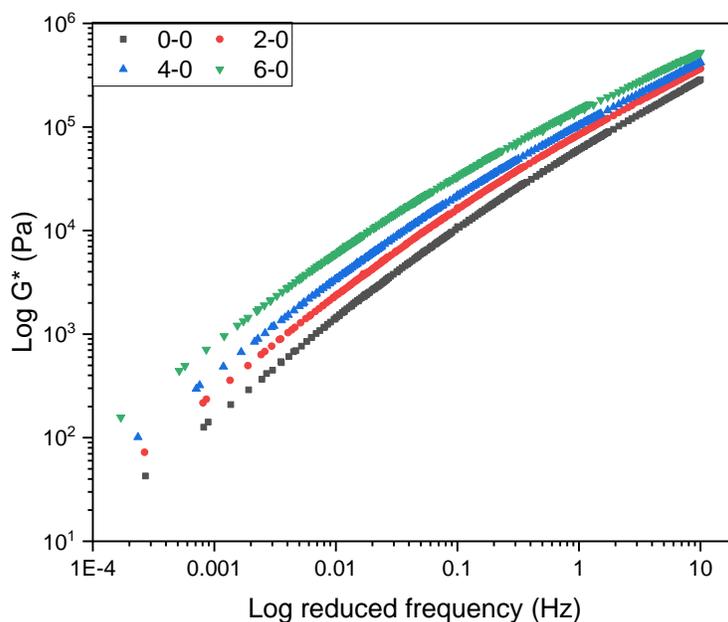


Figure 2: Muster curve complex modules of neat and modified binders at the reference temperature of 40 °C

Figure 3 shows the main curves of phase angle (δ) values of neat and Aerosil 150 modified binders at master curve reference temperature. At low frequency (high

temperature) values, the phase angle values of Aerosil 150 modified binders are lower than the pure binder. This means that the modified binders again exhibit more flexible behavior. By analyzing the phase angle values at 40 °C, 2%, 4%, and 6% Aerosil 150 modified binders, respectively, yielded 2.75 °C, 5.56 °C, and 9.17 °C lower phase angle values than pure binders at 0.1 Hz frequency. This decrease is 3.19°C, 5.04°C and 7.33°C at 5 Hz frequency and 3.09°C, 4.84°C and 6.76°C at 10 Hz frequency. 6% Aerosil 150 modified binder exhibits more flexible behavior at all frequencies (temperatures)..

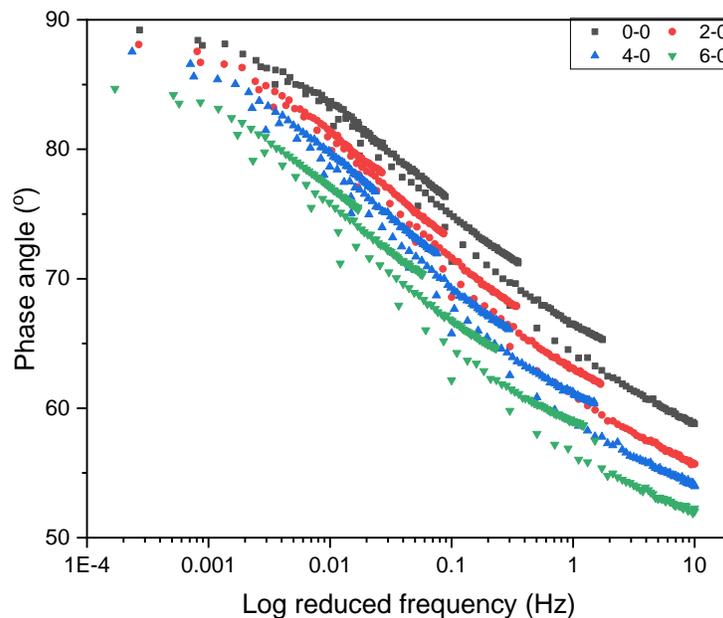


Figure 3: Muster curve phase angle of neat and modified binders at the reference temperature of 40 °C

Complex modulus versus phase angle is depicted in a black space diagram in Figure 4. The black space diagram, which displays the rheological information of bituminous materials as G^* versus δ , has been used successfully to interpret material behavior and offers a vital rheological characterization tool to look into and assess the characteristics and effectiveness of both binders and mixtures [15]. As can be seen in the figure, at low temperatures Aerosil 150 modified binders show a lower phase angle value against a higher G^* value. This indicates that the modified binders will give higher rutting resistance ($G^*/\sin\delta$). As the percentage of Aerosil 150 additive increases, G^* values increase while phase angle values decrease. As the temperature increased, 2% and 4% Aerosil modified binders showed similar performance with pure binder, while 6% Aerosil 150 modified binder gave the best rutting resistance.

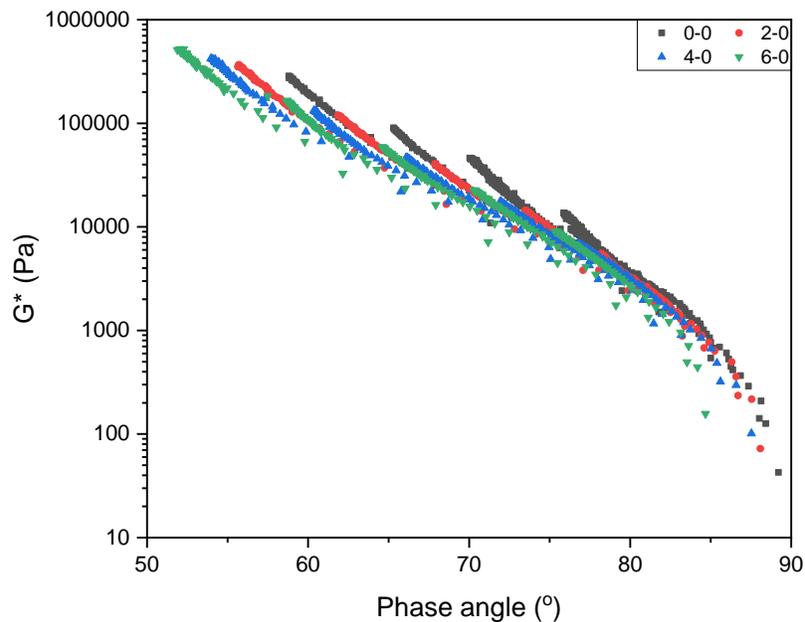


Figure 4: Black space diagram

Figure 5 shows the storage (elastic) modulus (G') versus loss (viscous) modulus (G'') plot (cole-cole diagram). The Cole-Cole plot is a method for displaying a graphical explanation of the viscous and elastic component of the stiffness of materials [$G''=f(G')$] on a linear or log scale, and it is frequently used for dielectric materials [16][17]. It is recommended to assess how much the elastic (shear storage modulus) and viscous (shear loss modulus) parts of the material contribute to overall stiffness [18]. The increased elastic behavior of the changed binders, as seen in the figure, causes the graph of the modified binders to shift in favor of the storage modulus axis.

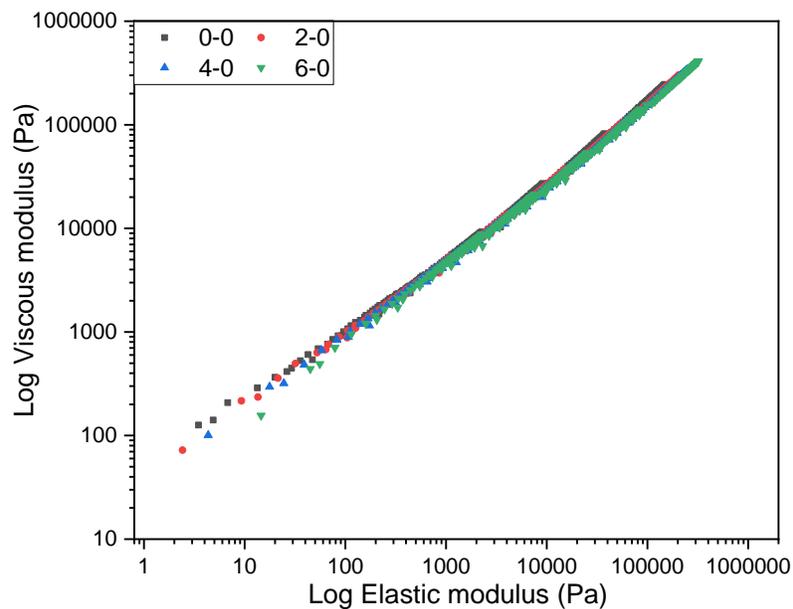


Figure 5: Cole-cole diagram

Figure 6 shows the change in loss factor ($\tan\delta$) versus frequency at a reference temperature of 40°C. A lower loss factor indicates a more flexible behavior of the binder [19] and is calculated according to the following equation.

$$\tan \delta = \frac{G''}{G'}$$

According to the figure, at low frequencies (high temperatures) the loss factor of Aerosil 150 modified binders is lower than that of the pure binder. As a result, Aerosil 150 modified binders will behave more elastically than pure binders, particularly at low frequencies.

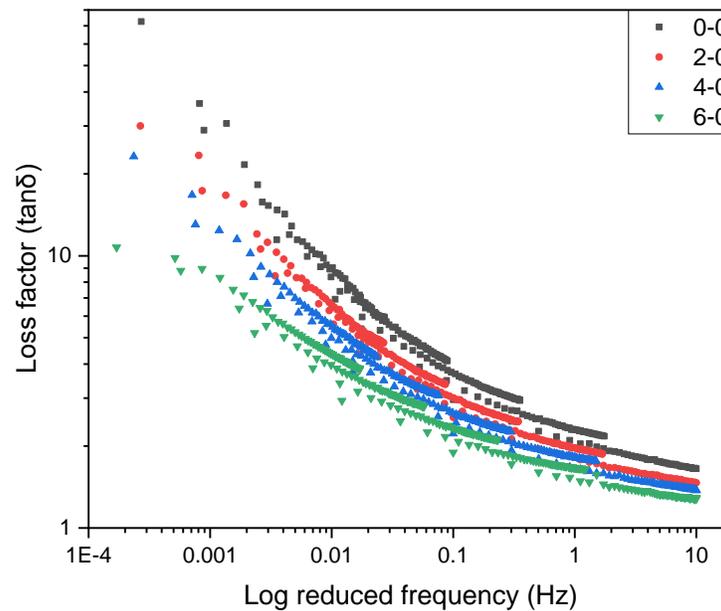


Figure 6: Loss factor versus reduced frequency

4. Discussion and Conclusion

In this study, the rheological effect of different ratios (2%, 4% and 6%) of nanomaterial (Aerosil 150) on asphalt binder was investigated by frequency sweep experiment. According to the results obtained:

- At low frequencies (high temperature) or high frequencies (low temperature), it was determined that Aerosil 150 modified asphalt binder gave higher complex values and the modulus of complex increased as the ratio of nanomaterial increased. In addition, it was determined that the phase angle values decreased as the nanomaterial ratio increased and exhibited more flexible behavior.
- At low temperatures, it was observed that Aerosil 150 modified binders gave lower phase angle values against higher G^* values and accordingly, the modified binders would give higher rutting resistance ($G^*/\sin\delta$).
- It was determined that the graph of the modified binders showed a shift towards the storage modulus axis, which is a result of the increase in the elastic behavior of the modified binders.
- According to the change in the loss modulus values, it was determined that the modified binders exhibited more flexible behavior.

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