Hindawi
Advances in Civil Engineering
Volume 2023, Article ID 7353949, 11 pages
https://doi.org/10.1155/2023/7353949

Research Article

Effect of Nano-Cobalt Oxide on the Rheological Behavior of Asphalt Binder and Mechanical Characteristics of Hot Mix Asphalt

Gholam Hossein Hamedi ,[1] Mohammad Mazhari Pakenari,[1] Masoud Toghrol Tabrizi,[2] and Zahra Ranjbar Pirbasti[1]

[1]*Department of Civil Engineering, University of Guilan, Rasht, Iran*
[2]*Department of Civil Engineering, Tarbiat Modares University, Tehran, Iran*

Correspondence should be addressed to Gholam Hossein Hamedi; hamedi@guilan.ac.ir

Received 6 October 2022; Revised 19 December 2022; Accepted 23 December 2022; Published 4 January 2023

Academic Editor: Jiaolong Ren

In this study, the effects of nano-cobalt oxide (nano-CoO) (1 and 2% by asphalt binder weight) on the rheological behavior of the asphalt binder and mechanical characteristics of asphalt mixtures were examined. To evaluate the behavior of the asphalt binder at moderate and high temperatures, the dynamic shear rheometer (DSR) test was used. Besides, to study asphalt mixtures' rutting potential and fatigue cracking, the repeated load axial (RLA) test and the indirect tensile fatigue test (ITFT) were conducted, respectively. Based on the rheological tests, adding 1 and 2% of nano-CoO to asphalt binder increases the complex modulus (G^*) and reduces the phase angle (δ) at high temperatures and significantly improves the modified asphalt binder's rutting parameter. Also, at moderate temperatures, the addition of nano-CoO reduced the fatigue parameter of the modified asphalt binder compared to the control asphalt binder. It was demonstrated that the permanent strain of the modified specimens was decreased by about 35% compared to that of the control specimens. The fatigue tests at two temperatures and five stress levels also showed that incorporating nano-CoO significantly increased (about 90%) the fatigue life of modified samples compared to controlled samples.

1. Introduction

Different repeated loads are applied to the pavement with the passage of heavy vehicles and their overloads. These loads often lead to distress (e.g., fatigue) on pavements, which can result in various failures. Extremely hot summers or cold winters, heavy rainfall, temperature variations, and freeze/thaw periods lead to significant stresses in asphalt mixture, which may lead to common pavement failures [1].

The rheological and viscoelastic characteristics of asphalt binder, as an asphalt mixture constituent, affect its mechanical properties. The rheological science expresses the rate of fluid deformation induced by stress and the impact of time on it. Because it behaves viscoelastically, asphalt binder rheological parameters are time- and temperature-variable, which alters its physical characteristics and leads to the occurrence of failures in the asphalt pavement such as rutting and fatigue [2, 3].

Asphalt binder rheological characteristics at various temperatures can be enhanced in different ways. Asphalt mixture performance can also be improved against various failures. Researchers have focused on the incorporation of high-quality materials, modification of asphalt binder and gradation of aggregates, the addition of proper fillers and additives, and also some methods of healing [4–10]. Additive incorporation has gained momentum in the past decades with respect to asphalt mixture type, mix design variables, and climatic conditions. Additive use has extended in the last 20 years with the progress in technology and the presentation of novel materials, e.g., nanomaterials and polymeric substances [11–16].

Ghile [17] reported that by adding 2% nanoclay, the fatigue life of asphalt samples at 20°C is doubled. However, at 5°C, the nanoclay had a negative effect on the fatigue life of the asphalt mixture and reduced it by 20%. Jahromi et al. [18] showed that the fatigue life of an asphalt sample containing 7% nanoclay at 25°C is 1.7 times higher than that of the control sample. In addition, Liu [19] performed fatigue tests at two stress levels and reported that the modified asphalt mixture's fatigue life is prolonged by 40% at lower stress levels, while this parameter showed no significant rise at higher stress levels. Xiao et al. [20, 21] evaluated the effect of carbon nanoparticles on the rheological characteristics of asphalt binders by rolling thin-film oven (RTFO) and pressure aging vessel (PAV) tests. A dynamic shear rheometer (DSR) test was conducted to investigate the fatigue and rutting behavior of the control and modified asphalt binder with 0.5%, 1%, and 1.5% carbon nanoparticles. Based on the findings, incorporating 1.5% carbon nanoparticles in the asphalt binder enhanced the resistance to rutting by 60%. Nevertheless, according to the statistical analysis, the type of asphalt binder affected the fatigue behavior of the asphalt binder more than the percentage change in nanoparticles. Khattak et al. [22] investigated the effect of carbon nanofibers on the rheological properties of asphalt binder. The results revealed that the fatigue parameter ($G^*.\sin\delta$) and the rutting parameter ($G^*/\sin\delta$) of the modified asphalt binder improve with adding carbon nanofibers. Furthermore, Shafabakhsh et al. [23] examined the fatigue and rutting behavior of asphalt mixtures modified with nano-titanium oxide. For this purpose, the indirect tensile fatigue test (ITFT) and repeated load axial tests (RLA) were performed on asphalt samples. The results of the tests revealed that the samples containing 5% nano-titanium oxide have the longest fatigue life and the least permanent deformation. Also, Shi et al. [24] evaluated the rheological performance of an asphalt binder containing nano-silica. In this study, 8% nano-silica was used for viscosity tests, DSR, and the bending beam rheometer (BBR) test. According to the results, with the addition of nano-silica, the resistance to rutting and cracking increased. In a study conducted by Mubaraki et al. [25], the rheological properties of an asphalt binder modified with nano-aluminum oxide were explored at three values of 3%, 5%, and 7% by weight of the asphalt binder. The results showed that the use of nano-aluminum oxide reduces the rutting potential. In addition, Ziari et al. [26] evaluated the effect of carbon nanotubes on asphalt binder performance. It was found that the incorporation of this additive improves the classic characteristics (softening point, penetration grade, and so on) and performance (complex modulus, phase angle, fatigue parameter, rutting, and so on). Shafabakhsh and Sajjadib [27] investigated the use of nano-copper oxide to improve the properties of an asphalt binder in 2.5%, 3%, and 5% of the mass of asphalt binder. The addition of nano-copper oxide considerably improved the modified asphalt binder's rheological performance against fatigue cracking (at medium temperatures) and thermal cracking (at low temperatures). In another study, the effect of using nano-copper oxide on the characteristics of asphalt binder and asphalt mixture modified with this nanoparticle was investigated; 1.5%, 3%, and 4.5% of nano-copper oxide were used in the modified asphalt binder samples. Based on the results of DSR and BBR tests, 1.5% was determined as the optimal value with the best results in both rheological and functional characteristics [28]. Sediq [29] studied the effect of two types of nanomaterial, namely, calcium carbonate and copper oxide, in 3% and 5% of the asphalt binder mass on the performance characteristics of the asphalt binder and asphalt mixture. The results showed that using nanomaterials reduces deformation and enhances the durability of the asphalt binder. The incorporation of these two types of nanomaterial increases viscosity and softening point and decreases the penetration grade of the modified asphalt binder. Rezvan and Izadi [30] examined two types of nanomaterial (iron oxide and aluminum oxide) as asphalt binder modifiers on the moisture damage of asphalt mixtures. The results of the modified Lottman test revealed that the use of nanomaterials enhances the indirect TSR in the modified samples. Also, nano-iron oxide had a more prominent effect on reducing the moisture damage potential in the asphalt mixture than nano-aluminum oxide. Another study performed a laboratory evaluation of the fatigue behavior and stiffness modulus of stone mastic asphalt (SMA) by adding different percentages of nano-aluminum oxide. Based on the experiments, the SMA containing 0.6% nano-aluminum oxide has the best results in stiffness modulus and fatigue life tests [31]. Baqersad and Ali [32] evaluated the use of nanoclay on the performance of RAP materials. In this study, fatigue cracking, rutting potential, and low-temperature performance of recycled asphalt mixture are assessed. The results indicated that nanoclay improves the performance of RAP and it can pave the way for industrialization and use in extreme weather conditions. Mirabdolazimi et al. [33, 34] investigated the effect of nano-silica on the moisture sensitivity of hot mix asphalt and asphalt emulsion mixture in two separate studies. The results showed that nano-silica considerably improves hot mix asphalt moisture susceptibility and asphalt emulsion mixture. Kamboozia et al. [35] investigated the intermediate-temperature cracking and rutting behavior of porous asphalt (PA) mixtures modified with different percentages of nano-ZnO (NZ) under the laboratory aging condition and freeze-thaw cycle by performing semicircular bending (SCB) and wheel track tests. The result showed that adding NZ enhanced PA mixtures' performances against cracking and permanent deformation by an average of 50% under both laboratory conditions. Ezzat et al. [36] reported that nano-silica leads to a decrease in the penetration grade and increases the softening point temperature; in contrast, the nanoclay increases the penetration and decreases the softening point temperature. At temperatures of 135°C and up to 150°C, increasing the nano-silica percentage displayed an increase in the RV, while nanoclay, at small percentages, increased the RV and then decreased it at higher percentages. Besides, the DSR results indicated a noticeable improvement in resistance to permanent deformation. Jeffry et al. [37] evaluated the effect of nano-charcoal coconut shell ash (NCA) on the mechanical characteristics of the asphalt mixture. Performance tests of asphalt mixtures including Marshall analysis, indirect tensile strength (ITS), resilient modulus, and dynamic creep test were carried out on 0% (control), 1.5%, 6%, and 7.5% NCA asphalt mixtures. The microstructure properties of the asphalt mixtures were assessed using atomic force microscopy (AFM) and field emission scanning electron microscopy (FESEM). Results indicated that the modified samples with 6% NCA considerably enhanced Marshall stability, ITS, resilient modulus, and dynamic creep of the asphalt mixture. Besides, AFM results demonstrated that 6% NCA has the lowest surface roughness which improved the adhesion of the asphalt mixture. Generally, most previous studies showed that nanomaterials improve the properties of asphalt binder and mechanical characteristics of asphalt mixtures.

1.1. Statement of the Problem and Objectives. Various failures in asphalt mixtures occur due to poor material properties and the impact of environmental and traffic conditions, the most common of which are rutting occurring at high temperatures and fatigue cracking occurring at medium temperatures. Asphalt mixture performance against these failures can be enhanced in several ways, one of the most widely used of which is the incorporation of modifiers for asphalt binders and, consequently, asphalt mixtures. Nanomaterials are among the additives that have been widely used in recent years. Although their technical results have generally been favorable, the use of these materials in executive projects has not been widespread due to their high price. Accordingly, the current study examines the effect of nano-cobalt oxide (nano-CoO) on the performance of asphalt binder and asphalt mixture, which has been less considered by other researchers. This material was chosen mainly due to its high stability to temperature, high chemical purity, good dispersibility along with its easy accessibility, and low cost of preparation, which partially overcame the general weakness associated with nanomaterial incorporation. This study pursued the following goals:

(i) Evaluating the effect of nano-CoO on asphalt binder rheological properties at medium and high temperatures

(ii) Investigating the rutting potential and fatigue life of asphalt mixtures modified with nano-CoO and comparing them with that of controlled asphalt mixtures

2. Materials and Methods

2.1. Materials

2.1.1. Aggregates. The aggregates utilized to fabricate the asphalt mixtures were crushed silica aggregates that had been screened based on the continuous type IV scale of the AASHTO standard. The aggregates' particle size gradation and specifications are given in Figure 1 and Table 1, respectively.

2.1.2. Asphalt Binder. PG64-16 asphalt binder, which is common in warm and moderate climates in different areas, is used in this study. Table 2 gives the characteristics of this asphalt binder.

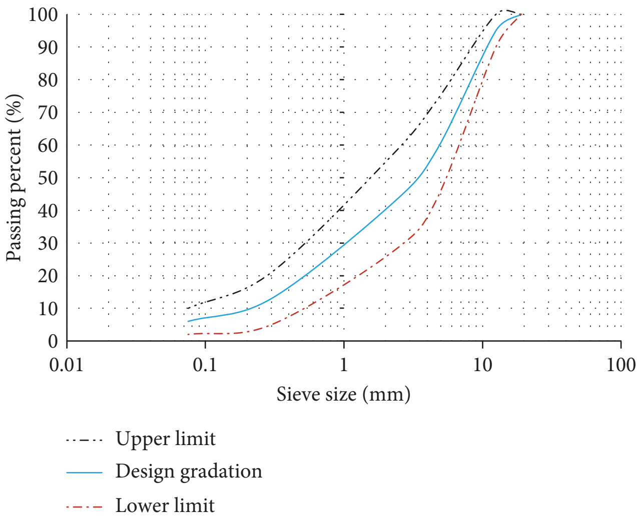


Figure 1: Gradation of aggregates.

Table 1: Properties of aggregates.

Test	Specification	Result
Coarse aggregates		
Bulk specific gravity (g/cm^3)		2.61
SSD specific gravity (g/cm^3)	ASTM C127	2.63
Apparent specific gravity (g/cm^3)		2.75
Maximum water absorption (%)	ASTM C127	1.2
Flat and elongated particles (%)	ASTM D4791	7.1
Los Angeles abrasion (%)	ASTM C131	17.3
Sodium sulfate soundness (%)	ASTM C88	1.9
Fine aggregates		
Bulk specific gravity (g/cm^3)		2.60
SSD specific gravity (g/cm^3)	ASTM C128	2.62
Apparent specific gravity (g/cm^3)		2.65
Specific gravity (filler) (g/cm^3)	ASTM D854	2.55
Maximum water absorption (%)	ASTM C127	1.2
Flat and elongated particles (%)	ASTM D4791	9
Sodium sulfate soundness (%)	ASTM C88	4
Crushed content (two faces) (%)	ASTM D5821	91
Fine aggregate angularity (%)	ASTM 1252	51.8

2.1.3. Nano-CoO. Nano-CoO was used at two percentages of asphalt binder weight, and its characteristics are presented in Table 3. Nanoparticle size and distribution in the asphalt binder were studied via electron microscopy. The appearance of these nanoparticles was almost circular (Figure 2). Nano-CoO is more filling than other nanomaterials having a larger specific surface area. The planetary ball mill was utilized to produce cobalt oxide nanoparticles. In this mill, four parameters of process control agent (PCA), rotation time, rotational speed, and bullet-to-cobalt oxide ratio constitute the mill process. PCA denotes the additives utilized in milling. By establishing a balance between material bond breakage and reconnection in milling, these materials eventually form a stable structure [39]. Isopropanol was used as the PCA; it belongs to the family of alcohols and prevents them from sticking to each other by repelling cobalt nanoparticles. Grinding operations were also performed using the PCA at 1% by weight of cobalt oxide.

Table 2: Physical characteristics of the asphalt binder.

Test method	Specification	Test results	Specification limit
Flash point (°C)	AASHTO T48	295	≥230
Rotational viscosity @ 135°C (Pa.s)	AASHTO T316	0.32	≤3.0
Rutting factor (G^*/Sin δ) @ 64°C (kPa)	AASHTO T315	3.1	≥2.20
Fatigue factor (G^*.Sin δ) @ 25°C (kPa)	AASHTO T315	2950	≤5000
Stiffness @ 22°C (MPa)	AASHTO T313	147	≤300
m value @ 22°C	AASHTO T313	0.3299	≥0.3

Table 3: Physical characteristics of nano-CoO [38].

Characteristics	Typical values
Compound formula	Co_3O_4
Purity (%)	99.9
Appearance	Fine dark gray to black powder
Melting point (°C)	895
Boiling point (°C)	900
Density (g/cm^3)	6.11
Bulk density (g/cm^3)	2.4
Specific surface area (m^2/g)	32
Average particle size (TEM)	80 nm
Acidity degree	8.3
Water percentage	≥0.5

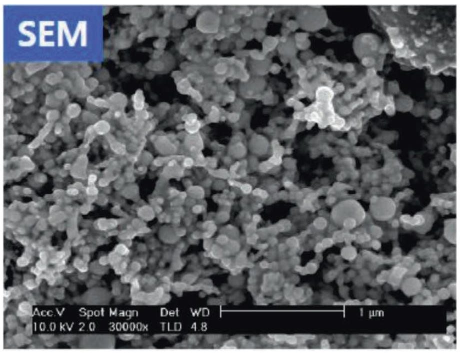


Figure 2: SEM images of nano-CoO.

2.2. Experimental Design. The DSR test was used to assess the effect of cobalt nanoparticles on the rheological parameters of asphalt binder, such as phase angle (δ) and complex modulus (G^*) at high and medium temperatures. Subsequently, the parameters associated with asphalt binder fatigue cracking (G^*.sin δ) and rutting (G^*/sin δ) performance were calculated. The influence of cobalt nanoparticles on asphalt mixtures' functional properties at medium and high temperatures was also explored. For this purpose, an ITFT was performed to determine fatigue life at 5 and 20°C at five stress levels, and the rutting test was conducted using the RLA test at 40 and 60°C under two stress levels. The experimental design flowchart of the present study is displayed in Figure 3.

2.3. Asphalt Binder Modification. The base asphalt binder was modified with nano-CoO with a high shear mixer. According to the literature, the asphalt binder was modified with nano-CoO by a mixer at a speed of 7000 rpm and a temperature of 160°C for 30 minutes. Subsequently, to guarantee the appropriate dispersion of nanomaterials in the asphalt binder, four samples were taken from different parts of the modified asphalt binder container, and the DSR test was performed on these samples. The results of these four samples showed that the nanoparticle additive is well distributed in the asphalt binder, and the obtained asphalt binder is homogeneous.

3. Experimental Tests

3.1. Rheological Tests of Asphalt Binder

3.1.1. RTFO. Asphalt binder short-term aging was simulated by using the RTFO test based on AASHTO T240. The asphalt binder specimens were placed in the oven at 163°C and were regularly exposed to hot air with the rotation of the shelves within the oven. Shelves should rotate at a rate of 15 ± 0.2 rpm, and the airflow should be set at 4000 ± 200 ml per minute. Samples were stored in this condition for 85 minutes. The RTFO test mainly aims to prepare aged asphalt binder for the DSR test to determine the rutting parameter at high temperatures.

3.1.2. PAV. The effect of long-term aging is simulated by the PAV under AASHTO R28. The asphalt binder specimen obtained from the RTFO was put in the machine in front of compressed air (at a pressure of 2070 kPa and a temperature of 110°C) for 20 hours. The output asphalt binder from the PAV test was used to perform the DSR test at medium temperatures and determine the fatigue parameter.

3.1.3. DSR. The elastic and viscous behavior of the asphalt binder (G^* and δ) was measured using the DSR test at intermediate and high service temperatures based on AASHTO T315-12. G^* refers to the maximum shear stress ($\tau_{\max}$) to the maximum shear strain ($\gamma_{\max}$) ratio. Phase angle (δ) denotes the interval between the applied stress and the resulting strain. In fully elastic materials, the phase angle (δ) is zero, and all the deformations are temporary. For a viscose material (such as a hot asphalt binder), the phase angle approaches 90°, and all the deformations are permanent. According to AASHTO T315-12 specifications, the rutting parameter (G^*/sin δ) should be at least >1 kPa and 2.2 kPa for unaged asphalt binders and RTFO-aged asphalt binders, respectively. Furthermore, the intermediate fatigue parameter (G^*.sin δ) should not exceed

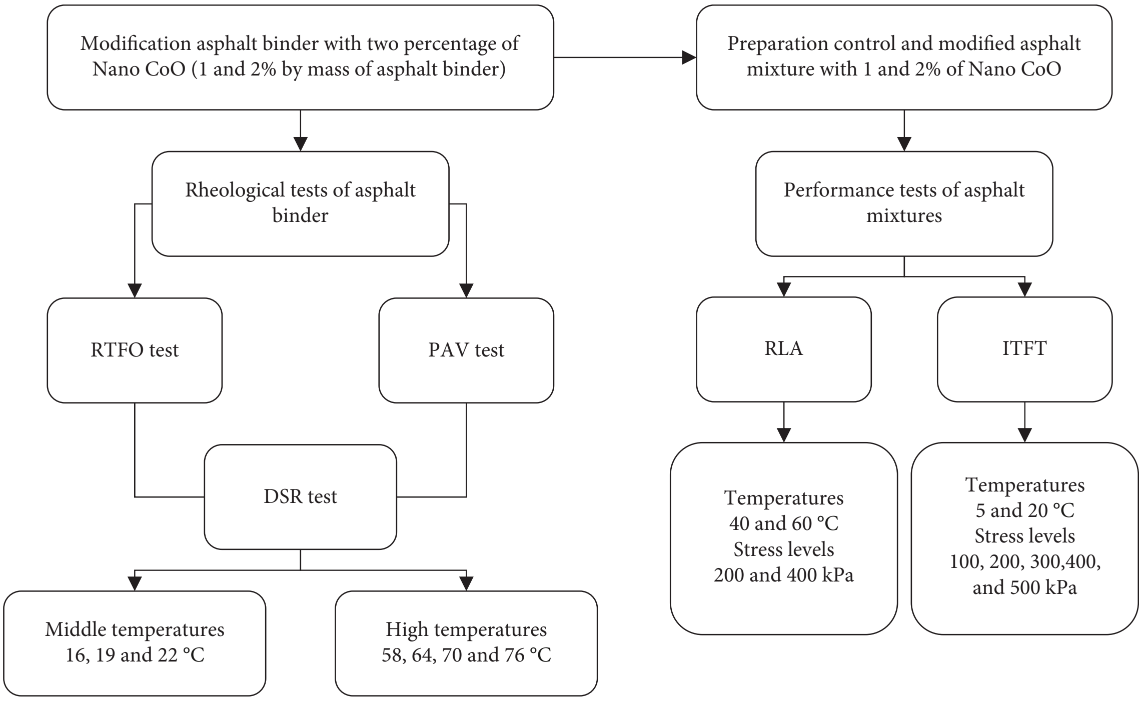


Figure 3: Experimental design steps.

5000 kPa for the PAV-aged asphalt binder. In terms of resistance to fatigue cracks, lower values of the fatigue parameter are more desirable.

3.2. Performance Tests of Asphalt Mixtures

3.2.1. Marshall Mix Design. The asphalt mixture mixing design was in accordance with Marshall's method. The optimum asphalt binder content was calculated based on Asphalt Institute MS-2 instruction. In the Marshall method, aggregates with a temperature of 160–170°C and heated asphalt binder up to 135°C are mixed and compacted by 75 blows of the Marshall hammer with a weight of 4.5 kg and a drop height of 45 cm on each side of the specimen. In order to determine the optimum binder content, six different asphalt binder contents (4.7, 5.0, 5.2, 5.5, 5.7, and 6.0) were used [40].

3.2.2. RLA. The dynamic creep or RLA test was carried out to calculate asphalt mixture resistance against rutting. Numerous studies have introduced the RLA test as an efficient technique for obtaining the rutting potential of asphalt mixtures, which is due to the test's simplicity and its logical association with asphalt mixture permanent deformation. The RLA test is conducted based on the BSEN-12697-25, and its main output is the curve of accumulative strain versus the number of loading cycles, which somehow depends on asphalt mixture rutting resistance (Figure 4). Based on the British standard, the specimens must be placed in the device's compartment a minimum of 4 hours prior to the test so that they reach the desired temperature range [42].

Here, the RLA test was carried out at stress levels of 200 and 400 kPa at 40 and 60°C. The specimens underwent the load for 4000 cycles, and then, the accumulative strain as a function of load cycles was displayed.

3.2.3. ITFT. Asphalt mixture fatigue was predicted via the ITFT. A flexible pavement's fatigue behavior directly affects the resistance of the hot mix asphalt to crack. This test is performed by two methods, namely, loading with constant stress and constant strain by the Nottingham machine. Loading with constant stress has advantages over the other method. The results of field studies show that this test is better correlated with the field results of pavements with a thick asphalt layer (thickness > 10 cm). Since heavy traffic was considered in this study, the thickness of the asphalt layer was taken to be >10 cm according to the structural design. The ITFT test was carried out according to BS EN12697-24 on specimens, with a height of 40 mm and a diameter of 101 mm. The loading was applied sinusoidally at a frequency of 1 Hz, with a loading time of 0.1 s and a rest time of 0.4 s. The strain generated in the sample was continuously measured by two sensors. The test is completed when the vertical deformation in the sample reaches 9 mm. In this study, the fatigue test was performed under the stresses of 100, 200, 300, 400, and 500 kPa at two temperatures of 5 and 20°C.

4. Results and Discussion

4.1. Rheological Tests of Asphalt Binder. Based on Figures 5(a) and 5(b), the modified asphalt binder has a larger rutting parameter than the control asphalt binder at all temperatures (58 to 76°C). Higher rutting parameter values show the modified asphalt binders' lower sensitivity to rutting or

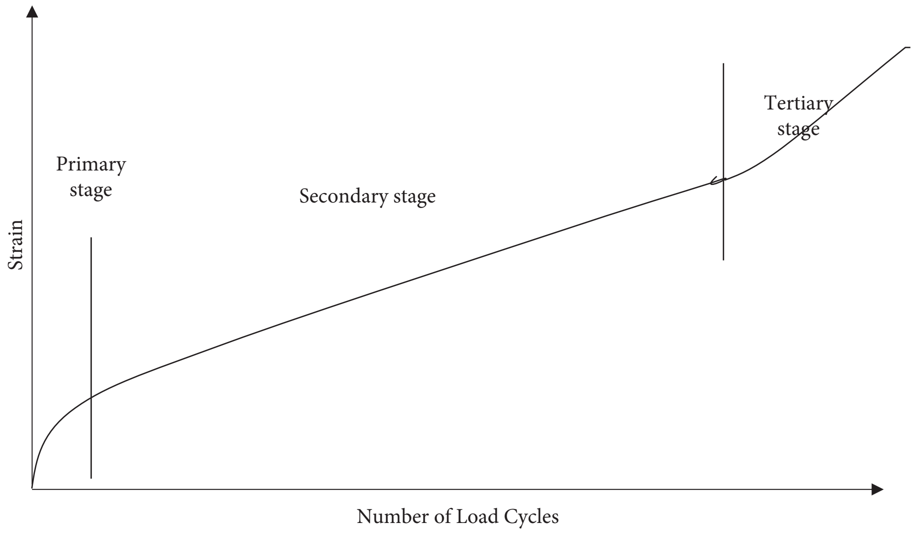
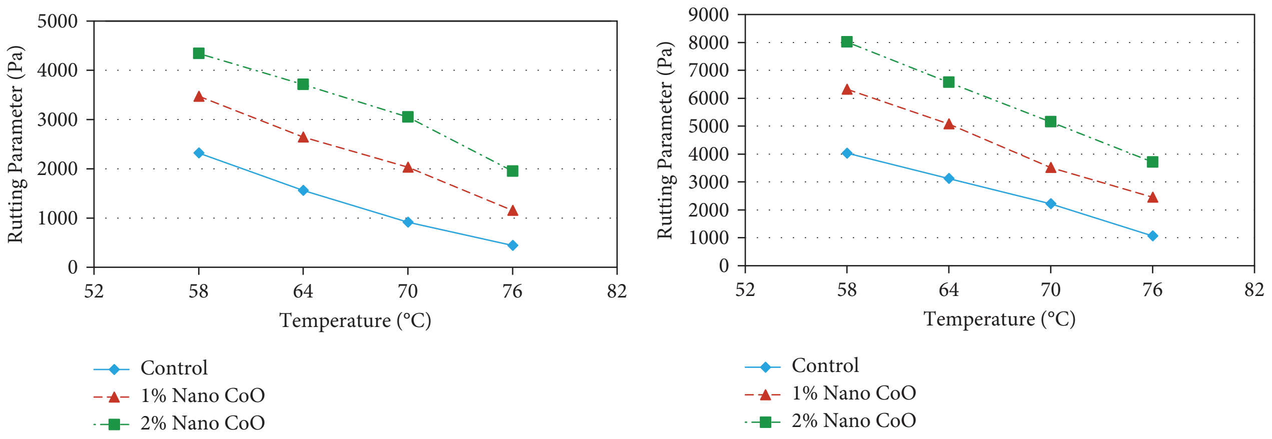


Figure 4: The curve of accumulative strain versus the number of loading cycles (RLA test) [41].



(a)

(b)

Figure 5: Rutting parameter ($G^*/\sin\,\delta$) at different temperatures for the (a) unaged and (b) RTFO-aged asphalt binder.

permanent deformation. For example, at a temperature of 58°C, the rutting parameter value of the control sample was 2.32 kPa, which increased to 1.36 and 4.34 kPa, respectively, with the addition of 1 and 2% nano-CoO. These values were enhanced by 49% and 87%, respectively, compared to the control asphalt binder.

This trend is also observed at temperatures of 64, 70, and 76°C. Clearly, in the asphalt binder containing 1 and 2% of nano-CoO at 76°C, the minimum value of the asphalt binder rutting parameter ($G^*/\sin\,\delta$ at least 1 and 2.2 kPa for unaged and aged asphalt binders by RTFO, respectively) is observed. The rutting parameter's value at the given temperature for the samples with 1% nano-CoO in the unaged and aged conditions was 1.16 and 2.45 kPa, respectively. Equivalent values of these two conditions in the samples containing 2% nano-CoO were 1.96 and 3.72 kPa in that order. Thus, incorporating nano-CoO promoted the modified asphalt binder's high-performance limit from 64 to 76°C, because the rutting parameter value of modified asphalt binder with 2% nano-CoO in both aged and unaged conditions at 76°C is higher than that of the control sample at 64, which makes it possible to use these asphalt binders in warmer climates.

The fatigue parameter values were measured at 16, 19, and 22°C, and the results are illustrated in Figure 6. Asphalt binder containing 1% and 2% nano-CoO had smaller fatigue parameter values than the control asphalt binder. The fatigue parameter value in the control asphalt binder at 16°C was 6.13 kPa, which decreased to 5.42 and 4.73 kPa in asphalt binders containing 1% and 2% nano-CoO, respectively. This trend is also visible at two temperatures of 19 and 22°C. At 19°C, the asphalt binder containing 1% and 2% of nano-CoO reduced the fatigue parameters by 16% and 35%, respectively. Also, at 22°C, these values decreased by 15% and 40%, respectively. As a result, asphalt mixtures containing nano-CoO are expected to display a longer fatigue life compared to the controls. Furthermore, at 16°C, asphalt binder modification with nano-CoO improved the performance-grade of the control asphalt binder by 1°.

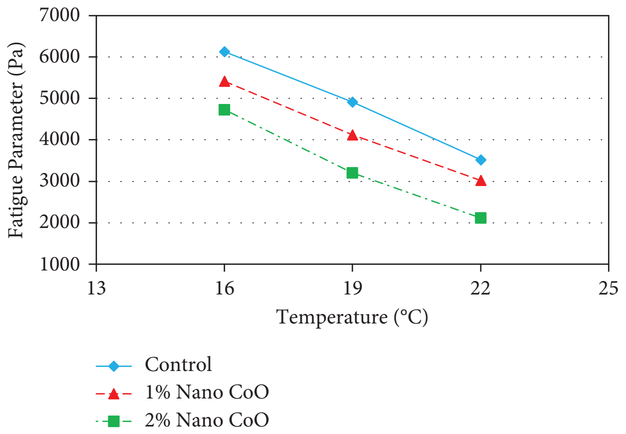


Figure 6: Fatigue parameter ($G^*.\sin\delta$) at different temperatures for the PAV-aged asphalt binder.

4.2. Marshall Mix Design. The optimum asphalt binder content for the asphalt mixing design is conducted based on maximum Marshall stability, maximum unit weight, flow, percentage of air void (AV), voids filled with asphalt binder (VFA), and voids in the mineral aggregate (VMA). According to Table 4, with increasing asphalt binder content, united weight and Marshall stability of asphalt mixture increased and then decreased. The VMA decreased with the increase of asphalt binder content and then increased after a minimum point. Besides, with the increase of asphalt binder content, flow and VFA increased and also, AV decreased. Based on the Marshall mix design criteria, the optimum asphalt binder content was calculated as 5.3% asphalt mixture weight. Table 4 lists the results of this experiment.

Table 4: Results of the Marshall mix design.

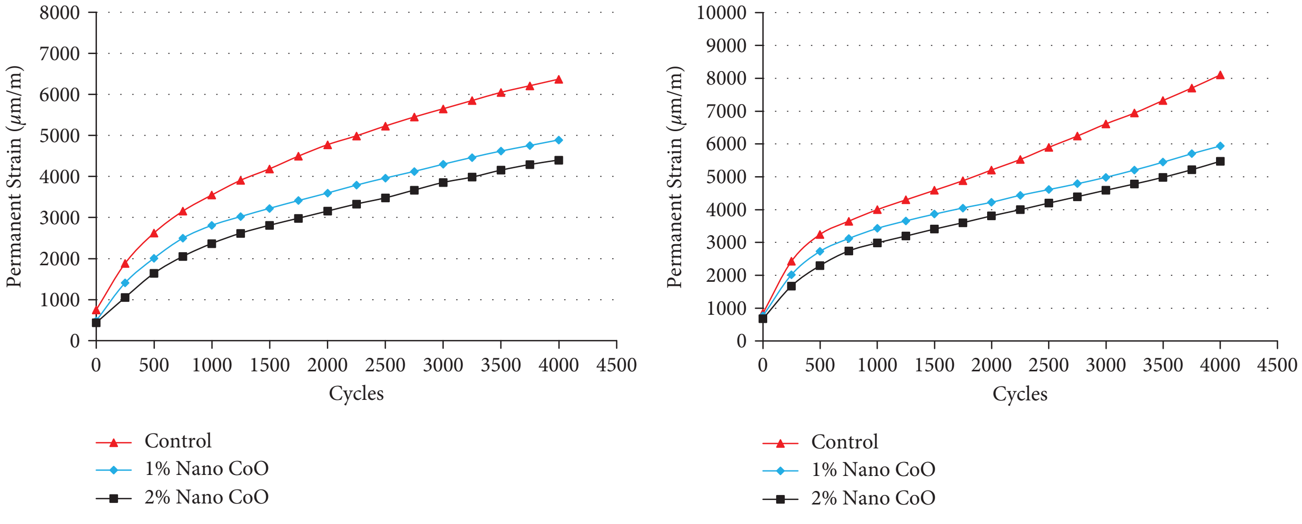
Asphalt binder content (%)	Stability	Flow	Unit weight	AV	VMA	VFA
4.7	925.2	3.0	2396.8	5.3	16.3	67.2
5.0	931.2	3.3	2416.2	4.8	15.1	68.4
5.2	1045.3	3.4	2424.3	4.3	15.9	72.8
5.5	973.2	3.5	2431.7	4.2	15.6	73.3
5.7	943.2	4.0	2422.6	3.9	16.1	75.4
6.0	895.2	4.2	2429.8	3.416	16.9	79.8

4.3. Rutting. Figures 7(a) and 7(b) illustrate the dynamic creep test results to calculate asphalt mixtures' rutting potential at 40°C and the stress levels of 200 and 400 kPa, respectively. Based on the findings, the permanent strain at the end of the 4000 cycles was significantly reduced in the samples containing nano-CoO compared to the controls. Nano-CoO has an amorphous structure. Besides forming nonpolar bonds with the asphalt binder that strengthen these structures' adhesion to aggregates, they can enhance asphalt binder hardness at high temperatures, thereby diminishing its rutting resistance. This reduction is quite significant in the samples containing 1% nano-CoO compared to the control, but there is no noticeable difference between the samples containing 1% and 2% nano-CoO. For example, at a stress level of 200 kPa, the permanent strain of the control samples at the end of the 4000 cycles reached 6372 microstrain, but in the samples containing 1% and 2% nano-CoO, it decreased to 4892 and 4402 microstrain, respectively. The values of permanent strain at the stress level of 400 kPa were significantly higher than the stress level of 200 kPa, and yet at the stress level of 400 kPa, the graphs did not enter the third phase of creep. The permanent strain at this stress level is depicted in Figure 7(b). Evidently, the permanent strain in samples containing 1% and 2% nano-CoO was reduced by 27% and 32%, respectively, compared with the control samples.

The dynamic creep test results of asphalt mixtures at 60°C and under the stress levels of 200 and 400 kPa are given in Figures 8(a) and 8(b), respectively. Clearly, the permanent strain of the modified samples was considerably reduced compared to the control specimens. According to Figure 8(a), the permanent strain of control samples at the end of the 4000 cycles reached 8526 microstrain, but in the samples containing 1% and 2% nano-CoO, it decreased to 5701 and 5364 microstrain, respectively. Also, the results in Figure 8(b) show that the permanent strain of the specimens containing 1% and 2% nanoparticles was reduced by 35% and 37%, respectively, compared to the control specimens.

According to the results, it is observed that at both levels of stress, the graph of the control samples entered the third phase of creep, but this did not happen in the modified samples. As expected, the flow number was less at the stress level of 400 kPa than 200 kPa.

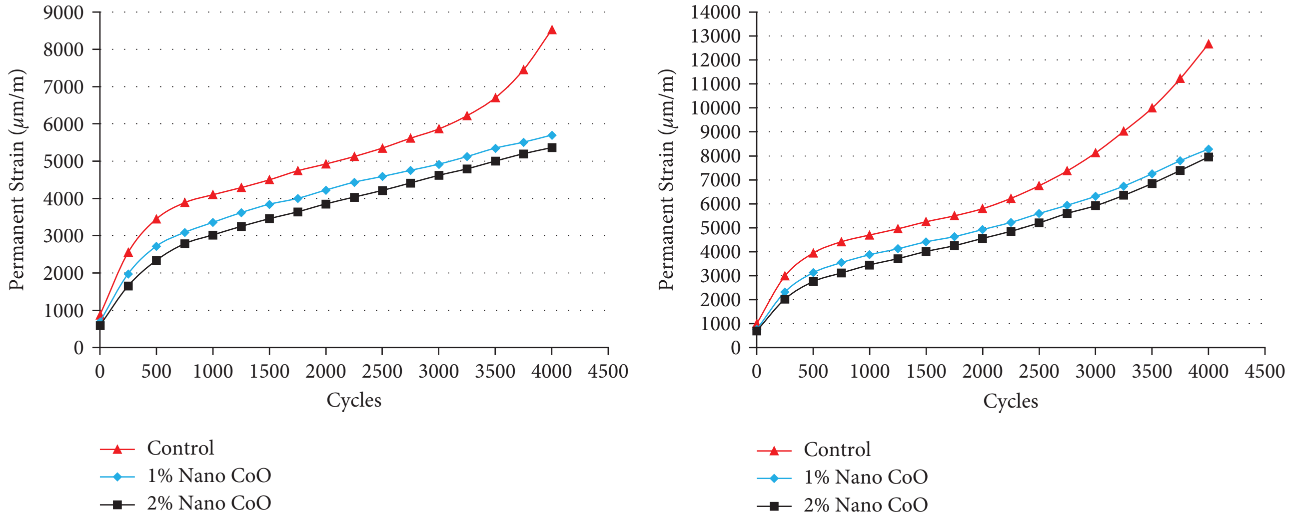
4.4. Fatigue Cracking. The results of the fatigue life of control samples and the samples modified with nano-CoO at 5 and 20°C are illustrated in Figures 9(a) and 9(b) in that order. The fatigue life of nano-CoO-containing asphalt samples was considerably enhanced compared to the controls. Asphalt binder generally has weak acidic properties, and the asphalt binder adhesion does not work well with acidic aggregates such as granite, which have a high SiO_2 content. Nano-CoO also has acidic properties, and using these particles increases the asphalt binder's acidic properties. A rise in asphalt binder-based properties reduces its adhesion to granite aggregates with acidic properties. The use of nanoparticles greatly increases the nonpolar component of the free surface energy of asphalt binders. This is also true of nano-CoO that has an amorphous and nonpolar structure. This significantly increases the adhesion of the modified asphalt binder to nano-CoO through nonpolar bonds with the aggregates. Notably, the acidic and base components of the asphalt binder, which are important in adhesion, are very small compared to its nonpolar component, and the role of nonpolar bonds in asphalt binder-aggregate adhesion is much more important than the role of polar properties of these two materials. Based on this, it can be said that using nano-CoO improves asphalt binder-aggregate adhesion and enhances the fatigue life of the modified asphalt mixtures.



(a)

(b)

Figure 7: Permanent strain versus the number of cycles at 40°C and stress of (a) 200 kPa and (b) 400 kPa.



(a)

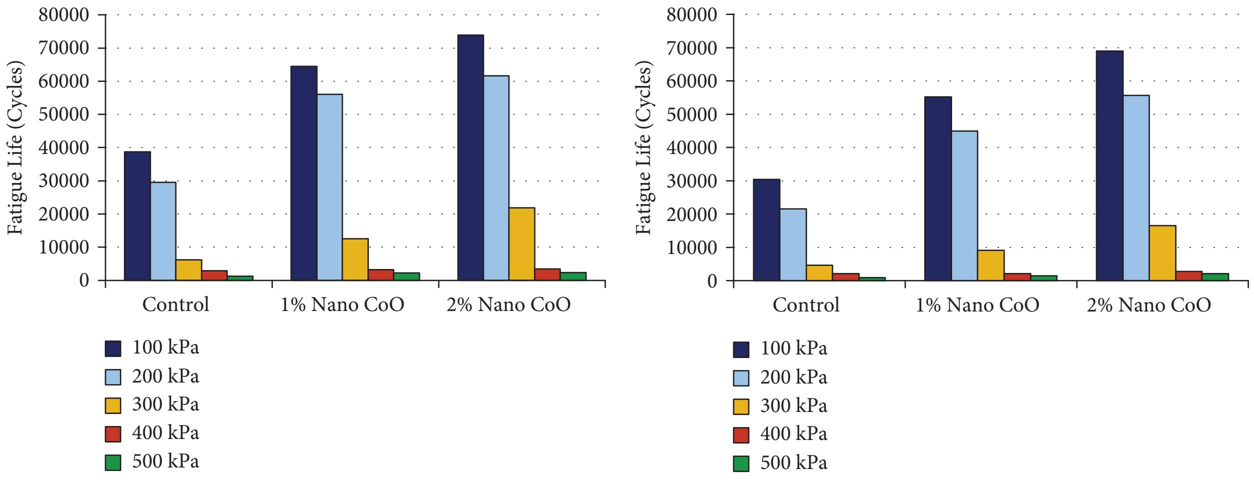
(b)

Figure 8: Permanent strain versus the number of cycles at 60°C and stress of (a) 200 kPa and (b) 400 kPa.

The incorporation of nano-CoO in this study enhanced asphalt mixture hardness. Elevating the hardness affects fatigue life in two ways as follows: (1) it diminishes the tensile strain under the top layer, thereby prolonging asphalt mixture fatigue life; (2) it decreases asphalt mixture flexibility and, consequently, decreases its fatigue life [43]. In experiments performed with a constant stress method on thick asphalt mixtures, such as the present study, the result of these two effects, one positive and the other negative, is that asphalt mixture fatigue life is increased.

The findings of fatigue life at 100 kPa stress level and 5°C temperature show that the use of 1% and 2% nano-CoO caused fatigue life from 38724 cycles to 64438 and 73895 cycles, indicating an increase by 66 and 90%, respectively. This trend was observed at other stress levels at 5°C. Also, at 100 kPa stress level and 20°C temperature, the fatigue life of the control sample was 30364 cycles and reached 55257 and 69015 cycles, respectively, in the samples containing 1% and 2% of nano-CoO. This increase in fatigue life was 82% and 127%, respectively. The fatigue life increase obtained with the nano-CoO modification is consistent with the results reported by other authors. Bala et al. [44] and Cai et al. [45] showed that the fatigue lives of the modified mixture with nanomaterials are 88% and 97% greater than that of the control mixture, respectively.

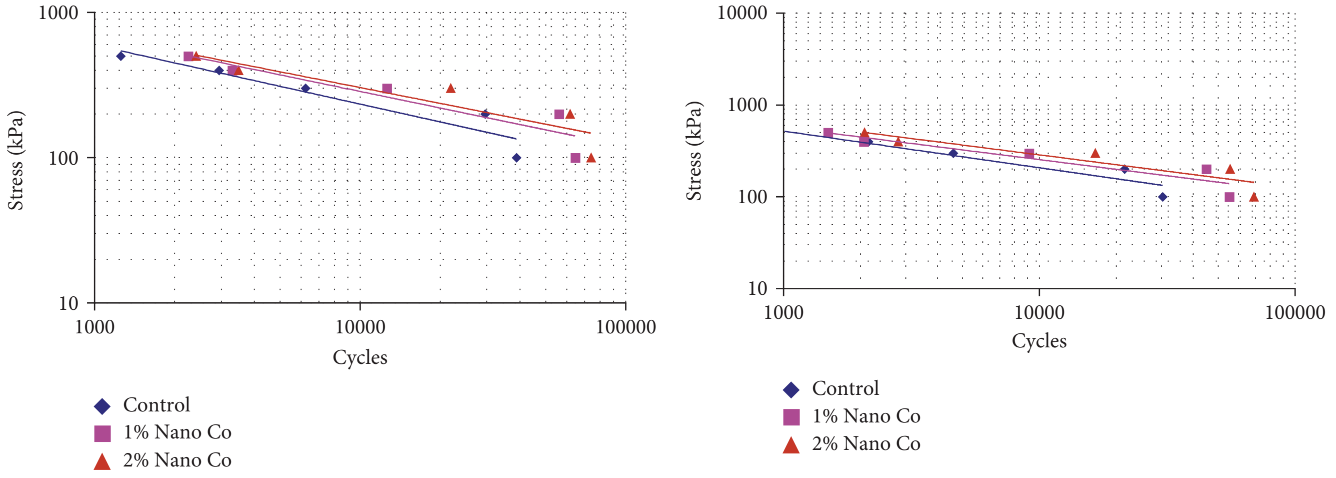
Also, with increasing the temperature, the fatigue life of samples decreased due to the great sensitivity of the samples' stiffness modulus to temperature variations. By increasing the temperature and, thus, decreasing the samples' stiffness modulus, a reduction was caused in the fatigue life of the



(a)

(b)

Figure 9: The fatigue life of control and modified asphalt mixtures at (a) 5°C and (b) 20°C.



(a)

(b)

Figure 10: Comparison of the fatigue behavior of the mixtures at (a) 5°C and (b) 20°C.

Table 5: Regression equations for fatigue life of asphalt mixtures.

Num	Temp	Mixture	Fatigue equation	K_1	K_2	R^2
1	5	Control	$N_f = 9873\,\sigma^{-0.406}$	9873	0.406	0.8875
2	5	Modified with 1% nano-CoO	$N_f = 9321\,\sigma^{-0.378}$	9321	0.378	0.8566
3	5	Modified with 2% nano-CoO	$N_f = 8440\,\sigma^{-0.361}$	8440	0.361	0.8188
4	20	Control	$N_f = 8110\,\sigma^{-0.398}$	8110	0.398	0.8949
5	20	Modified with 1% nano-CoO	$N_f = 6465\,\sigma^{-0.351}$	6465	0.351	0.8626
6	20	Modified with 2% nano-CoO	$N_f = 7612\,\sigma^{-0.356}$	7612	0.356	0.8383

samples under cyclic loading. Based on the figures, the fatigue life was diminished by using a higher stress level. In fact, increasing the stress level enhanced the tensile strain of the samples and decreased their fatigue life. Therefore, increasing stress from 200 to 300 kPa significantly decreased the fatigue life of all samples.

The results of ITFT tests on control and modified samples are compared in Figures 10(a) and 10(b). In these figures, regression lines are plotted for samples at each stress. The findings indicated a proper linear relationship between the logarithm of fatigue and that of stress. Evidently, the use of nano-CoO significantly increased the fatigue life at a certain stress. Moreover, an increase in stress levels considerably decreased fatigue life. The analysis indicated a salient enhancement in the fatigue life of the modified samples. The fatigue equations, K_1 and K_2 values, and the coefficient of determination for each sample are shown in Table 5. R^2 is referred to the coefficient of determination that shows the percentage of variance being explained and changes in the dependent variable by the independent variables. According to Table 5, the models had R^2 values > 0.80, which indicates the relationship between the fatigue life and applied stress based on the power model used.

5. Conclusions

The present study assessed the effect of nano-CoO addition on the asphalt binder's viscoelastic properties and investigated the fatigue and rutting behavior of asphalt mixtures. The most important results are as follows:

(i) The rutting parameter in the samples modified with nano-CoO in unaged and aged states significantly increased in comparison to the controls. The main reason for this can be the increase in hardness and asphalt binder temperature sensitivity due to the incorporation of nano-CoO.

(ii) The addition of nano-CoO enhanced the fatigue parameter of the modified samples. The main reason is the improvement in the modified asphalt binder's elastic characteristics, which reduces its dissipated energy in loading cycles.

(iii) The results of dynamic creep tests at 40 and 60°C and at different stress levels showed a significant reduction in permanent strain in the modified specimens compared to the controls

(iv) The addition of nano-CoO demonstrated an increase in modified asphalt mixtures' fatigue life at two temperature and five stresses

(v) The samples containing 1% nano-CoO remarkably improved asphalt mixture performance against fatigue cracking and rutting. However, samples containing 2% nano-CoO do not significantly differ in terms of mechanical characteristics compared to samples containing 1% of this nanoparticle. Therefore, due to the relatively higher cost of nanomaterials than asphalt binders, using 1% of this additive seems more economical.

Data Availability

The data in this research are obtained through experiments by the authors and there are no restrictions on sharing.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

References

[1] F. Moghadas Nejad and A. Azarhoosh, "Evaluating fatigue life of asphalt mixtures using surface free energy parameters," *Amirkabir Journal of Civil Engineering*, vol. 50, no. 2, pp. 365–376, 2018.

[2] P. Kandhal and I. Rickards, "Premature failure of asphalt overlays from stripping: case histories," *Asphalt Paving Technology*, vol. 70, pp. 301–351, 2001.

[3] S. Fatemi, J. Bolouri Bazaz, and S. A. Ziaee, "Evaluation of rutting and fatigue behaviors of asphalt binders modified with calcium lignosulfonate," *Advances in Civil Engineering*, vol. 2021, Article ID 6894514, 12 pages, 2021.

[4] A. Kargari, M. Arabani, and S. M. Mirabdolazimi, "Effect of palm oil capsules on the self-healing properties of aged and unaged asphalt mixtures gained by resting period and microwave heating," *Construction and Building Materials*, vol. 316, Article ID 125901, 2022.

[5] I. Amin, S. M. El-Badawy, T. Breakah, and M. H. Ibrahim, "Laboratory evaluation of asphalt binder modified with carbon nanotubes for Egyptian climate," *Construction and Building Materials*, vol. 121, pp. 361–372, 2016.

[6] G. H. Hamedi, K. Ghalandari Shamami, and K. Ghasemdoost Abadi, "Effect of antistripping additives on the cohesion, adhesion, and performance of different asphalt mixtures in dry and wet conditions," *Journal of Materials in Civil Engineering*, vol. 34, no. 9, Article ID 04022225, 2022.

[7] M. Nikookar, M. Bagheri Movahhed, J. Ayoubinejad, V. Najafi Moghaddam Gilani, and S. M. Hosseinian, "Improving the moisture sensitivity of asphalt mixtures by simultaneous modification of asphalt binder and aggregates with carbon nanofiber and carbon nanotube," *Advances in Civil Engineering*, vol. 2021, Article ID 6682856, 11 pages, 2021.

[8] J. Choudhary, B. Kumar, and A. Gupta, "Utilization of waste glass powder and glass composite fillers in asphalt pavements," *Advances in Civil Engineering*, vol. 2021, Article ID 3235223, 17 pages, 2021.

[9] G. H. Hamedi, M. R. Esmaeeli, V. Najafi Moghaddam Gilani, and S. M. Hosseinian, "The effect of aggregate-forming minerals on thermodynamic parameters using surface free energy concept and its relationship with the moisture susceptibility of asphalt mixtures," *Advances in Civil Engineering*, vol. 2021, Article ID 8818681, 15 pages, 2021.

[10] S. N. A. Jeffry, R. P. Jaya, N. A. Hassan, H. Yaacob, J. Mirza, and S. H. Drahman, "Effects of nanocharcoal coconut-shell ash on the physical and rheological properties of bitumen," *Construction and Building Materials*, vol. 158, pp. 1–10, 2018.

[11] G. Hossein Hamedi, K. Ghalandari Shamami, and M. Mazhari Pakenari, "Effect of ultra-high-molecular-weight polyethylene on the performance characteristics of hot mix asphalt," *Construction and Building Materials*, vol. 258, Article ID 119729, 2020.

[12] M. Fakhri and A. Rahimzadeh Mottahed, "Improving moisture and fracture resistance of warm mix asphalt containing RAP and nanoclay additive," *Construction and Building Materials*, vol. 272, Article ID 121900, 2021.

[13] G. H. Hamedi, A. Sahraei, and M. Hadizadeh Pirbasti, "An experimental investigation into the effect of asphalt binder modified with SBR polymer on the moisture susceptibility of asphalt mixtures," *Periodica Polytechnica: Civil Engineering*, vol. 65, no. 2, pp. 546–555, 2021.

[14] Z. Li, W. Chen, Y. Li, H. Liu, Z. Zhao, and L. Cao, "Characteristic evolution of GO/SBS-modified asphalt during aging," *Advances in Civil Engineering*, vol. 2022, Article ID 4060013, 16 pages, 2022.

[15] L. Chen, W. Gu, and X. Zhang, "Environment effect on the rutting resistance of nano-SiO_2-modified asphalt concrete: temperature and water," *Advances in Civil Engineering*, vol. 2021, Article ID 7439006, 9 pages, 2021.

[16] A. A. Hussein, R. P. Jaya, N. Abdul Hassan, H. Yaacob, G. F. Huseien, and M. H. W. Ibrahim, "Performance of nanoceramic powder on the chemical and physical properties

of bitumen," *Construction and Building Materials*, vol. 156, pp. 496–505, 2017.

[17] D. B. Ghile, "Effects of nanoclay modification on rheology of bitumen and on performance of asphalt mixtures," Master thesis, Delft University of Technology, Delft, Netherlands, 2006.

[18] S. G. Jahromi, B. Andalibizade, and S. Vossough, "Engineering properties of nanoclay modified asphalt concrete mixtures," *Arabian Journal for Science and Engineering*, vol. 35, 2010.

[19] G. Liu, "Characterization and identification of bituminous materials modified with montmorillonite nanoclay," Doctoral thesis, Delft University of Technology, Delft, Netherlands, 2011.

[20] F. Xiao, A. N. Amirkhanian, and S. N. Amirkhanian, "Influence of carbon nanoparticles on the rheological characteristics of short-term aged asphalt binders," *Journal of Materials in Civil Engineering*, vol. 23, no. 4, pp. 423–431, 2011.

[21] F. Xiao, A. N. Amirkhanian, and S. N. Amirkhanian, "Long-term ageing influence on rheological characteristics of asphalt binders containing carbon nanoparticles," *International Journal of Pavement Engineering*, vol. 12, no. 6, pp. 533–541, 2011.

[22] M. J. Khattak, A. Khattab, H. R. Rizvi, and P. Zhang, "The impact of carbon nano-fiber modification on asphalt binder rheology," *Construction and Building Materials*, vol. 30, pp. 257–264, 2012.

[23] G. Shafabakhsh, S. Mirabdolazimi, and M. Sadeghnejad, "Evaluation the effect of nano-TiO2 on the rutting and fatigue behavior of asphalt mixtures," *Construction and Building Materials*, vol. 54, pp. 566–571, 2014.

[24] X. Shi, L. Cai, W. Xu, J. Fan, and X. Wang, "Effects of nanosilica and rock asphalt on rheological properties of modified bitumen," *Construction and Building Materials*, vol. 161, pp. 705–714, 2018.

[25] M. Mubaraki, S. I. A. Ali, A. Ismail, and N. I. M. Yusoff, "Rheological evaluation of asphalt cements modified with ASA polymer and Al2O3 nanoparticles," *Procedia Engineering*, vol. 143, pp. 1276–1284, 2016.

[26] H. Ziari, H. Farahani, A. Goli, and S. Sadeghpour Galooyak, "The investigation of the impact of carbon nano tube on bitumen and HMA performance," *Petroleum Science and Technology*, vol. 32, no. 17, pp. 2102–2108, 2014.

[27] G. Shafabakhsh and S. Rsajadib, "Evaluation of rheological behavior of bitumen modified with nano copper oxide," *International Journal of Engineering and Technology*, vol. 7, no. 4, pp. 13–18, 2018.

[28] S. Karahancer, "Investigating the performance of cuprous oxide nano particle modified asphalt binder and hot mix asphalt," *Construction and Building Materials*, vol. 212, pp. 698–706, 2019.

[29] P. A. Sediq, "Characterization of asphalt binder modified with nanocomposite," Doctoral dissertation, Near East University, Nicosia, Cyprus, 2018.

[30] M. Rezvan and A. Izadi, "Investigation of the effect of iron and aluminum nano-oxides on reduction of moisture sensitivity in hot-mix asphalt," *Journal Of Transportation Infrastructure Engineering*, vol. 1, 2016.

[31] S. Kordi and G. Shafabakhsh, "The Feasibility of the effect of nano Al2O3 on behavior of stone mastic asphalt mixtures against dynamic loads," *Journal Of Transportation Infrastructure Engineering*, vol. 2, 2016.

[32] M. Baqersad and H. Ali, "Recycling of RAP using nanoclay modified asphalt binder," *International Journal of Pavement Research and Technology*, vol. 14, no. 6, pp. 778–788, 2021.

[33] S. M. Mirabdolazimi, M. M. Pakenari, and A. Kargari, "Effect of nanosilica on moisture susceptibility of asphalt emulsion mixture," *Arabian Journal for Science and Engineering*, vol. 46, no. 11, pp. 11139–11151, 2021.

[34] S. M. Mirabdolazimi, A. H. Kargari, and M. M. Pakenari, "New achievement in moisture sensitivity of nano-silica modified asphalt mixture with a combined effect of bitumen type and traffic condition," *International Journal of Pavement Research and Technology*, vol. 14, pp. 105–115, 2020.

[35] N. Kamboozia, S. Mousavi Rad, and S. A. Saed, "Laboratory investigation of the effect of nano-ZnO on the fracture and rutting resistance of porous asphalt mixture under the aging condition and freeze–thaw cycle," *Journal of Materials in Civil Engineering*, vol. 34, no. 5, Article ID 04022052, 2022.

[36] H. Ezzat, S. El-Badawy, A. Gabr, E.-S. I. Zaki, and T. Breakah, "Evaluation of asphalt binders modified with nanoclay and nanosilica," *Procedia Engineering*, vol. 143, pp. 1260–1267, 2016.

[37] S. N. A. Jeffry, R. P. Jaya, N. Abdul Hassan, H. Yaacob, and M. K. I. M. Satar, "Mechanical performance of asphalt mixture containing nano-charcoal coconut shell ash," *Construction and Building Materials*, vol. 173, pp. 40–48, 2018.

[38] I. Luisetto, F. Pepe, and E. Bemporad, "Preparation and characterization of nano cobalt oxide," *Journal of Nanoparticle Research*, vol. 10, no. 1, pp. 59–67, 2008.

[39] M. Pilar, J. Sunol, J. Bonastre, and L. Escoda, "Influence of process control agents in the development of a metastable Fe–Zr based alloy," *Journal of Non-crystalline Solids*, vol. 353, no. 8-10, pp. 848–850, 2007.

[40] R. F. Bonaquist, "Mix design practices for warm mix asphalt," *Transportation Research Board*, vol. 691, 2011.

[41] M. Arabani and S. A. Tahami, "Assessment of mechanical properties of rice husk ash modified asphalt mixture," *Construction and Building Materials*, vol. 149, pp. 350–358, 2017.

[42] M. Mazhari Pakenari and G. H. Hamedi, "Investigating the effective laboratory parameters on the rutting behavior of warm mix asphalt," *International Journal of Pavement Research and Technology*, vol. 15, no. 5, pp. 1180–1194, 2021.

[43] M. Mazhari Pakenari and G. H. Hamedi, "Investigating the effective laboratory parameters on the stiffness modulus and fatigue cracking of warm mix asphalt," *International Journal of Civil Engineering*, vol. 19, no. 6, pp. 685–698, 2021.

[44] N. Bala, M. Napiah, and I. Kamaruddin, "Effect of nanosilica particles on polypropylene polymer modified asphalt mixture performance," *Case Studies in Construction Materials*, vol. 8, pp. 447–454, 2018.

[45] L. Cai, X. Shi, and J. Xue, "Laboratory evaluation of composed modified asphalt binder and mixture containing nano-silica/rock asphalt/SBS," *Construction and Building Materials*, vol. 172, pp. 204–211, 2018.