Research Article

Evaluation of Fatigue Behavior of Asphalt Layers Containing Nanosilica Modified Tack Coat

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1. Introduction

Traffic loads along with environmental factors are two major causes of many kinds of damage to asphalt pavement. Every year, a significant amount of the national wealth of countries is lost because of premature failures of asphalt pavements. Moreover, the occurrence of pavement failures affects the frequency of accidents in countries [1, 2]. Traffic loads (in proportion to the amount of load applied to the pavement), contact surface, pavement thickness, and ambient temperature may impose various types of tensile, shear, and compressive stresses or a combination of them on the pavement [3]. Major failures in flexible pavements occur due to two factors, namely, rutting or cracking. Rutting generally occurs due to the passage of loads beyond the pavement capacity, while cracks are usually caused by high traffic of vehicles, and pavement shrinkage and expansion from temperature changes [4]. Among these two types of failures (i.e., rutting or cracking), cracks are more common on asphalt surfaces. Fatigue cracks in pavements generally occur due to such changes in environmental conditions, especially temperature changes, and repeated traffic loads.

In general, various factors affect the behavior of asphalt against cracking and rutting, one of the most important factors of which is the role of loading speed on the tensile strain below the asphalt layer. Fatigue is defined as the phenomenon of failure due to repeated loads, and dynamic load changes and periods. The fatigue life of an asphalt mixture displays the ability of the mixture to withstand repeated flexural loads without failure occurrence in the mixture.

Poor adhesion between the pavement interlayers can lead to several kinds of damage and, consequently, reduce the durability of the pavement. Furthermore, poor adhesion...
causes the sliding of pavement layers on each other [5], which is another type of damage and is more evident in slopes, detours, and situations where the traffic flow intends to increase or decrease speed (acceleration or stop) [6]. Poor adhesion can also create other failures such as premature fatigue, top-down cracking, and fragmentation of the pavement surface. Among the factors that affect the sliding of layers on each other are material type, compaction rate, size of aggregates, type of bitumen used in asphalt, amount of tack coat, weather conditions during execution, cleanliness of surfaces during execution, amount of moisture or penetration in the interface, the surface texture of surfaces, amount of traffic loads, operating temperature, type of asphalt mixture, manner and amount of uniformity of tack coat distribution, and method of tack coat treatment (for soluble bitumen or bitumen emulsion) [7–10].

According to previous research, the presence of moisture (water) and dust cover before the application of the upper asphalt layer weakens the adhesion performance of asphalt layers, and thus, the application of tack coat improves performance and increases adhesion [10, 11]. In the case of the presence of moisture, the application of tack coat using pure bitumen has shown better performance than that of specimens containing emulsion tack coat [12].

Bitumen emulsions are the most common tack coats and include various types of slow-setting, medium-setting, rapid-setting, and highly rapid-setting bitumen, and modified with polymer and rubber powder. However, pure bitumen used in the production of asphalt mixtures can also be utilized as a tack coat and the application of soluble bitumen is very limited due to its destructive effects on the environment [6]. According to a study on various types of tack coats, it was found that the use of pure bitumen could improve the fatigue performance of asphalt pavement [13], although another research showed that using bitumen emulsion for tack coats increased adhesion between layers [8].

In recent years, many researchers have attempted to use additives in bitumen and mixtures to improve the performance of asphalt mixtures. With the advancement of nanotechnology, researchers have investigated the effect of these materials on the properties of asphalt and bitumen mixtures. The following section provides some research conducted on the application of nanomaterials in bitumen and asphalt mixtures. Based on the results, nanosilica had a positive effect on the reverse strain and led to maximum recovery for bitumen modified with 2% nanosilica [14].

Regarding the formation of strong networks in bitumen, nanomaterials often cause bitumen stiffness, increase rutting resistance, enhance the resilience modulus of asphalt, and in some cases, increase the fatigue life of bitumen and asphalt mixtures. In this regard, hydrated nanolime, nanoclay, carbon nanofibers, and nanosilica are among the nanomaterials added to bitumen or asphalt mixtures as modifiers in recent years [15–17].

Nanosilica is a white crystalline material with the chemical formula of SiO2 in nanometer size that is abundant on Earth. The lower production cost and higher performance properties are among the most important advantages of nanosilica compared to other nanomaterials [18]. Nanosilica is used to produce silica gel, silica gas, and the like. According to laboratory works, nanosilica modified asphalt mixtures have a longer fatigue life, upper rutting resistance, and increased antiaging properties, by delaying oxidation, increasing stability against moisture damages, increasing antistripping properties, and reducing creep strain deformation [19]. In another study, it was stated that the fatigue life of nanosilica modified bitumen increased more than that of nanotitanium and nanocalcium carbonate, and adding 4% nanosilica to bitumen increased the fatigue life [20].

Nanosilica can significantly improve the thermal properties of hot mix asphalt so that the stiffness modulus of these mixtures is improved, resulting in increasing their resistance to incoming loads [21]. The modification of bitumen with nanosilica increases viscosity, softening point, and elasticity modulus and decreases ductility. The application of nanosilica modified bitumen improves some properties such as dynamic modulus and viscosity, increases the Marshall resistance and the stiffness modulus, and causes less sensitivity to temperature variation [15].

As mentioned, various modifiers are available to improve and eliminate the weaknesses of bitumen, one of the most important types of which is nanomaterials. In recent decades, high attention has been paid to nanomaterials, due to their various capabilities. The use of nanoadditives in tack coats may play an effective role in improving pavement performance by improving the adhesion between pavement layers. Therefore, this question is raised whether using modifiers such as nanomaterials in bitumen used as tack coat can be expected to increase the fatigue life of the asphalt pavement. This issue is one of the topics that require laboratory research to better investigate the performance of such materials.

So far, few studies have been conducted on the use of nanomaterial modified tack coats in pavements, despite proving the positive effect of using nanomaterials on improving the performance of asphalt binder in many studies. Considering the advantages of nanomaterials, this study seeks to investigate the effectiveness of using tack coats modified with nanomaterials as an adhesive between the upper and lower layers of asphalt on the fatigue life of pavements. This research aims to evaluate the fatigue behavior of asphalt mixture specimens containing nanosilica modified tack coat (NSMTC) and compare it with specimens containing unmodified tack coat (UMTC).

2. Materials and Methods

To determine the effectiveness of modified tack coat with nanosilica on the fatigue life of hot mix asphalt layers, slabs were made using the following materials in two modes of applying UMTC and NSMTC and, then, were compacted by slab roller compactor. Finally, slabs were cut to standard sizes to prepare for a 4PB beam fatigue test.

2.1. Materials. The aggregate materials used in this research included materials with dense granulation, the specifications
of which are described in Table 1. Bitumen was also pure bitumen with a penetration degree of 60–70, as presented in Table 2.

The nanomaterial used to modify the tack coat was silicon dioxide nanoparticles made by a US company. Regarding previous research and economic issues, the optimum percentage of nanosilica was equal to 1.2% of the bitumen weight [19]. Table 3 presents the specifications of the nanosilica used in this research. Furthermore, the wet method was used to mix nanomaterials with bitumen, and kerosene solvent was utilized to disperse nanomaterials into bitumen. The selected solvent should have a low viscosity at ambient temperature to homogeneously disperse the nanomaterials. Finally, the evaporation rate of the solvent should be low at ambient temperature and high at medium and high temperatures.

To determine the optimal percentage of bitumen in asphalt mixtures, the Marshall method was used according to the ASTM D1559 standard. Then, two different types of slabs were constructed to prepare the asphalt slabs required for the fatigue test. The basis of the difference between these slabs was the type of tack coat (unmodified and nanosilica modified). After preparing the asphalt mixture, it was poured into slab forms and compacted by a slab roller compactor, and ultimately, it was cut into beams with dimensions of 380 mm in length, 63 mm in height, and 55 mm in width.

### 2.2. Four-Point Bending Beam Fatigue Test

The 4 PB beam fatigue test was performed according to the AASHTO T321 standard in two states (modes) of controlled stress and controlled strain. In this test, repetitive bending loads were applied to the asphalt concrete beam specimen and the amount of applied load and deformation in the middle of its opening were measured. The loading waveform was sinusoidal in the controlled stress state and sinusoidal or semisinusoidal in the controlled strain state.

Considering the reduction in stress in the controlled strain state, the specimen can last for a long time in the third stage without a significant reduction in flexural stiffness. The fracture criterion is usually specified as the reduction in flexural stiffness to a percentage of the initial flexural stiffness. The AASHTO T321 standard sets this rate at 50%. Due to the differences in the calculation methods of the initial flexural stiffness and, sometimes, the dispersion in the results, the best criterion for determining the failure limit of the specimen is to consider the flexural stiffness reduction versus the repeated load (fatigue life) curve. Equations (1) to (4) indicate the relationships applied by the device to estimate results.

\[
\sigma_i = \frac{G_0.P}{b.h^2}, \quad (1)
\]

\[
\varepsilon_i = \frac{(12 \times 10^6)h.\delta}{3.G_0^2 - 4.G_i^2}, \quad (2)
\]

\[
E = \left( \frac{G_i.P}{b.h.\delta} \right) \left( \frac{3.G_0^2 - 4.G_i^2}{4.h^2 + K.\left(1 + \nu\right)} \right), \quad (4)
\]

where \(\sigma_i\) represents the maximum tensile stress in kPa, \(P\) indicates the load on the specimen in kN, \(b\) shows the average width of the specimen in mm, \(h\) displays the average height of the specimen in mm, \(G_0\) demonstrates the distance between supports in mm, and \(G_i\) depicts the distance between the loading clamps. Moreover, \(\varepsilon_i\) is the tensile strain, \(\delta\) is the mean displacement in the middle of the beam in millimeters, \(E_i\) is the flexural stiffness in MPa, \(E\) is the elasticity modulus in MPa, \(\nu\) is Poisson’s coefficient, and \(K\) is the real shear stress ratio in terms of average shear stress, which is assumed 1.5 [15].

The \(IF\) parameter is related to the recovery coefficient, which shows the number of loading cycles at the turning point of the flexural stiffness diagram. This parameter is calculated in equation (5) [15].

\[
IF = \frac{N_{f}^{th} - N_{f}^{control}}{N_{f}^{control}}, \quad (5)
\]

where \(N_{f}^{th}\) represents the number of loading cycles of the specimen \(i\), and \(N_{f}^{control}\) indicates the number of loading cycles of the control specimen. The higher the value of \(IF\), the greater the ability of the asphalt mixture to delay crack propagation [15].

Generally, several equations are available for predicting fatigue life (\(N_{f}\)), one of the most common of which is the exponential function presented in equation (6) [22].

### Table 1: Mixture gradations.

| Sieve size (mm) | % Passing | Gradation limits (%) |
|-----------------|-----------|----------------------|
| 19 mm           | 100       | 100                  |
| 12.5 mm         | 96        | 90–100               |
| 9.5 mm          | 85        | —                    |
| 4.75 mm (no. 4) | 66.5      | 44–74                |
| 2.36 mm (no. 8) | 36.8      | 28–58                |
| 0.3 mm (no. 50) | 10        | 7–23                 |
| 0.075 mm (no. 200) | 4       | 2–10                 |

### Table 2: Specifications of asphalt binder (AC 60–70).

| Test                                      | Method       | Unit   | Value |
|-------------------------------------------|--------------|--------|-------|
| Penetration (25°C, 100 g, 5 s)            | ASTM D-5     | mm     | 0.1   |
| Softening point                           | ASTM D-2398  | °C     | 50    |
| Specific gravity                          | ASTM D-70    | Gr/cm³ | 1.01  |
| Ductility (25°C, 5 cm/min)                | ASTM D-113   | cm     | 102   |

### Table 3: Specifications of nanosilica.

|        | Ti    | Ca    | Na    | SiO2  |
|--------|-------|-------|-------|-------|
| <200 ppm | <120 ppm | <20 ppm | <50 ppm | >99%  |
where $\varepsilon$ is the initial tensile strain, and the parameters $k$ and $n$ are constant coefficients that can be calculated using the fitted line equation. The values of $n$ and $k$, and the correlation coefficient ($R^2$) will be reported in an individual table.

The dissipated energy approach, as one of the approaches to studying the fatigue behavior of asphalt mixtures, examines the relationship between fatigue life and the amount of dissipated energy. When a material undergoes a repetitive loading cycle in the plastic region, loops are formed in the stress-strain curve, which are called hysteresis loops. The formation of these loops indicates that some of the input energy is dissipated in each loading cycle, due to internal friction or heat. Hence, the dissipated energy can be considered as the result of subtracting the amount of energy consumed in the system (surface below the load curve) and improved energy (surface below the loading curve). In other words, the energy dissipated in each cycle is the internal area of the hysteresis loop of that cycle [23, 24].

Among the advantages of this method for viscoelastic materials such as asphalt mixture is that this approach allows analyzing fatigue behavior by performing a limited number of fatigue tests. The amount of energy dissipated in each loading-unloading cycle is determined by equation (7). By summing the values of all cycles, the total dissipated energy (equation (8)) can also be estimated. In tests under a controlled strain state, increasing the number of repetitions of the loading cycles leads to a decrease in dissipated energy [25].

\[
DE_i = \pi \sigma_i \varepsilon_i \sin \phi_i, \quad (7)
\]

\[
DE_{\text{Total}} = \sum_{i=1}^{N_{f50}} DE_i, \quad (8)
\]

where $DE_i$ is the energy dissipated in cycle $i$, $\sigma_i$ is the amount of stress in cycle $i$, $\varepsilon_i$ is the amount of strain in cycle $i$, $\phi_i$ is the fuzzy angle for cycle $i$, and $DE_{\text{Total}}$ is the total energy dissipated during the test to the end of the mixture fatigue life. It should be noted that this fatigue life ($N_{f50}$) is equivalent to the number of repetitions of the loading cycles, which reduces the flexural stiffness by up to 50% of the initial flexural stiffness.

The variation curve of cumulative dissipated energy against the fatigue life can be independently used to determine the fatigue behavior of the asphalt mixture. The slope of this curve is affected by various parameters such as type of bitumen, type of aggregate, percentage of air voids, temperature, controlled stress level, and controlled strain level [23, 25]. Based on the results of previous research, the power function can be used to provide a relationship between the amount of cumulative dissipated energy and the fatigue life of the asphalt mixture, as shown in equation (9). Therefore, equation (9) allows for predicting the fatigue life in terms of total dissipated energy.

\[
N_f = k \left( \frac{1}{\varepsilon} \right)^n, \quad (6)
\]

where $DE_i$ represents the cumulative dissipated energy for failure in cycle $i$, $N_f$ is the fatigue life in cycle $i$, and the values $a$ and $k$ are power function constants determined by model calibration.

Although the main assumption in the dissipated energy method is that this energy is used to cause damage to materials, and part of this energy in viscoelastic materials such as asphalt concrete is converted into heat and mechanical work and, thus, is consumed. In other words, a major part of energy dissipated in asphalt concrete, which is a kind of viscoelastic and nonlinear material, is dissipated in the form of heat and deformation, and only a limited part of the dissipated energy is spent on failure (crack formation and expansion).

### 3. Results and Discussion

#### 3.1. Flexural Stiffness Changes in UMTC and NSMTC Specimens

The fatigue life of specimens containing unmodified tack coat (UMTC) and specimens containing nanosilica modified tack coat (NSMTC) was determined by performing a 4PB beam fatigue test with the controlled strain state and at three strain levels of 400, 550, and 700 $\mu$e. It is possible to determine the performance of the modified tack coats by comparing them with the control specimens. Table 4 provides values obtained from this test.

Figure 1 compares the test results for different specimens. As shown, the trend of changes in flexural stiffness against fatigue life indicates that the curve of the specimen containing the NSMTC well corresponds to the curve of the specimen containing the UMTC. However, the fatigue life of the specimen containing the modified tack coat at the strain level of 400 $\mu$e has increased to about 2,000 cycles. Although an increase in the controlled strain level to higher values has significantly reduced the fatigue life of the mixtures, the application of NSMTC increases the fatigue life by about 1,000 cycles. As observed in Figure 1(c), the effectiveness of NSMTC is quite evident for the strain level of 700 $\mu$e and this increase has reached about 1.75 times.

Generally, reduced flexural stiffness of the asphalt mixture indicates an increase in flexibility and better behavior of the specimen of asphalt mixtures against repeated loadings, resulting in increasing the fatigue life of the asphalt layer. The amount of flexural stiffness (according to equation (3)) is a function of the amount of cross-sectional dimensions (width and height) of the beam, the distance between the supports, the distance between the loading clamps, and the average displacement in the middle of the beam. Therefore, any change in the thickness of the beam layer(s) or the displacement of the middle of the beam will change the flexural stiffness of the beam. According to the measurements made in the four-point bending beam fatigue test, the initial flexural stiffness is almost the same for all specimens, although an increase in the number of repetitions and the controlled strain level causes specimens with modified tack coat to have a higher flexural stiffness at a constant load.
repetition value. Although the flexural stiffness of the specimen containing the modified tack coat has increased at a constant load repetition value, the continuity of loading indicates that the specimens containing the modified tack coat could have a longer fatigue life.

3.2. Fatigue Life Variations of UMTC and NSMTC Specimens. The fatigue life of the UMTC and NSMTC specimens at the strain levels of 400, 550, and 700 με is illustrated in Figure 2. The fatigue life values presented in this figure are based on the amount of repetition of loading until the flexural stiffness is reduced to about 50% of the initial flexural stiffness.

As shown in Figure 2, the NSMTC has been an effective factor in increasing the fatigue life of the studied specimens compared to other UMTC specimens. For example, the fatigue life of NSMTC specimens increased by about 17.6 and 14.8% at the strain levels of 400 and 550 με, respectively. Moreover, the fatigue life of NSMTC specimens at a strain level of 700 με increased by 57.15% compared to UMTC specimens.

Table 5 presents the results of the fatigue life of the UMTC and NSMTC specimens. In all cases, the specimens with the modified tack coat have a longer fatigue life compared to UMTC samples.

| Sample type of asphalt mixture beam | Fatigue life at strain level of | Initial flexural stiffness at strain level of |
|------------------------------------|--------------------------------|-------------------------------------------|
|                                    | 400   | 550   | 700   | 400  | 550  | 700  |
| Unmodified tack coat (UMTC)        | 9100  | 4900  | 2100  | 2597 | 2463 | 2148 |
| Nanosilica modified tack coat (NSMTC)| 10700 | 5625  | 3300  | 2598 | 2486 | 2185 |

3.3. Improvement Factor (IF). The IF parameter estimation is one of the quantitative solutions for evaluating the effectiveness of NSMTC. According to this method, increasing the IF parameter enhances the ability of the asphalt mixture to delay crack propagation [22]. Table 5 presents the IF parameter for different specimens.

According to the values in Table 5, NSMTC could improve the fatigue life by at least 15% at the strain level of 550 με and up to 57% at the strain level of 700 με. In addition to the specified factors that increase the fatigue life, such as aggregate granulation, type of bitumen, and the amount of bitumen, we can also refer to tack coat modification such that using modified bitumen as tack coat significantly reduces the crack formation and propagation in asphalt pavement.

3.4. Fatigue Life Prediction Functions of UMTC and NSMTC Specimens. In this research, the fatigue function (equation (6)) has been used to predict the fatigue life concerning different strain levels. For this purpose, values of constant coefficients (including n and k) can be obtained for both sets of UMTC and NSMTC specimens, by performing exponential regression on fatigue life data at different strain levels. To evaluate the goodness of fit, the correlation coefficient (R²) has been used, the values of which are presented in Table 6.

As shown in Figure 2, the NSMTC has been an effective factor in increasing the fatigue life of the studied specimens compared to other UMTC specimens. For example, the fatigue life of NSMTC specimens increased by about 17.6 and 14.8% at the strain levels of 400 and 550 με, respectively. Moreover, the fatigue life of NSMTC specimens at a strain level of 700 με increased by 57.15% compared to UMTC specimens.

Table 6 also shows the reduction in fatigue life at different levels of strain for each of the NSMTC and UMTC specimens. Accordingly, an increase in the controlled strain level from 400 to 550 με reduced the fatigue life in UMTC and NSMTC specimens by about 46.15 and 47.43%, respectively. In UMTC samples, increasing the controlled strain level from 550 to 700 με decreased the fatigue life by about 57.14%, while this value was about 41.33% in the case of NSMTC samples. Thus, it can be said that the reduction rate of the fatigue life in UMTC and NSMTC specimens is close to each other by increasing the controlled strain level at low strain levels. At high strain levels, however, the reduction rate of fatigue life in NSMTC specimens is significantly lower than that of UMTC specimens, by increasing controlled strain levels. In other words, at the high controlled strain levels, NSMTC could provide higher efficiency and better performance compared to UMTC samples.

3.5. Variation of Dissipated Energy and Cumulative Dissipated Energy of UMTC and NSMTC Specimens. The formation of closed stress-strain curves in viscoelastic materials indicates energy dissipation in this type of material, and in other words, the area of these curves in each cycle is equivalent to the amount of energy dissipated in that cycle. As shown in Figure 3, an increase in the fatigue life decreases the amount of energy dissipated in the cycles. Furthermore, increasing the fatigue life decreases the flexural stiffness modulus and, consequently, reduces the maximum tensile stress on the specimen under controlled strain conditions. The formation of closed stress-strain curves in the asphalt mixture shows that part of the energy dissipated in the materials is wasted by the materials in the form of heating and lubrication, and the other part leads to the failure of the asphalt specimen.

As shown in Figure 3, increasing the amount of controlled strain leads to an increasing trend for the energy dissipated and, consequently, decreases the fatigue life of the specimens. In all cases, the specimens with the modified tack coat have a higher amount of energy dissipation.

By summing the area of all closed curves in the stress-strain diagram, it is possible to determine the amount of cumulative dissipated energy for each sample of asphalt mixture. Figure 4 depicts the values of cumulative dissipated energy for each of the UMTC and NSMTC samples. As
observed, increasing the strain level from 400 to 700 \( \mu \varepsilon \) decreases the cumulative dissipated energy. In other words, the cumulative dissipated energy of the specimen decreases by increasing the controlled strain level. Figure 5 gives the bar graph of the cumulative dissipated energy values for a more detailed study of the cumulative dissipated energy of the UMTC and NSMTC specimens at the controlled strain levels of 400, 550, and 700 \( \mu \varepsilon \).

According to the values of cumulative dissipated energy shown in Figure 5, NSMTC could increase the cumulative dissipated energy for the strain levels of 400, 550, and 700 \( \mu \varepsilon \) by about 37, 42, and 60% compared to the UMTC.
Figure 2: The fatigue life of UMTC and NSMTC specimens at strain levels of 400, 550, and 700 με.

Table 5: Improvement factor (IF) for UMTC and NSMTC specimens at 400, 550, and 700 με.

| Controlled strain level | 400     | 550     | 700     |
|-------------------------|---------|---------|---------|
| Improvement factor (IF) | 0.18    | 0.15    | 0.57    |

Table 6: Values of $n$, $k$, and correlation coefficients for fatigue life prediction functions.

| Sample type of asphalt mixture beam | $N$   | $k$    | Correlation coefficient ($R^2$) |
|-------------------------------------|-------|--------|---------------------------------|
| Unmodified tack coat (UMTC)         | 0.376 | 12700  | 0.9716                          |
| Nanosilica modified tack coat (NSMTC)| 0.476 | 33364  | 0.9993                          |

Figure 3: Continued.
Figure 3: Changes in dissipated energy against fatigue life of UMTC and NSMTC specimens at the strain levels of (a) 400, (b) 550, and (c) 700 με.

Figure 4: Continued.
Figure 4: Changes in cumulative dissipated energy against fatigue life of UMTC and NSMTC specimens at the strain levels of (a) 400, (b) 550, and (c) 700 με.

Figure 5: Cumulative dissipated energy of UMTC and NSMTC specimens at the controlled strain levels of 400, 550, and 700 με.
specimens, respectively. In other words, the NSMTC could significantly increase the cumulative dissipated energy of the samples for different strain levels. Nanosilica modifier plays an important role in increasing the capability of bitumen (used for tack coat) in further absorption and dissipation of energy from traffic load, leading to a reduced fatigue failure in asphalt mixtures containing tack coat.

4. Conclusions

This study sought to investigate the fatigue life of asphalt mixture samples containing unmodified tack coat (UMTC) and samples containing nanosilica modified tack coat (NSMTC) under each of the proposed conditions. To this aim, a 4 PB beam fatigue test was conducted under semisinusoidal load with a frequency of 10 Hz and without rest in a controlled strain mode (three strain levels of 400, 550, and 700 με) at a temperature of 20°C. The results of the test are as follows:

(i) The addition of nanosilica as a tack coat modifier failed to make a significant difference in the initial flexural stiffness, and therefore, it can be argued that nanosilica did not have a significant effect on the changes in the initial flexural stiffness.

(ii) As shown in Figure 1, the trend of changes in NSMTC and UMTC specimens was perfectly consistent with each other in the flexural stiffness, except for the initial flexural stiffness values.

(iii) Increasing the number of loading cycles caused NSMTC specimens to have a higher flexural stiffness in each given cycle compared to UMTC specimens. In other words, NSMTC when applying asphalt pavement layers had a positive effect on increasing the flexural stiffness of asphalt pavement and, consequently, increased its fatigue life.

(iv) Enhancing the strain level to 550 and 700 με caused more differences in the flexural stiffness of the samples containing the NSMTC compared to UMTC and highlighted the effectiveness of nanosilica in increasing the flexural stiffness (for any given number of load repetitions), as shown in Figures 1(b) and 1(c).

(v) By increasing the controlled strain level, the effectiveness of NSMTC on fatigue life (especially for strain level of 700 με) has become more evident. According to the values in Table 5, the IF value for the strain level of 700 με is about 0.57.

(vi) The addition of nanosilica to bitumen used in tack coat increases the elasticity modulus, reduces its ductility, and improves pavement continuity by creating high adhesion between pavement layers. Moreover, this material significantly improves the amount of cumulative dissipated energy, in addition to increasing the fatigue life of the pavement. Note that this improvement was evident for all strain levels considered in this study so that an increase in the strain level increases the amount of cumulative dissipated energy.

Data Availability

Access to data is restricted, except for the revealed data in the manuscript. Some or all data are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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