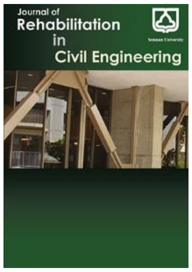
Journal of Rehabilitation in Civil Engineering 11-3 (2023) 144-157



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

Laboratory Evaluation of Fatigue and Rutting Performance of Nano $CaCO_3$ Modified Asphalt Binders

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ARTICLE INFO

Article history:
Received: 06 May 2022
Revised: 05 August 2022
Accepted: 21 September 2022

Keywords:
Asphalt binder;
Nano $CaCO_3$;
Fatigue;
Rutting.

ABSTRACT

Evaluating the efficacy of Nano CaCO3 particles on amelioration of fatigue and rutting behavior of asphalt binder is the principal aim of this article. To this end, asphalt binder specimens are fabricated by incorporating various amounts of Nano CaCO3 (0.3%, 0.6%, 0.9%, and 1.2%) with asphalt binder 60-70. Fatigue and rutting performance of the asphalt binder specimens are examined by implementing linear amplitude sweep and multiple stress creep recovery experiments. Results indicated that incorporating Nano CaCO3 with the asphalt binder specimens enhanced their resistance to rutting. Asphalt binder samples containing Nano CaCO3 showed higher potential for compensating the induced strains than unmodified samples. Also, by adding Nano CaCO3, the asphalt binder specimens showed improved fatigue behavior. Asphalt binder samples modified with Nano CaCO3 exhibited better behavior when subjected to cyclic loads than unmodified ones. Also in all cases, the asphalt binder specimens containing 0.9% Nano CaCO3 demonstrated the best performance.

1 Introduction

Binders are an integral part of asphalt pavements since their purpose is to bind aggregates together and form a stone structure that can sustain loads. Fatigue and rutting distress, which are prevalent in asphalt pavements, are caused by repetitious loading and accumulation of strains. These damages increase the maintenance cost and decrease the service life of asphalt pavements considerably. Hence, in recent years,

How to cite this article:
Yarahmadi, A. M., Shafabakhsh, G., & Asakereh, A. (2023). Laboratory Evaluation of Fatigue and Rutting Performance of Nano CaCO3-Modified Asphalt Binders. Journal of Rehabilitation in Civil Engineering, 11(3), 144-157. https://doi.org/10.22075/JRCE.2022.27095.1651

researchers are trying to find solutions to solve this issue. One of the approaches is to ameliorate the asphalt binder properties using Nanomaterials. These modifiers can significantly improve the asphalt binder characteristics because of two reasons: (a) their high specific surface area, and (b) their interaction with asphalt binder particles. Therefore, in this study, a specific type of Nanomaterial (Nano $CaCO_3$) is selected as a modifier.

Nano $CaCO_3$ is manufactured in two ways: (a) the mineral carbonation process of industrial wastes like CaO and $CaCl_2$ (as the source of calcium) in a packed bed reactor [1], and (b) using the emitted-CO_2 of the cement manufacturing process at cement plant [2]. Therefore, using Nano $CaCO_3$ as a modifier additive not only mitigates the CO_2 emissions, but also is a cost-effective idea for ameliorating the rheological behavior of the asphalt binder.

Preceding research examined the effects of Nano $CaCO_3$ in a composite form with other modifiers (e.g., styrene–butadiene rubber, SBS, Nano TiO_2, Nano ZnO, and waste polyethylene) on the properties of asphalt mixtures and asphalt binders [3-10]. Also, in these studies, Nano $CaCO_3$ was used in high percentages (more than 1.5%), which is not economically viable, because Nanomaterials constitute expensive modifiers. Moreover, these studies used asphalt binders like AH-70, AH-90, 90A#, and SK-90 as their base asphalt binders. This research specifically examines the effect of Nano $CaCO_3$ in lower dosages (0.3% - 1.2%) on the rutting and fatigue of 60-70 asphalt binder to not only improve these characteristics but also make the binder modification affordable in real projects. In this study, for evaluating the rutting behavior and fatigue life of binder samples, multiple stress creep recovery (MSCR) and linear amplitude sweep (LAS) tests are performed.

2. Literature Review

Yarahmadi, et al. [11] investigated the effects of various ratios of Nano $CaCO_3$ (0.3%, 0.6%, 0.9%, and 1.2%) on the fatigue and rutting of stone mastic asphalt mixtures (SMA) using indirect tensile fatigue (ITF) and wheel track tests. It was revealed that the fatigue and rutting performance of SMA mixtures were improved by adding Nano $CaCO_3$.The impact of Nano silica with various amounts (2, 4, and 6%) on the rutting behavior of asphalt binder 60/70 containing tyre pyrolysis oil (TPO) was investigated by Al-Sabaeei, et al. [13]. In that research, MSCR, penetration, and softening point tests were conducted. Findings indicated that the rutting behavior of the asphalt binder containing TPO was ameliorated by adding Nano silica. Zhong, et al. [13] studied the influence of 2, 4, and 6% of Carbon black on fatigue and rutting performance of 70# asphalt binder using the LAS and MSCR experiments. Generally, it was found that the binder specimens incorporated with Carbon black demonstrated improved fatigue and rutting behavior. Huang, et al. [14]assessed the effects of eggshell powder with different dosages of 3%, 6%, 9%, and 12% on the rutting performance of SK-70 asphalt binder and HMA mixture using MSCR and wheel track experiments. Results demonstrated that the rutting resistance of the asphalt binder and asphalt mixture was increased by adding eggshell powder. Li, et al. [4]studied the influence of Nano $CaCO_3$/Nano ZnO/SBR composite modifier on the rutting resistance and viscosity of AK-70 asphalt binder. In this study, different dosages of Nano $CaCO_3$

(4%, 5%, 6%), Nano ZnO (1%, 3%, 5%), and SBR (3%, 4%, 5%) were used. By conducting DSR and Brookfield viscosity tests, rutting resistance and viscosity of asphalt binder samples were assessed. Results showed that composite-modified binder samples showed higher viscosity and rutting resistance than neat samples.The efficacy of composition of crude palm oil (CPO) ratio of 5% and TPO ratio of 5% (CPO/TPO) as a modifier on the improvement of rutting behavior of the asphalt binder 60/70 was analyzed by Al-Sabaeei, et al. [15]. MSCR test was performed. It was shown that Compared to base asphalt binder, Asphalt binder modified with CPO/TPO showed better rutting resistance. The efficacy of different contents of Nano Al2O3 (0.5, 1, and 2%) on the amelioration of fatigue and rutting behavior of the VG-10 asphalt binder was assessed by Bhat and Mir [16]. For achieving this goal, a time sweep and the MSCR tests were conducted. Nano Al2O3 was shown to improve asphalt binder fatigue and rutting behavior. The impacts of 0.3, 0.6, 0.9, and 1.2% of Nano TiO2 and Nano SiO2 on the rutting resistance and fatigue behavior of asphalt binder 60-70 were studied by Shafabakhsh, et al. [17]. Moghadas Nejad, et al. [18] assessed the influence of 2% and 4% of Nano CaCO3 on the fatigue and rutting of hot mix asphalt (HMA) using ITF and Dynamic creep tests. It was shown that Nano CaCO3 improved fatigue life and reduced the rut depth of HMA mixtures. In that research, MSCR and LAS experiments were implemented. It was found that the rutting resistance and fatigue behavior of the asphalt binder was improved by using Nano SiO2 and Nano TiO2. Motamedi, Shafabakhsh, and Azadi examined the fatigue life of PG 58-22 binder specimens containing 3, 5, and 7% of Nano-silica and Synthesized Polyurethane [19]. To assess fatigue behavior, LAS and time sweep (TS) experiments were implemented. The results indicated that the fatigue life of the binder specimens was ameliorated when Nano-silica and Synthesized Polyurethane were utilized. The influence of Different amounts of Nano Al2O3 (0.3, 0.6, 0.9, 1.2, and 3%) on the rutting performance of AC60/70 asphalt binder incorporated with various amounts of SBS (3% and 5%) was examined by Shafabakhsh, et al. [20]. To do so, binder specimens containing composite modifiers were subjected to the MSCR experiment. Results indicated that the rutting behavior of the SBS-modified binder specimens was ameliorated by using Nano Al2O3. The impact of the Nano silica modifier with different dosages (2, 4, and 6%) on the rutting performance of the PG64-22 asphalt binder was explored by Ghanoon and Tanzadeh [21]. The Nano silica-modified binder specimens and control specimens were subjected to the MSCR experiment. Results indicated that the binder samples containing Nano silica were found to be more resistant to rutting than those without the modification. Xing, et al. [7]evaluated the effects of the Nano CaCO3 ratio of 2% on the rutting of SK-90 asphalt binder using the MSCR test. It was revealed that binder samples containing Nano CaCO3 were more resistant to rutting compared to neat samples. Li, et al. [22] investigated the effects of 0.5%, 1%, 1.5%, and 2% of Modified heavy calcium carbonate on the rutting of modified asphalt binder containing 5% of SBS using MSCR tests. Results showed that modified heavy calcium carbonate improved the rutting of SBS-modified binders. Akbari and Modarres [23] investigated the fatigue behavior of asphalt binder 60-70 incorporated with varying concentrations of Nano alumina and Nano clay (2%, 4%, and 6%). Using time sweep tests, it was demonstrated that modified binder samples with Nano alumina and Nano clay had higher fatigue life in comparison with the control binder samples. Arshad, et al. [24] investigated the impacts of various Nano silica amounts (1-5%) on the rutting resistance of asphalt binder 60/70. For this purpose, an MSCR test was performed. It was seen that modification of the asphalt binder with Nano silica raised its resistance to rutting. López-Contreras, et al. [25]studied the adhesion force between asphalt binder 60-70 and aggregates at their interface using atomic force microscopy (AFM). To do this, AFM tips were modified with usual minerals (e.g., CaCO3 and SiO2) that are found in aggregates. Based on the results, the work of adhesion of asphalt binder and SiO2 was higher than that of asphalt binder and CaCO3. Huang and Tang [26] examined how sulfur (0.15 wt% asphalt binder) affects the rutting behavior of the PG64-16 asphalt binder modified with 3 to 5% SBS by using the MSCR experiment. Results indicated that the SBS-modified binder showed improved rutting performance when sulfur was added. Vasilievici, et al. [27] examined the effects of a Polystyrene ratio of 5% on the stiffness of the asphalt binder D50/70 containing Nano CaCO3 using Dynamic mechanical analysis. It was revealed that Polystyrene elevated the stiffness of the Nano CaCO3-asphalt binder.

The preceding research demonstrated that polymers and nanomaterials can significantly improve the rutting and fatigue behavior of the asphalt binders. Hence, nanomaterials are utilized in this research for ameliorating the binder performance. Although many studies have assessed the efficacy of nanomaterials on the improvement of fatigue and rutting behavior of the asphalt binders, further evaluation is needed regarding the effects of Nano CaCO3. Also, previous studies have shown that MSCR and LAS experiments are reliable and accurate means of assessing the fatigue and rutting behavior of the asphalt binders. Thus, these experiments are implemented in this research to examine the behavior of the binder samples.

3 Materials and Methods

3.1 Asphalt Binder

Asphalt binder consists of mostly hydrocarbons. The exposure of the asphalt binder to high temperatures and air changes its characteristics dramatically [28]. Loading application rate and temperature highly affect the resistance to damage, failure, and viscoelastic characteristics of the asphalt binder [29]. Asphalt binder 60-70 (which is equivalent to PG 64-22) is used in this study for preparing asphalt binder specimens. This asphalt binder is provided by the Pasargad oil refinery in Tehran. Table 1 and Table 2 illustrate the characteristics of the asphalt binder.

Table 1. Asphalt binder properties.

Test	Result
Ductility (25°C, 5cm/min), cm	102
Loss of heating, %	0.2
Softening point, °C	50
Penetration (100 g, 5 s, 25°C), 0.1 mm	68
Solubility in trichloroethylene, %	99.6
Flash point, °C	308

Table 2. PG characteristics of asphalt binder.

Aging state	Test properties	Test result
Unaged binder	Viscosity @ 135°C (Pa . s)	0.308
	$G^{*}/\sin\delta$ @ $64^{\circ}\ C\ (kPa)$	1.14
RTFO aged residual	$G^{*}/\sin\delta$ @ $64^{\circ}\ C\ (kPa)$	2.42
RTFO+PAV aged residual	$G^{*}\times\sin\delta$ @ $25^{\circ}\ C\ (kPa)$	2500
	Stiffness @ -12°C (N/m^2)	197
	m-value	0.32

3.2 Nano CaCO3

Nano CaCO3 particles have a cubic morphology, large specific surface area (30-60m^2/g), and a diameter ranging from 10-80 nm. Because of their high utilization in the fields of rubber, plastic, and polymers, nowadays they are gaining growing attention [30]. Nano CaCO3 particles can be produced by applying the carbonation process in a packed bed reactor (PBR). In this case, two approaches are considered for synthesizing Nano CaCO3. In the first approach, the waste of CaO is utilized as a calcium source, and in the second one, CaCl2 and NH3 are used in the manufacturing process [1]. In this research, Nano CaCO3 is used in various dosages (0.3, 0.6, 0.9, and 1.2% by weight) to modify binder samples. The reason for considering Nano CaCO3 as a modifying additive of asphalt binder is that Nano CaCO3 is environmental-friendly, also, it is cheaper than other types of Nanomaterials [1, 2]. Table 3 presents the Nano CaCO3 characteristics.

Table 3. Nano CaCO3 characteristics.

purity	99.9
Density g/cm^3	2.93
color	white
Diameter Nm	20
Water absorption %	0.2<
Surface-volume ratio m^2/g	40
morphology	cubic

3.3 Mixing Plan of Nano Caco3 and Asphalt Binder

The wet method is chosen in this study to mix Nano CaCO3 with asphalt binder. Accordingly, Nano CaCO3 particles should first be dispersed in the solver. Following this, the resultant mixture is incorporated with the heated asphalt binder at a temperature of 150°C. As a solvent, Kerosene is used because of three main reasons: (a) low viscosity (at room temperature), (b) good ability for uniformly diffusing Nano CaCO3 particles, and (C) being an oil derivative product, which results in a lower negative impact on the asphalt binder. Table 4 represents the properties of Kerosene.

Table 4. Kerosene characteristics.

Structure	C_6
Density (gr/cm^3)	0.75
Degree of ignition (°C)	85
Evaporation point (°C)	155
Solubility in water and oil derivatives	soluble

The mixing method is selected according to the previous research by Sadeghnejad and Shafabakhsh [31]. Based on this method, for evaluating the proper diffusion and stability of Nano CaCO3 materials in the Kerosene, different Nano CaCO3-kerosene samples are created by high shear mixer apparatus at various mixing times and rounds per minute. Then, every mixture is poured into a separate graduated cylinder and maintained standstill for two weeks. Afterward, the samples are compared and the best mixture with the highest stability is selected. It was observed that 30 minutes of mixing time with 2500 rpm has the best result. By this approach, Nano CaCO3 is distributed better in Kerosene, leading to the highest stability. In the next phase, the asphalt binder is warmed up to 150°C. Kerosene-Nano CaCO3 mixture is then added to the asphalt binder over 30 minutes, at regular intervals. In this step, a high shear mixer with 4000 rpm is used for mixing the Nano CaCO3 and asphalt binder. Figure 1 exhibits the utilized high-shear mixer of this research.

Fig 1. The high shear mixer apparatus.

3.4 Aging and Sample Preparation

Asphalt binder is aged because of two main reasons: (a) oxidation, and (b) high temperature [32]. The asphalt binder undergoes chemical changes upon oxidation, and high temperatures cause the light oils in it to evaporate. Both of these mechanisms harden the asphalt binder and make it susceptible to cracking [33]. After incorporating Nano CaCO3 with the asphalt binder, to create the MSCR test specimens, the asphalt binder is first aged for two hours according to AASHTO T240, using the RTFO apparatus (Figure 2). In this procedure, the heated asphalt binder is poured into glass containers, and they are then placed into the RTFO device. The conditioning process is continued for 85 min at 164°C. Finally, a silicone mold (dimension = 25 mm x 1 mm) is filled with the RTFOT-aged asphalt binder, and after cooling, it is removed from the specimen mold and tested in a DSR device (detailed information about the RTFOT process can be found in AASHTO T240 [34]). For making the LAS samples, the RTFO conditioned asphalt binder is tested in a PAV device (Figure 3) at 100°C and 2.1 MPa pressure. In this step, the conditioning procedure lasts for 20 hours. Following this, the degassing of the asphalt binder is conducted for 30 minutes at the temperature of 170°C using a vacuum oven (Figure 4). Eventually, an 8 mm x 2 mm silicone mold is filled with the PAV-aged asphalt binder. After cooling of the asphalt binder, it is then taken out from the specimen mold and tested in the DSR apparatus (detailed information on the long-term aging of the asphalt binder is found in AASHTO R28 [35]). Table 5 shows a summary of the implemented test conditions. In both MSCR and LAS experiments, two samples are tested to determine the result of each combination, and their average results are reported as the result of each combination.

Fig 2. RTFO apparatus.

Fig 3. PAV device.

Fig 4. Degassing machine.

Table 5. Laboratory tests conditions of this research.

Tests	Standard	Test condition
RTFOT	AASHTO T240	85 min at 164°C
PAV	AASHTO R28	20 hours at a pressure of 2.1 MPa and 100°C
LAS	AASHTO TP 101-12	25°C at 2.5% and 5% strain levels
MSCR	AASHTO T350-14	40°C at 0.1 kPa and 3.2 kPa stress levels

3.5 Laboratory Tests

3.5.1 Multiple Stress Creep Recovery

The MSCR test of this research is performed following AASHTO T350-14 [36]. The use of this test is to assess the rutting behavior of the binder specimen. The creep compliance (J_{nr}) in this test is the residual strain in an asphalt binder sample after consecutive cycles of creep and recovery divided by applied shear stress (1/kPa). Percent recovery (R%) is the magnitude of recovered strain when the sample is unloaded.

The MSCR test is performed using DSR apparatus (Figure 5). The asphalt binder specimen undergoes a total of 30 consecutive cycles of creep and recovery and each cycle lasts for 10 seconds (1 s creep and 9 s recovery). First, 20 cycles are applied at a 0.1 kPa stress level (the initial 10 cycles are conducted to condition the asphalt binder samples). Following this, the next 10 cycles are exerted at a 3.2 kPa stress level. The MSCR test of this study is carried out at 40°C, which is in the range of high-performance temperature of asphalt binder 60-70.

For each creep and recovery cycle, the value of the induced strain at the first and tenth second is recorded. Then, the R%, Jnr, Jnr-diff, and R-diff are calculated using the following equations:

$$R_\tau = \frac{SUM[\frac{(\in_1 - \in_{10}) \times 100}{\in_1}]}{10} \quad (1)$$

$$J_{nr,\tau} = \frac{SUM[\frac{\in_{10}}{\tau}]}{10} \quad (2)$$

$$J_{nr-diff} = \frac{[J_{nr,3.2} - J_{nr,0.1}] \times 100}{J_{nr,0.1}} \quad (3)$$

$$R_{diff} = \frac{[R_{0.1} - R_{3.2}]}{R_{0.1}} \times 100 \quad (4)$$

where $\in_1$ and $\in_{10}$ are the induced strains in the asphalt binder sample at the first and tenth second of each creep and recovery cycle, respectively. τ is the applied shear stress (0.1 or 3.2 kPa), R_τ is the average percent recovery, $J_{nr,\tau}$ is the average creep compliance, $J_{nr-diff}$ is the stress sensitivity of the nonrecoverable creep compliance, and R_{diff} is the stress sensitivity of percent recovery. In this experiment, 20 specimens were subjected to loading to determine the results.

Fig 5. DSR device used in this study.

3.5.2 Linear Amplitude Sweep

In this research, by conducting the LAS test following AASHTO TP 101-12 [37], the fatigue life of the binder specimens is assessed. To speed up the fatigue process of the binder sample, cyclic loads with a fixed frequency (10 Hz), and increasing linear amplitudes are applied using a DSR apparatus. In order to determine the rheological specifications of the binder specimen (e.g., the damage analysis parameter (α)), a frequency sweep test is first performed. In the next phase, the amplitude sweep test is executed on the asphalt binder specimen. Using Eq. (5), the asphalt binder specimen fatigue life is calculated.

$$N_f = A_{35}(\gamma_{max})^{-2\alpha} \quad (5)$$

where N_f is the fatigue life, α is the damage analysis parameter, and γ_{max} is the maximum shear strain and it is determined based on the structure of the pavement (2.5% and 5% for strong and weak pavement, respectively). A_{35} is a parameter relating to the asphalt binder specifications (detailed information on test procedures and parameters calculation is found in AASHTO TP 101-12 [37]).

The LAS test of this research is carried out at 25°C (the intermediate temperature of the asphalt binder 60-70), and 2.5% and 5% strain levels. The results of this experiment were determined by testing 20 samples.

4 Results and Analysis

4.1 Multiple Stress Creep Recovery Results

The Jnr is known as the rutting index, and it determines how the asphalt binder affects the rutting behavior of the asphalt mixture. When the value of Jnr decreases, permanent deformation declines, and the asphalt binder shows better elastic behavior. Thus, the potential of asphalt binder for compensating induced strains is enhanced. Strain recovery (R %), as its name denotes, represents the amount of recovered strain during the unloading of samples. A higher strain recovery indicates a more elastic asphalt binder. JNR-diff indicates how stress-sensitive an asphalt binder is. An asphalt binder sample with higher Jnr-diff values can recover induced strains better.

Figures 6 and 7 show the changes of Jnr and R% at different stress values (0.1 and 3.2 kPa), and Figure 8 represents the stress sensitivity of the binder specimens containing various Nano CaCO3 ratios. At different stress levels (0.1 and 3.2 kPa), the binder specimens incorporated with nano-

CaCO3 had lower Jnr in comparison with control samples. For example, at 3.2 kPa, by adding Nano CaCO3, the Jnr parameter is decreased by 2.64-12.16%. These results are likely due to the desirable impacts of Nano CaCO3 on the asphalt binder characteristics. Nanomaterials have high specific surfaces, which can ameliorate the bonding force between asphalt binder particles. Hence, the cohesion of the asphalt binder and its viscosity are enhanced. As a result, Nano CaCO3-modified binders exhibit better resistance against the applied cyclic loading and dissipate more energy per loading cycle. Moreover, Nano CaCO3-modified asphalt binder samples show superior elastic behavior compared to control samples. As a result of the same cause, samples modified with Nano CaCO3 show higher strain recovery and more stress sensitivity than control specimens. For instance, at 3.2 kPa, modifying the binder samples with Nano CaCO3, increased the strain recovery by 26.14-52.94%. Also, Nano CaCO3-modified samples showed higher Jnr-diff (3.12-9.29%) than unmodified ones. Figures 9 and 10 demonstrate creep compliance and strain recovery equations of Binder samples containing Nano CaCO3. As shown, a line with a polynomial function is best fitted to all data.

By increasing the amount of Nano CaCO3 to 0.9%, the creep compliance is reduced and strain recovery and stress sensitivity are increased. When the amount of Nano CaCO3 exceeds 0.9%, creep compliance starts to climb, and strain recovery and stress sensitivity tend to decline. These results are likely because of the overuse of Nano CaCO3 (more than 0.9%) for modifying asphalt binder specimens, which makes the asphalt binder particles become further apart. Therefore, the cohesive forces among asphalt binder particles are diminished, and the capability of the binder sample to withstand the applied cyclic stresses is reduced.

Rising the stress value (0.1 to 3.2 kPa) causes an increase in creep compliance because samples subjected to higher stress levels experience more shear stresses. As a consequence, the bonding force between asphalt binder particles doesn't have the preceding strength. Due to the same reason, the strain recovery is reduced. When the stress level is elevated (0.1 to 3.2 kPa), creep compliance of the control sample is climbed by about 11.83, and strain recovery is decreased by 13.9%. At 0.1 and 3.2 kPa, binder samples incorporated with 0.9% Nano CaCO3 revealed the lowest creep compliance and highest strain recovery and stress sensitivity compared to other samples.

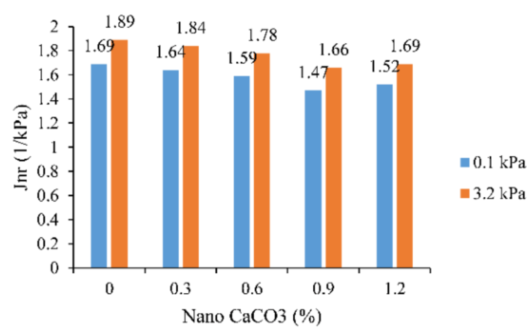

Fig 6. Jnr versus Nano CaCO3 ratio.

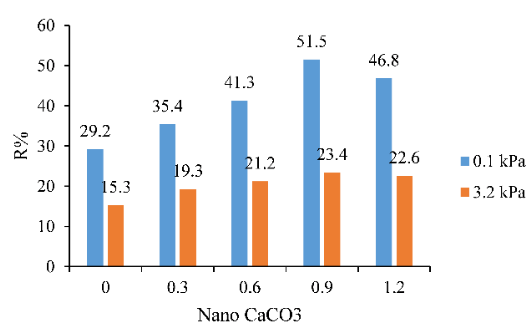

Fig 7. R% versus Nano CaCO3.

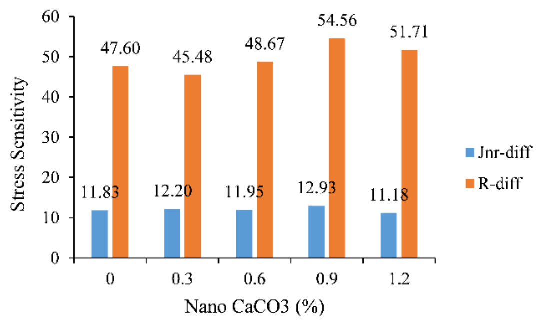

Fig 8. Stress sensitivity of Jnr and R% of Nano CaCO3-modified asphalt binder.

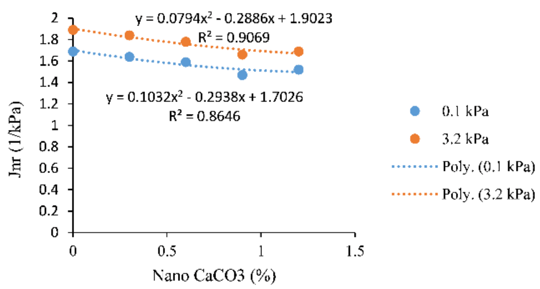

Fig 9. Jnr equations.

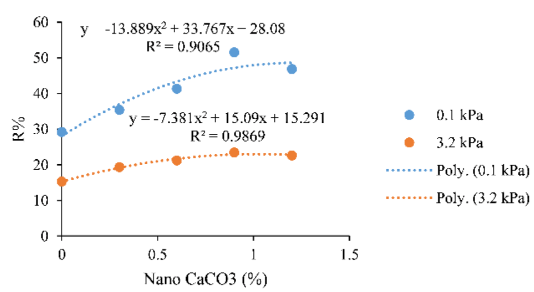

Fig 10. R% equations.

4.2 Linear Amplitude Sweep Results

The fatigue life of binder specimens containing Nano CaCO3 at different strain levels (2.5% and 5 %) is demonstrated in Figure 11. The binder specimens containing Nano CaCO3 showed improved fatigue behavior. For instance, at the strain level of 5%, incorporating Nano CaCO3 with asphalt binder results in the increment of fatigue life by 3.8-22.4%. These results are likely due to the positive impact of Nano CaCO3 on asphalt binder properties. Since Nanomaterials have a high specific surface area, they have a great ability to enhance the asphalt binder properties like viscosity and cohesion. As a result, the overall rheological characteristics of the binder specimens are improved. Also, Nano CaCO3-modified samples can better absorb, and dissipate the energy of the sequential applied cyclic strain levels. Figures 12 show the fatigue life equations of the binder samples containing Nano CaCO3 at 2.5 and 5% strain levels. It is seen that a line with a polynomial function is best fitted to all data.

Utilizing Nano CaCO3 particles up to 0.9% for modifying asphalt binder samples, increases the fatigue life. When the amount of Nano CaCO3 exceeds 0.9%, the fatigue life of the binder specimens begins to decrease. For instance, at 2.5 and 5% strain levels, incorporating 1.2% Nano CaCO3 with asphalt binder reduces the fatigue life by 3.5% and 3.6 % in comparison with binder specimens containing 0.9% Nano CaCO3. The observed result is likely because of the overuse of Nano CaCO3 (more than 0.9%) for modifying asphalt binder specimens, which makes the asphalt binder particles become further apart. Thus, the cohesion force among the asphalt binder particles is not capable to withstand the applied cyclic strains like before. Therefore, in modification of the asphalt binder, Nano CaCO3 has only a positive effect when utilized as an additive, and excessive dosage of it has an unfavorable effect on asphalt binder properties. However, binder specimens containing 1.2% Nano CaCO3 still have longer fatigue life than control specimens. For example, at both 2.5 and 5% strain levels, adding 1.2% Nano CaCO3 to binder specimens increases their fatigue life by 14.81% and 17.95%, respectively, compared to control samples.

By elevating the strain level from 2.5% to 5%, fatigue life is diminished significantly. This result is because higher strain levels induce higher deformations in asphalt binder samples. As a result, the strength of the cohesive force among the asphalt binder particles is weakened and cannot recover the induced strains like before. For example, the rise in strain level (from 2.5 to 5%) declines the fatigue life of the control samples by 86.61%. At these strain levels, binder samples containing 0.9% Nano CaCO3, demonstrate the highest fatigue life among all samples.

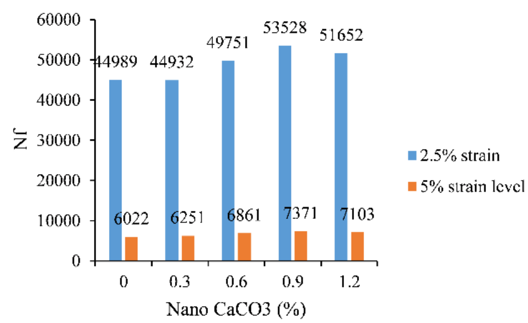

Fig 11. Fatigue life versus Nano CaCO3 ratio.

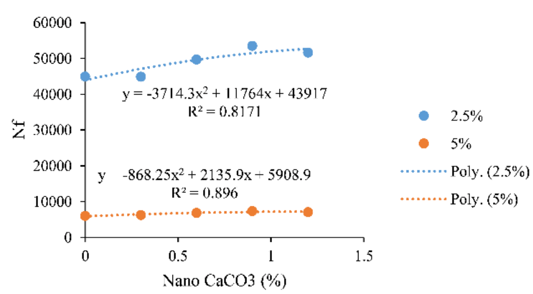

Fig 12. Fatigue life equations.

5 Conclusions

In this research, the principal aim was to assess the efficacy of Nano CaCO3 on the improvement of fatigue and rutting behavior of the asphalt binder 60-70. To this end, binder samples containing various Nano CaCO3 contents (0.3 – 1.2%) were subjected to the LAS and MSCR tests. According to the results, binder specimens incorporated with Nano CaCO3 performed noticeably better than control specimens. In details:

- Addition of Nano CaCO3 particles led to the decrease of creep compliance by a maximum of 13.01 and 12.16 at 0.1 kPa and 3.2 kPa. Nano CaCO3-modified asphalt binder samples demonstrated better resistance to permanent deformation than control specimens. In other words, Nano CaCO3 particles diminished the rutting susceptibility of the asphalt binder.
- Nano CaCO3-modified asphalt binder samples showed superior elastic behavior to control samples. Incorporating Nano CaCO3 with asphalt binder increased the percent recovery of the asphalt binder by a maximum of 76.36 and 52.94 at 0.1 kPa and 3.2 kPa stress levels. It was demonstrated that the ability of the binder to recover the induced strains and return to its preloading state is ameliorated by adding Nano CaCO3.
- By adding Nano CaCO3 particles to asphalt binder specimens, their fatigue life was ameliorated by a maximum of 18.98 and 22.4 at 2.5% and 5% strain levels. All of the Nano-modified asphalt binder samples demonstrated higher fatigue life than unmodified ones.
- Asphalt binder specimens containing 0.9% Nano CaCO3 demonstrated the best fatigue and rutting performance among all specimens.
- Utilizing Nano CaCO3 particles for modifying asphalt binder samples had only a positive effect when utilized as an additive, and overuse of it (more than 0.9%) decreased the fatigue life and

permanent deformation resistance of asphalt binder samples.

All in all, binder samples containing Nano CaCO3 showed ameliorated fatigue and rutting behavior. It is important to consider the economical and environmental aspects of using nanomaterials for modifying asphalt binders. Nanomaterials are more expensive than other modifiers. Therefore, overuse (more than 1.5%) of them is not economically viable. Nano CaCO3 is environmentally friendly and less expensive compared to other nanomaterials. Therefore, considering the mentioned economical and environmental aspects, and also the results of this study, it is inferred that binder samples containing 0.9% Nano CaCO3, were the best samples compared to other samples. This study evaluated the effects of Nano CaCO3 on the rutting and fatigue of a specific type of asphalt binder with a 60-70 penetration grade. Moreover, the rutting and fatigue behavior of the asphalt binder specimens were investigated at 40°C and 25°C. These aspects of the behavior of the asphalt binders can be assessed at different temperatures in future studies.

Declaration of Interest Statement

The authors report there are no competing interests to declare.

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