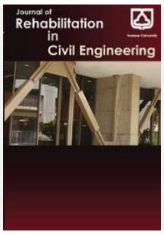
Journal of Rehabilitation in Civil Engineering 13-2 (2025) 1-17



Journal of Rehabilitation in Civil Engineering

Journal homepage: https://civiljournal.semnan.ac.ir/

Rutting Characteristics of Bio-Asphalt Binder Based on the Multiple Stress Creep Recovery Test Results

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ARTICLE INFO

Article history:
Received: 12 December 2023
Revised: 29 April 2024
Accepted: 01 August 2024

Keywords:
Asphalt binder;
Bio-oil;
Rice bran oil;
Nano CaO;
Rejuvenator.

ABSTRACT

The phenomenon of asphalt binder aging can lead to various failures, such as rutting in the asphalt mixture. Rejuvenator materials are used to mitigate asphalt binder aging. Bio-asphalt, as a binder modified with bio-waste materials, offers environmental benefits and enhances asphalt binder aging. Recent research has indicated that bio-oils improve the effectiveness of asphalt binders at moderate and low temperatures, but they may exacerbate the susceptibility to rutting at high temperatures. This study employed rice bran oil (RBO) as an environmentally friendly rejuvenating agent in asphalt binder and leveraged the benefits of nano-CaO to enhance asphalt binder performance at high temperatures. Based on the findings of this study, The binder sample with 5% RBO and 3% nano-CaO exhibited superior performance in the multiple stress creep recovery (MSCR) test, and rutting susceptibility decreased by 13-34% compared to the unmodified samples. Conversely, utilizing 5% RBO without nano-CaO increased rutting susceptibility by 35-50%.

E-ISSN: 2345-4423

How to cite this article:
Sadeghnejad, M., Arabani, M., Haghanipour, J., & Hassanjani, M. H. (2025). Rutting Characteristics of Bio-Asphalt Binder Based on the Multiple Stress Creep Recovery Test Results. Journal of Rehabilitation in Civil Engineering, 13(2), 1-17. https://doi.org/10.22075/jrce.2024.32651.1951

1. Introduction

The proper management and recycling of biomass waste is a significant global concern [1,2]. An efficient method for repurposing agricultural biomass is to incorporate it into the asphalt binder as a modifying agent [3]. Due to the decrease in oil resources worldwide, there has been a substantial rise in the demand for oil-derived products, including asphalt binders [4]. As a result, all industries, including the asphalt paving industry, must adopt sustainable economic, social, and environmental approaches to improve the quality of the materials used [5–9]. The bio-binder is a sustainable alternative to pure asphalt binder, obtained from several organic sources, such as pig manure, urban yard waste, grass, waste tea, bio-oils, and spent coffee grounds [10–13]. Bio-oil can be obtained from biomass by several physical and chemical techniques, including ultrasonic and microwave treatments. An environmentally benign and sustainable substance can be produced with this process [14,15].

Recently, biomass-derived oils have found widespread application in modifying and replacing asphalt binders. Environmental problems can be mitigated by the efficient utilization of cotton stalk waste (CS) [16], palm oil [17,18], cedar oil [19], sunflower oil [20], and soybean oil [21] to generate bio-oil, which is compatible with asphalt binder. Bio-oils enhance the low- and intermediate-temperature characteristics of asphalt binder while adversely affecting its high-temperature properties [22,23]. The physicochemical characteristics of various oils obtained from biological sources, with their moisture content and volatile constituents, have different impacts on performance, oxidation, and thermal aging [24,25].

A study modified two distinct sources of asphalt binder with a penetration grade of 40-50 using collected waste cooking oil from homes and neighborhood canteens without financial expense. Zeolite, sulfuric acid (as a catalyst), and methanol were examined during modification. The utilized bio-asphalt binder, when combined with modified oil, demonstrated superior performance compared to the control asphalt binder [26]. Another study evaluated the impact of date palm oil as a modifier for asphalt binder on the compressive strength of both the binder component and hot-mix asphalt (HMA). The antioxidant isomers found in date palm oil improved the performance and durability of asphalt binders. Cubic samples of asphalt mixture modified with 0%, 2.5%, 5%, 7.5%, and 10% date palm oil were made according to the total weight of the sample. Based on the results, palm oil as a substance used to modify asphalt binders reduced the compressive strength of HMA pavement. The researchers pointed out that their findings require more trials to understand the impacts of palm oil on asphalt pavements under long-term traffic loads and diverse environmental conditions [27]. A separate study was carried out to examine the effects of bio-oil, particularly waste oil (WCO), on the mechanical characteristics of asphalt binders. The physical and rheological properties of the pure asphalt binder and the modified WCO asphalt binder were assessed using experiments measuring penetration degree, softening point, viscosity, heat loss, and dynamic shear rheometer (DSR). This investigation altered 80/100 asphalt binder by using different proportions of WCO, specifically, 1%, 2%, and 3% relative to the weight of the asphalt binder. The application of WCO in the asphalt binder decreased its hardness and increased its susceptibility to temperature changes. By incorporating up to 2% WCO, the asphalt binder was enhanced and exhibited rutting resistance like that of the PG 64 asphalt binder [28].

The utilization of modified bio-asphalt is crucial to improving performance at various temperatures, conserving oil resources, and protecting the environment [29]. Previous research has demonstrated that nanomaterials can effectively modify asphalt bonds to enhance pavement performance at high temperatures [30]. Researchers have shown interest in nanoparticles because of their enormous specific surface area (SSA), higher surface free energy, appropriate dispersion in asphalt binder, chemical purity, and strong absorption ability [31]. In a study, bio-oil was combined with two kinds of silica nanoparticles (hydrophilic or hydrophobic) to increase the adhesion characteristics of asphalt binder. The morphological and rheological characteristics of the modified asphalt binder at intermediate and high temperatures were also comprehensively investigated. According to the results, 5% bio-oil was the best dosage because it increased the asphalt binder's adhesion and strength by 16–21%. At the intermediate temperature, the asphalt binder's hardness and elasticity were further improved, and the yield stress was significantly increased when silica nanoparticles were added up to 15% by weight. Furthermore, the asphalt binder's strength and adhesion were increased by 60% by the nanoparticles [32]. In another study, a bio-binder containing crude palm oil (CPO) was modified using nano-silica (NS) to enhance high-temperature performance. Adding nanoparticles to the bio-binder improved its rigidity and increased its viscosity. Additionally, aging sensitivity was decreased, the rutting parameter ($G^*/\sin\delta$) increased with the NS particles, the recovery percentage grew, and the non-recoverable creep compliance (Jnr) and permanent strain dropped. The Fourier-transform infrared spectroscopy (FTIR) analysis indicated that the addition of NS led to a novel chemical activity, and scanning electron microscope (SEM) observations showed that NS was uniformly incorporated in the bio-binder [33]. In a recent study, researchers have examined the effects of organic calcium carbonate ($CaCO_3$) on the ability of bio-asphalt against aging. This study found that nano-$CaCO_3$ absorbs the light components in the bio-asphalt because of its extensive SSA. This reduces the loss and evaporation of light components and slows down the oxidation process. The inclusion of nano $CaCO_2$ helps decrease the rate of change of the carbonyl and sulfoxide index [34].

Based on the reviewed research, asphalt binder's aging process is decelerated by rejuvenating bio-oils, which increase the material's resilience to potential thermal cracks at intermediate and low temperatures by softening and lowering its viscosity. Nevertheless, the behavior of asphalt binders at high temperatures is susceptible to the phenomenon of rutting. Prior research has indicated that using bio-oils in asphalt binders enhances their ability to resist fatigue and thermal cracking by softening and enhancing antioxidant characteristics. However, their vulnerability is due to their performance under high temperatures. This is attributed to the increased elasticity phase and reduced molecular weight, resulting in a considerable drop in the rutting resistance of asphalt binder samples containing bio-oil. Hence, the primary objective of this research was to enhance rutting resistance in samples using bio-oil. To this end, nano-CaO was employed as a secondary modifier owing to its notable absorbent surface area, reduced molecular weight, and ability to enhance hardness. This study utilized oil derived from rice bran, a crucial agricultural waste, combined with nano-CaO for the first time to enhance the high-temperature characteristics of bituminous mixes. The goal was to develop a novel combination of bio-binder and additional substances to enhance the performance of pavements at varying temperatures and traffic conditions. Additionally, this study aimed to utilize more cost-effective raw materials to extend the longevity and durability of the pavement, thereby reducing the total cost related to the construction and maintenance of road pavements. First, RBO with 3%, 5%, and 7% weight percentages of asphalt binder was mixed with the base asphalt binder. Subsequently, nano-particles of around 20-30 nm were blended into the bio-binder combination. The FTIR infrared spectrum was used to chemically analyze the asphalt binder containing additives in unaged and short-term aged stages. The behavior of the asphalt binder below high temperatures was evaluated using the multiple stress creep recovery (MSCR) test. In the process of conducting the tests, the most appropriate percentage of RBO in asphalt binder was first determined. Then, the samples containing the asphalt binder with the proper ratio of RBO were mixed with different percentages of nano-CaO.

2. Materials and methods

2.1. Materials

Asphalt binder acts as a binding agent in the asphalt mixture, binding the aggregates as a continuous volume. Asphalt binder is a material with visco-elastoplastic behavior, whose resistance, physical, and behavioral characteristics depend on temperature [31]. Asphalt binder 60/70 (equivalent PG 64-22) provided by the Pasargad Oil Refinery (Tehran, Iran) was chosen in this investigation. This asphalt binder was selected due to its widespread application in constructing asphalt pavements in mild and tropical climates. Table 1 provides a comprehensive compilation of the specifications for the utilized asphalt binder.

Despite its significant production volume, rice bran oil (RBO) generated from biomass has not been assessed as an asphalt binder modifier. Approximately 114 countries cultivate roughly 645 million metric tons of rice. Furthermore, only 10% of the bran obtained is utilized for oil extraction and animal feed [35]. A small quantity of RBO is used in the cosmetic and edible oil sectors [36]. The rice bran utilized in this investigation was acquired from a rice-milling facility in Rasht, a city in the north of Iran. After separating rice bran from waste materials, the moisture content of the rice bran was reduced, and the material was subjected to microwave treatment.

Table 1. Specifications of the utilized asphalt binder.

Specification	Value	Standard Range	Test Method
Specific gravity at 25 °C (g/cc)	1.018	-	ASTM D70
Penetration at 25 °C (0.1 mm)	65	60-70	ASTM D5
Softening point (°C)	51	49-56	ASTM D36
Ductility at 25 °C (cm)	110	100>	ASTM D113
Flash point (°C)	320	232>	ASTM D92
Degree of purity with trichloroethylene (%)	99.7	99>	ASTM D2042

When a portion of the plant is removed, the application of heat elevates the pressure, resulting in the rupture of the plant's cell wall. This rupture facilitates the exchange of substances between the solvents and the extracted chemicals [37]. According to previous studies, this study used isopropanol instead of hexane, which is a petroleum-based and toxic solvent. Isopropanol increases the efficiency of oil extraction [38]. Moreover, the microwave method is more effective in extracting oils when utilizing polar solvents, such as isopropanol, because these solvents have a greater ability to absorb microwaves. Fig. 1 shows the RBO production process.

Table 2 displays the properties of the nano-CaO utilized in this study. Its illustration can also be seen in Fig. 2.

Table 2. Properties of nano-CaO used in this research.

Chemical Formula	CaO
Density (g/cc)	0.5
Particle Size (Nm)	20-30
Color	White
Morphology	Spherical
Specific Surface Area (m^2/g)	5-10
Purity (%)	98
Melting Point (^{o}C)	2572

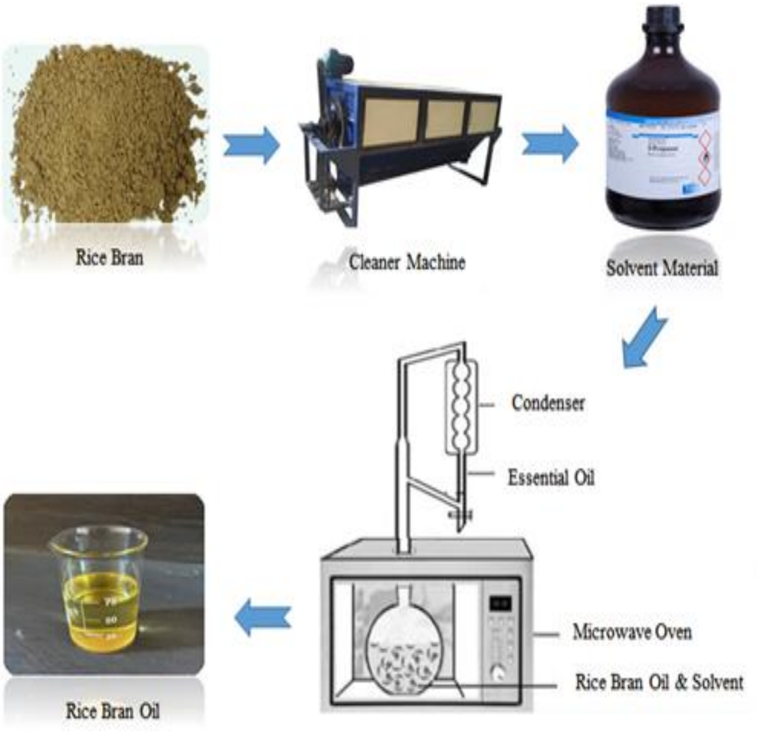


Fig. 1. Rice bran oil production process.

Fig. 2. The nano-CaO used in this research.

2.2. Methods

Different percentages of asphalt binder samples were going to be mixed with RBO and nano-CaO. Initially, the asphalt binder was heated and raised to a temperature range of 145-150 °C. Subsequently, the amalgamation of the asphalt binder and additions was executed in three stages (each in 5 minutes) using a high-speed mixer. The entire process took 15 minutes.

During the initial 5 minutes, different percentages of oil and nano-CaO were gradually incorporated into the asphalt binder within a high-shear mixer. The device was rotating at a speed of around 1500 to 2000 rpm during this stage. During the second 5 minutes, the velocity escalated to 5000 rpm, and during the third phase, the specimens were blended for another 5 minutes at a velocity of 5000 rpm. The target samples of this research were acquired at the end of the mixing process, as outlined in Table 3.

Table 3. Different asphalt binders used in this study.

Base Asphalt Binder (B.A)	Asphalt Binder + Rice Bran Oil	Asphalt Binder + Rice Bran Oil + Nano-CaO
Asphalt Binder 60-70	B.A + 3% R	B.A + 5% R + 1% N
	B.A + 5% R	B.A + 5% R + 3% N
	B.A + 7% R	B.A + 5% R + 5% N

3. Experimental procedures

3.1. Microstructure analysis

FTIR is a common technology for monitoring the changes of molecules associated with the modification and oxidation of bituminous samples [39]. The chemical groups of bio-binder were analyzed using the Brucker-Alpha spectrometer in two states: unaged and short-term aged. For the FTIR analysis, the solution resulting from dissolving a small asphalt binder sample in carbon disulfide was desiccated on a KBr slide. Spectroscopy was conducted in the 400 cm^{-1} to 4000 cm^{-1} range.

SEM was also utilized to obtain high-resolution images providing detailed information about the surface characteristics and morphology of the asphalt binders with and without modifiers.

3.2. MSCR test

The MSCR test is a highly accurate method for assessing the resistance of short-term aged samples to permanent deformation. This test examines the behavior of asphalt binders at high temperatures. The MSCR test was conducted based on the ASTM D7405-20 standard. The samples had a diameter of 25 mm and a thickness of 1 mm. A creep load was applied to each sample for 1 second, and then, there was a 9-second recovery interval. After undergoing 10 cycles of shear stress at 0.1 kPa, the samples were subjected to an additional 10 cycles of shear stress at 3.2 kPa. During the laboratory testing process, there is a direct correlation between the percentage of recovery (R), which indicates the delayed elasticity of asphalt binder and the percentage of strain in the creep section of the test. Additionally, there is a correlation with the non-recoverable creep compliance (J_{nr}), which indicates the hardness of asphalt binder. This method standardizes the asphalt binder to the exerted stress and effectively differentiates the variations among different types of asphalt binder. $J_{nr\text{-}diff}$ also demonstrates the asphalt binder's sensitivity to changes in stress levels, and in certain instances, it can provide insight into the effectiveness of the network formed by the modifier inside the bituminous mixture against stress. The performance rating standard for asphalt binder (AASHTO M332) specifies the maximum non-recoverable creep at a stress level of 3.2 kPa for standard (S), heavy (H), very heavy (V), and extremely heavy (E) traffic loadings, respectively. It is limited to the values of 4.5, 2, 1, and 0.5 kPa^{-1} [40].

4. Results and discussion

4.1. Microstructure analysis

The combination of bio-oil and nano-CaO in asphalt binder results in the interaction and alteration of the pure asphalt binder's structure. Asphalt binder composition can also change due to oxidative aging, simulated by laboratory-based artificial aging techniques [33,41]. It is crucial to identify and analyze the functional groups in the binders using FTIR to assess the effect of these changes on the asphalt binder's performance. Fig. 3 displays the FTIR spectrum of the modified asphalt binder that includes RBO and nano-CaO, both before and after undergoing short-term aging. The strongest band belonged to 2920 cm^{-1} and 2484 cm^{-1}. Within this peak, a significant amount of CH_2 functional groups was present in the CH bonds, encompassing both symmetric and asymmetric tension. The secondary peak was observed at 1378 cm^{-1} and 1460 cm^{-1}, corresponding to the C-H scissor vibration absorption peak and the bending symmetry of the CH_3 functional group. Peaks 1597 cm^{-1} and 1691 cm^{-1} showed C=C and C=O aromatic hydroxyl chains. Peaks 1374 cm^{-1} and 1458 cm^{-1} proved the 3CH chain. Besides, the peaks in the range of 1225-1085 cm^{-1} belonged to the C-O stretching bond, and the peak 1239 cm^{-1} was associated with the C-N functional group. Peak 1032 cm^{-1} displayed S=O carboxylic functional group, and peaks 723 cm^{-1} and 873 cm^{-1} were para and meta aromatic functional groups.

The peaks seen in the fingerprint region corresponded to two distinctive features of the CH_2-R--CH functional group. Furthermore, the most prominent secondary peak band occurred before the aging process.

Through meticulous analysis of all the peaks and the interplay between bio-oil peaks and asphalt binder within narrower ranges, it can be deduced that adding bio-oil altered the peaks, indicating a chemical reaction between asphalt binder and bio-oil. Furthermore, the occurrence of carbon and nitrogen bonding observed at peaks 1747 cm^{-1} and 1239 cm^{-1} provides further evidence of the chemical makeup of oil-containing asphalt binder.

Adding nano-CaO induced a minor peak within the 510 cm^{-1}-540 cm^{-1} range associated with the CaO group. The augmentation of CaO elevated the intensity of all peaks due to the carbonation occurring on the CaO surface.

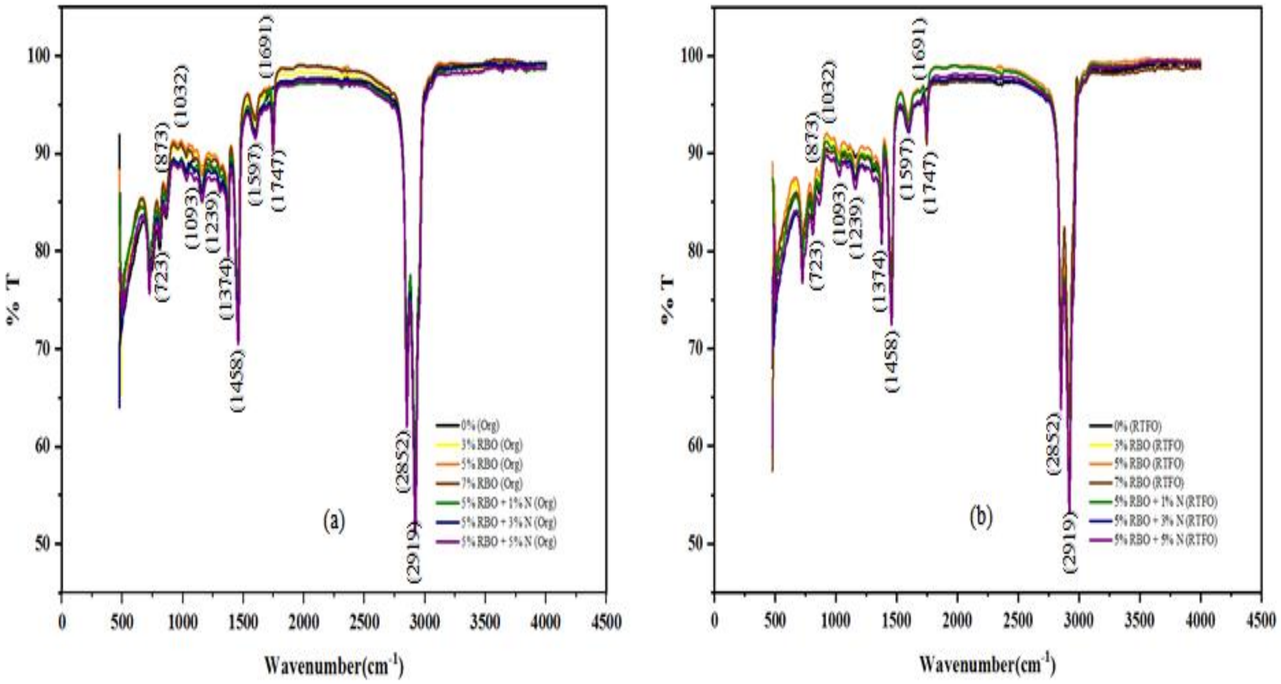
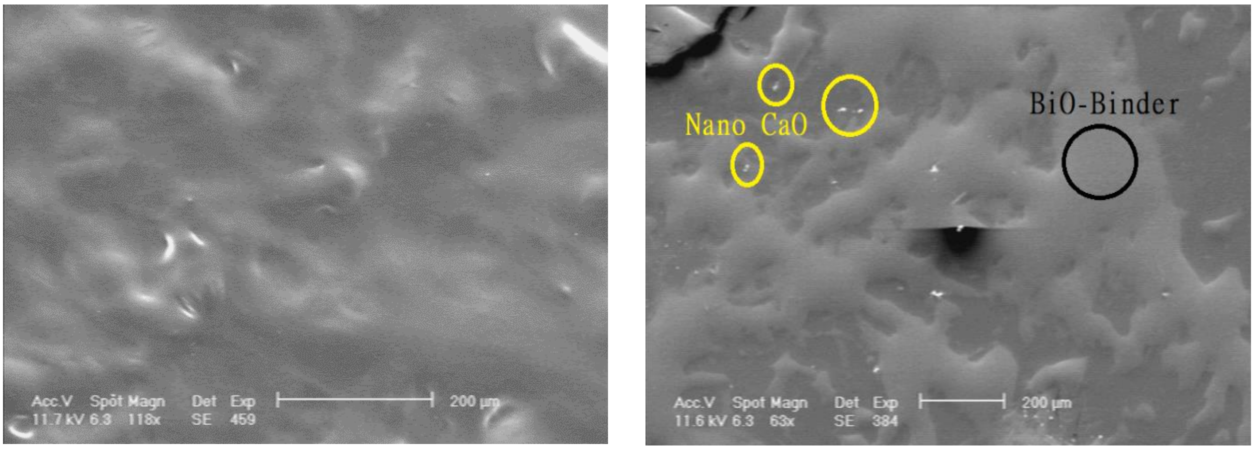


Fig. 3. FTIR spectrum of the control and modified asphalt binder samples.

The analysis of bio-binder samples undergoing the aging simulation process revealed a decrease in two types of functional groups, sulfoxide (S=O) and carbonyl (C=O), indicating chemical changes. This reduction can be attributed to the antioxidant properties of RBO. However, when introducing nano-CaO into the aged samples, the C-O bonds contributing to the flexibility of the asphalt binder underwent noticeable breakage throughout the aging process. This demonstrates the generation of free radicals, which readily react with oxygen and increase the C=O bond. Furthermore, as the aging process advanced, there was a corresponding rise in the quantity of S=O bonds.

However, the modified asphalt binder mixed with 5% oil and 3% nano-CaO showed improved resistance in the aging process compared to other asphalt binder types. This indicates that oil served as a rejuvenating substance by preventing the increase of C=O and S=O bonds. Additionally, the added nano-CaO increased the amount of C-O bond, resulting in the enhanced adhesive ability of the asphalt binder.

Fig 4 displays the SEM image of the unmodified asphalt binder and the asphalt binder modified with RBO-nano-CaO. To exploit the full of potential of nano as an asphalt binder modifier, it is necessary to disperse these nanomaterials in the binder as much as possible. As shown in the SEM images, the mixing procedure was a successful technique for mixing nano-CaO in asphalt binder and making a nano-RBO–asphalt binder matrix.



(a) (b)

Fig. 4. SEM images of a) Control asphalt binder, b) Modified asphalt binder.

4.2. MSCR test results

Following the ASTM D7405-20 standard, the MSCR test was carried out on the rolling thin-film oven (RTFO) samples at PG temperatures (58 and 64 °C in this study). The non-recoverable creep compliance (J_{nr}) and the creep recovery percentage (R) were measured in each cycle to assess the asphalt binder's efficiency at high temperatures. The values of these two parameters for the samples examined in this study at various temperatures are depicted in Figs. 5 and 6.

Based on the results, RBO elevated the non-recoverable creep compliance and reduced the recovery percentage. This suggests that there was an increase in permanent strains and rutting in the asphalt binder and asphalt mixture. The procedure remained consistent across all temperatures and stress levels. As a sample in the worst case, consider a specimen with an oil content of 7%, a temperature of 64 °C, and a stress level of 3.2 kPa. The J_{nr} in this sample was about 2.1 times more, and the recovery percentage was 0.28 lower than the B.A sample. This observation indicates that the oil caused the asphalt binder to become more fluid and reduced its capacity to adhere, hence rendering it particularly susceptible to rutting under high temperatures.

As shown in Fig. 6 with red dashed line, when the oil concentration rose from 5% to 7%, there was a rapid and substantial decline in the descending trend of R. Consequently, although using oil in the initial stage of the tests caused the tensile bonds of the asphalt binder to break, it was chosen to utilize the advantages of rejuvenation, which are more noticeable at low and intermediate temperatures, and enhance the effectiveness of asphalt binder. A 5% oil was selected in this study, and various percentages of nano-CaO were employed to address creasing. The findings demonstrated that adding nano-CaO has lowered J_{nr} and increased R, showing an improvement in the efficacy of asphalt binder against rutting.

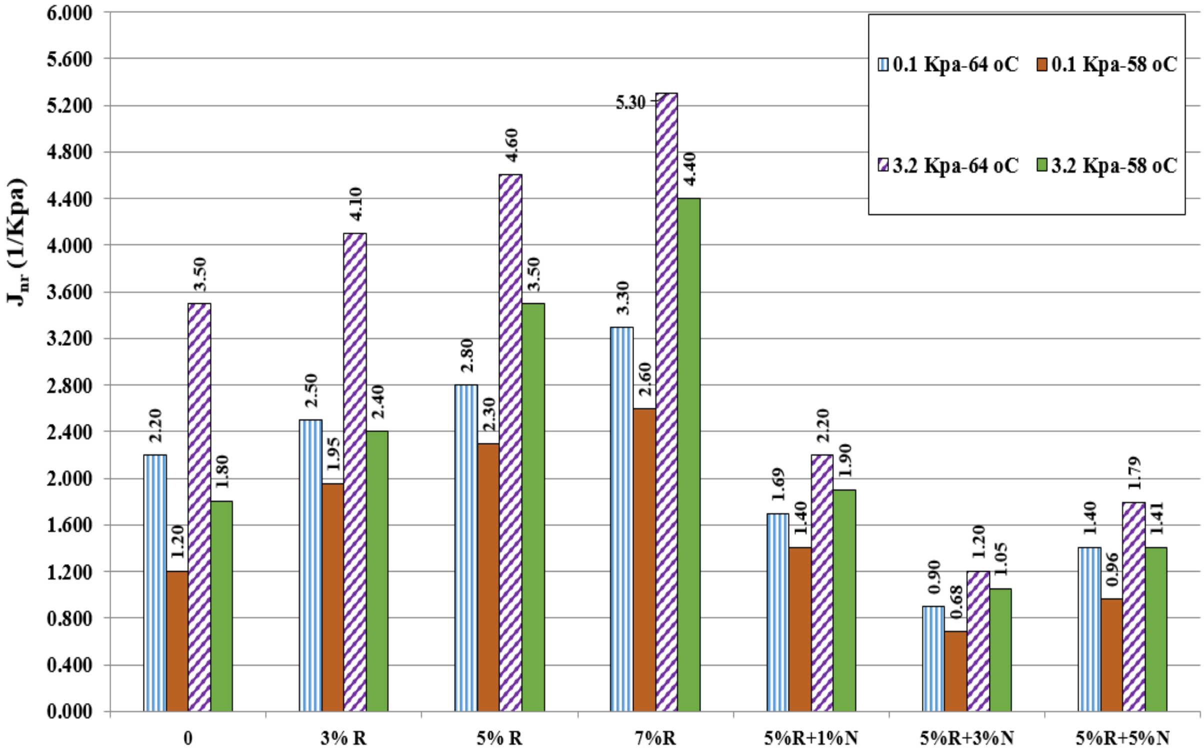


Fig. 5. Non-recoverable creep compliance (J_{nr}) values at different temperatures.

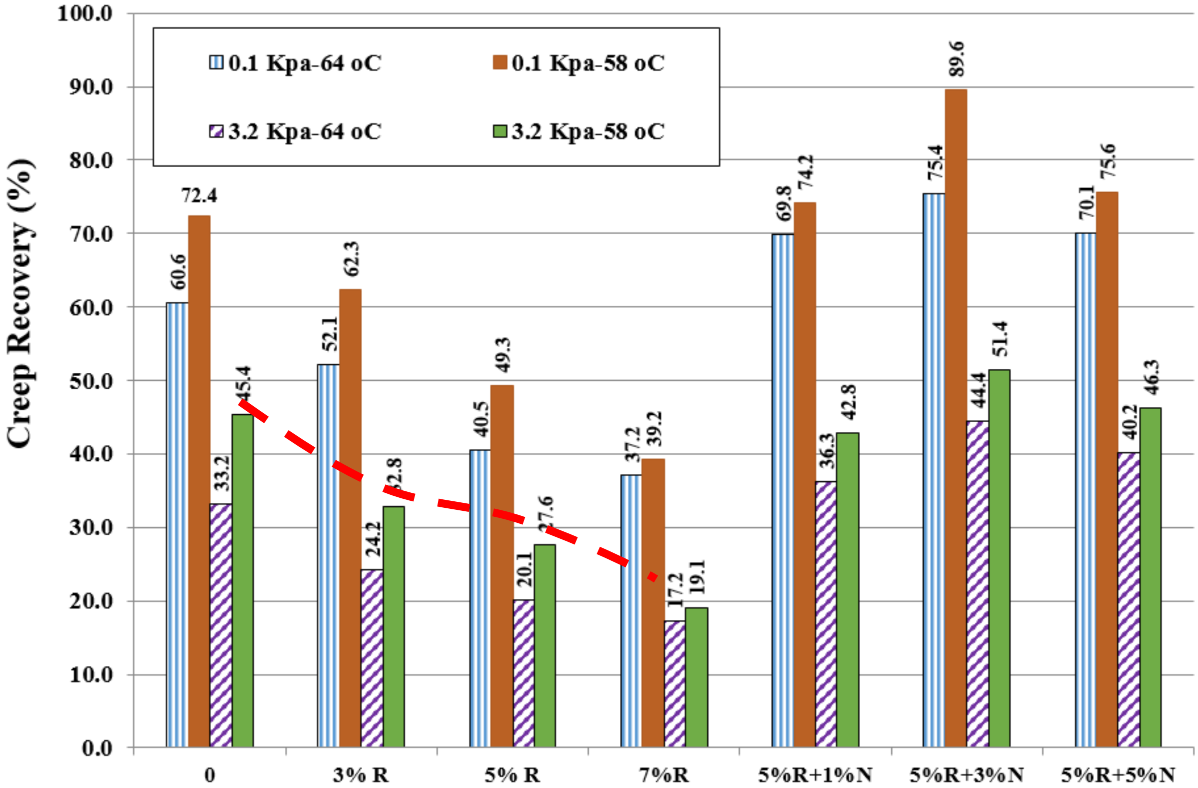


Fig. 6. Percentage of recovery (R) at different temperatures.

The highest level of performance was achieved in the sample with 5% oil and 3% nano-CaO. In this sample and at different temperatures, the value of J_{nr} was about 0.35-0.58 of the control sample.

However, the value of R% was about 1.13-1.34 times that of the unmodified sample. Significantly, as the nano content rose from 3% to 5%, there was a noticeable decline in both J_{nr} and R. The issue could be due to the excessive increase of nanoparticles, causing excessive separation of asphalt binder constituent particles; instead of strengthening its cohesion, they caused them to disintegrate. So, the sample's resistance against rutting decreased. Among the many samples used in this investigation, the one containing 5% oil and 3% nano-CaO exhibited the lowest rutting potential. This reduction amounted to around 13-34% compared to the control sample, regardless of temperature and stress levels. Additionally, utilizing 5% oil without the nano-particles resulted in a significant rise of 35-50% in rutting inside the asphalt binder.

$J_{nr\text{-}diff}$ is a parameter examined in the MSCR test that measures asphalt binder's sensitivity to stress increments ranging from 0.1 kPa to 3.2 kPa. A lower $J_{nr\text{-}diff}$ value suggests a more effective network built by the modifier within the bituminous mortar to resist increases in stress. The ASTM D7405 standard restricts this value to a maximum of 75%. Fig. 7 demonstrates that in every sample analyzed in this study, the value was below 75%.

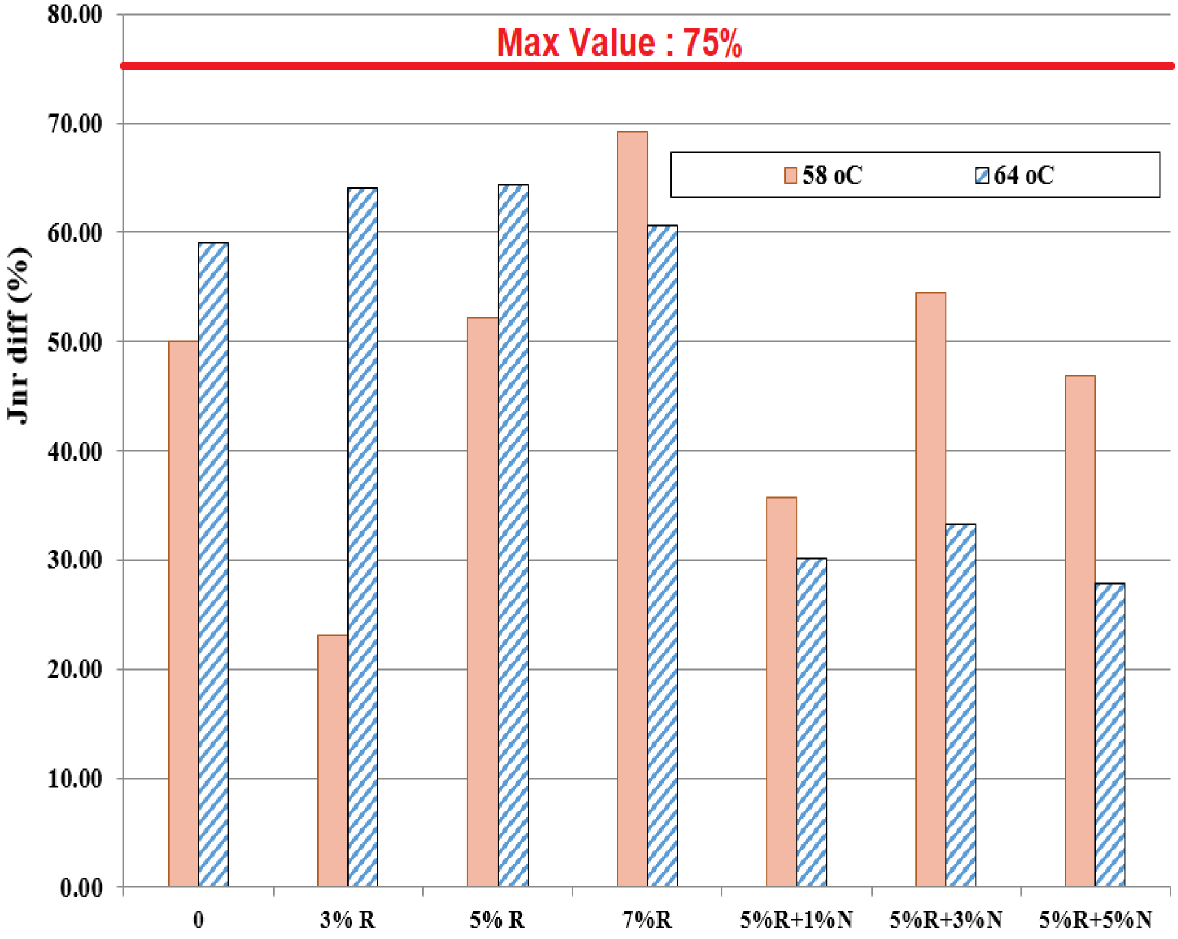


Fig. 7. The recovery percentage at different temperatures.

Asphalt binder classification is determined by evaluating its maximum non-recoverable creep compliance, as outlined in Section 3.2.2. The results of this investigation are shown in Table 4. At 58 °C, with increasing the dosage of RBO, the J_{nr} value increased, and the asphalt binder performance rating decreased from heavy traffic (H) to standard traffic (S). This deficiency was compensated by adding 3% nano-CaO; the passable traffic level was upgraded to H, with a much better condition than the B.A. The special effect of adding 3% nano-CaO to the asphalt binder containing 5% oil at 64 °C was determined in the B.A sample which lacks a performance level;

meanwhile, at the same temperature and in the combination of 5% oil and 3% nano, the status has been upgraded to H.

Table 4. Tolerable traffic level in the asphalt binders made in this research based on the ASTM M332 standard.

Samples	**58 °C**		**64 °C**	
	Jnr 3.2 kPa (kPa^{-1})	Traffic Level	Jnr 3.2 kPa (kPa^{-1})	Traffic Level
B.A	1.8	H	3.5	S
B.A + 3% R	2.4	S	4.1	S
B.A + 5% R	3.5	S	4.6	-
B.A + 7% R	4.4	S	5.3	-
B.A + 5% R + 1% N	1.9	H	2.2	S
B.A + 5% R + 3% N	1.05	H	1.2	H
B.A + 5% R + 5% N	1.41	H	1.79	H

This section examines the variations in shear strain in the MSCR test for the control sample, the asphalt binder containing 5% oil, and the sample with 5% oil and 3% nano-CaO, found to be the best among all the samples analyzed. Figs. 8 and 9 illustrate the changes in shear strain per loading cycle at a stress level of 0.1 kPa and two temperatures (58 and 64 °C).

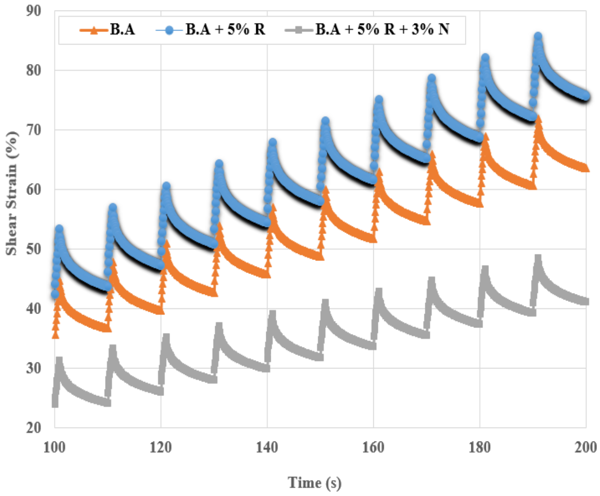


Fig. 8. The shear strain of the samples at a stress level of 0.1 kPa at 58 °C.

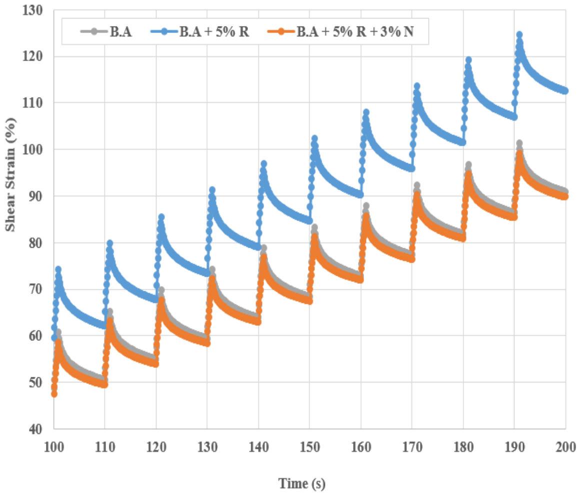


Fig. 9. The shear strain of the samples at a stress level of 0.1 kPa at 64 °C.

The shear strain of the specimens at the stress level of 3.2kPa is depicted in Figs. 10 and 11. Elevating the temperature of the samples from 58 to 64 °C increased the shear strain, thereby raising the rutting potential. This observation was due to the asphalt binder becoming more viscous due to the rise in temperature.

Adding oil to the asphalt binder increased the shear strain at all temperatures and stress levels. As previously noted, this problem arises due to the breaking of C-O bonds, which is linked to the stretchability of asphalt binder after adding oil.

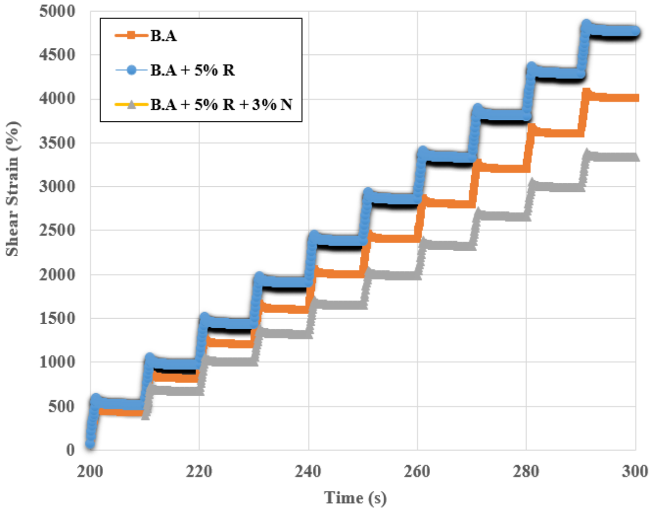


Fig. 10. The shear strain of the samples at a stress level of 3.2 kPa at 58 °C.

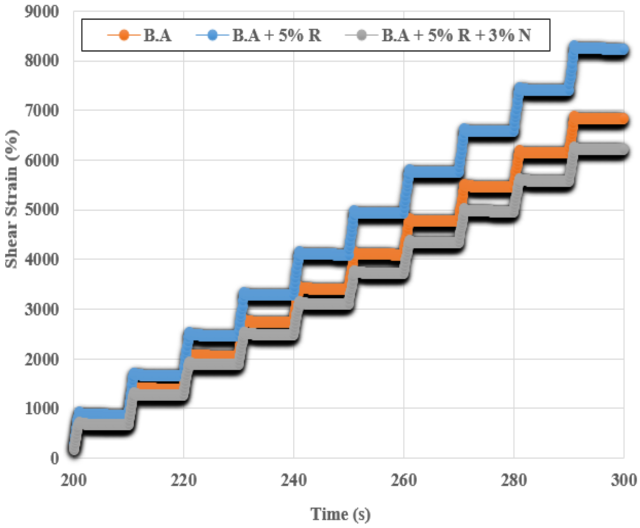


Fig. 11. The shear strain of the samples at a stress level of 3.2 kPa at 64 °C.

However, research shows that including 3% nano-CaO leads to the least amount of shear strain; this causes a decrease in the possibility of rutting occurring under any temperature and stress conditions. This phenomenon is also due to the increase in the C-O bond after adding CaO, which enhances the asphalt binder's adhesive ability. The crucial point is that the efficacy of nano-CaO decreased as the temperature rose from 58 to 64 °C.

At a stress level of 0.1 kPa, the shear strain of the modified sample containing 5% oil and 3% nano-CaO (orange) closely resembled that of the B.A sample. This was observed at a stress level of 3.2 kPa. This phenomenon occurred because nano-CaO lost its effectiveness at higher temperatures due to its thermal sensitivity.

4.3. Cost-effective evaluation

This paper also examined the economic implications of including RBO and nano-CaO for asphalt binder pricing and asphalt production. The analysis was based on the worldwide prices of asphalt binder, mixtures, and additives as observed in the global commodities exchange markets. The initial price of RBO and nano-CaO is generally higher than the global average price of binder. This disparity can be attributed to the higher processing costs associated with these substances. The primary factor contributing to this higher cost is the limited advancement of the asphalt modification process involving oil and nano on an industrial level [42]. Employing asphalt modification technology using these materials can greatly reduce associated costs by up to 90% in a short time. Incorporating biological oils into asphalt samples has been discovered to improve fatigue resistance due to their capacity to soften the material [43]. This study primarily focused on enhancing the rutting behavior at elevated temperatures. Prior studies have demonstrated that enhancing the ability to withstand fatigue cracking lowered the thickness of asphalt pavement by about 20% to 30% [44,45]. Based on the long-term pavement performance (LTPP) data, it can be shown that the unit cost of HMA coating per m^2 per 1 cm depth is around 1.1 USD [46]. Consequently, using RBO and nano-CaO as novel and ecologically sustainable materials presents a very cost-effective solution to reduce the expenses associated with the building and maintenance of asphalt pavements. In contrast, the findings of this study indicated that using RBO and nano-CaO in asphalt modification resulted in a notable enhancement (20%) in rutting resistance at elevated temperatures. Consequently, it is anticipated that the asphalt mixture using modified binder will experience rutting over an extended duration, which decreases maintenance expenses. The cost-effectiveness of utilizing these two modifiers as a substitute for binder was assessed by calculating the price of each ton of HMA in the modified condition and comparing it to the cost for unmodified HMA.

- Cost of asphalt binder: 600 USD/ton, and cost of aggregates: 14 USD/ton
- Total cost of 1 ton of HMA: 65 USD
- Binder required for 1 ton of HMA (5.5% OBC): 55 kg
- Cost of 55 kg of binder: 55 × 0.6 = 33 USD
- Binder required when replacing with 5% RBO and 3% nano CaO: 55 × 0.92 = 50.6 kg
- Cost of 50.6 kg of binder: 50.6 * 0.6 = 30.36 USD
- Reduction in the cost of the consumed binder after using the additives: 33-30.36 = 2.64 kg
- The cost of RBO/kg: 1.35 USD, and the cost of nano CaO/kg: 2.4 USD
- The weight of asphalt binder replacement with 5% RBO into binder: 55× 0.05 = 2.75 kg
- Cost of 2.75 kg of RBO: 1.35 × 2.75 = 3.71 USD
- The weight of substituting 3% nano-CaO into binder: 55 × 0.3 = 1.65 kg
- Cost of 1.65 kg of nanoCaO: 2.4 ×1.65 = 3.96 USD
- Total cost of RBO and nano-CaO to produce 1 ton of HMA: 3.71 + 3.96 = 7.67 USD
- Total cost of 1 ton of HMA modified with RBO and CaO: (65-2.64) + 7.67 = 70.03 USD

The manufacturing costs of the unmodified HMA and the HMA modified with RBO and nano CaO are depicted in Fig. 12. Evidently, the cost of the modified asphalt mixture was 7% more than that of the unmodified HMA. Considering the reasons described before, it is possible to anticipate a 20% decrease in the manufacturing cost of the modified asphalt mixture, given the observed enhancements in rutting and fatigue performance. Fig. 12 illustrates the reduction in the cost of asphalt mixture following modification, indicating the economic feasibility of producing a mixture containing RBO and nano-CaO.

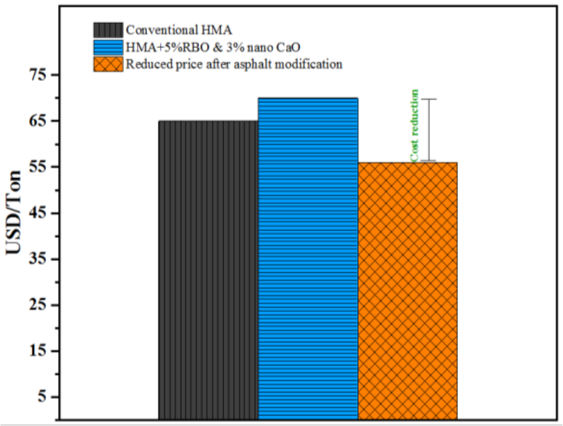


Fig. 12. Cost comparison of unmodified and modified HMA.5. Future research directions.

The primary objective of this study was to investigate the rutting characteristics of asphalt binders modified with RBO and nano-CaO, which were determined using MSCR and FTIR tests. The findings demonstrated that while using RBO increased rutting, the addition of nano-CaO counterbalanced this effect. The chemical analysis revealed that utilizing this oil rejuvenated the asphalt binder, hence improving its resistance to fatigue and heat cracking. According to the results, it is important and possible to conduct more laboratory research to explore the use of RBO and nano-CaO in modifying asphalt binders. A comprehensive examination of bituminous mixtures in a controlled environment is essential to enhancing the comprehension of chemical bonds, aging processes, viscoelastic behavior, impact of environmental factors on modification performance, and stability of modifications made during storage. Such a study should conduct various tests and use several analytical techniques, including nuclear magnetic resonance (NMR), thermosgravimetric analysis (TGA), linear amplitude sweep (LAS), life cycle assessment (LCA), and storage stability analysis. A complete series of mechanical tests must be conducted to evaluate the effectiveness of an asphalt mixture containing RBO and nano-CaO. These tests encompass dynamic creep, indirect tensile strength, and semicircular bending. Furthermore, it is advantageous to construct a test section of asphalt pavement with a modified asphalt mixture incorporating the suggested modifiers. This will enable the assessment of its performance and durability under various traffic and weather situations over a designated duration, thereby offering more confidence.

6. Conclusion

This study assessed the rutting characteristics of asphalt binder based on a useful and novel method: MSCR test. The chemical properties of asphalt binders were also evaluated with FTIR. In this way, the effect of RBO, as a bio-waste material and nano-CaO on the rutting behavior of the asphalt binder was examined. The primary findings of the current study were:

- The chemical reaction between RBO and asphalt binder rejuvenated the asphalt binder. Based on the MSCR test outcomes, this procedure also made the asphalt binder more sensitive to rutting. For the sample with 7% RBO, the J_{nr} was around 2.1 times greater than the unmodified asphalt binder. Besides, the creep recovery was only 0.28 that of the unmodified sample.
- Based on chemical analysis, a sample containing 5% RBO and 3% nano-CaO was the best. This is because when asphalt binder and RBO reacted, C-O bonds were broken, thereby reducing the tensile strength of the base asphalt, resulting in more susceptibility to rutting. However, by adding more than 3% nano-CaO to the mixture, the broken C-O bonds could be re-formed and increased, thereby restoring the tensile strength of the base asphalt to normal levels. The sample with 5% RBO and 3% nano-CaO demonstrated superior performance in

the MSCR test. The rutting susceptibility decreased by 13-34% compared to the unmodified sample. However, utilizing 5% RBO alone resulted in a 35-50% rise in rutting.

- The sample with 5% RBO and 3% nano-CaO demonstrated a quality traffic level of H at both temperatures of 58 and 64 ^{o}C. This suggests that it is suitable for use on roads with heavy traffic volumes.
- Based on the economic evaluation, adding these two additives to asphalt mixtures may initially increase the price by up to 7%. However, rheological data analysis confirmed the potential for an absolute reduction of 20% in the overall costs associated with the construction and maintenance of modified asphalt mixtures, which makes the utilization of modified asphalt economically feasible.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Authors contribution statement

Mostafa Sadeghnejad: Conceptualization, Methodology, Investigation, Formal analysis, Writing-Original Draft, Software.

Mahyar Arabani: Supervision, Conceptualization, Validation, Writing-Review & Editing, Project Administration.

Javad Haghanipour: Writing-Original Draft, Formal analysis, Resources.

Mohammad Hossein Hassanjani: Formal analysis, Investigation, Data Curation, Writing-Review & Editing.

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