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Research Article

Creep Stiffness Assessment of Green Asphalt Binder After Digestion with Nano and Micro Additives

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Keywords

Flexural creep stiffness, Micro additives,
Nano additives,
Green Asphalt cement binder,
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Abstract

The green asphalt cement binder is composed of asphalt and additives which are obtained from waste materials. Flexural-creep stiffness of asphalt binder is an indicator of its performance at low temperatures. In the present work, the influence of Nano and Micro additives (fumed silica, silica fumes, hydrated lime, and coal fly ash) on flexural creep stiffness of the green binder was evaluated. Conventional asphalt cement binder with penetration grades (60-70) and (40-50) were investigated. A significant control of such modification on creep stiffness was detected from the experimental program. It was detected that the creep stiffness of (60-70) binder is lower than that of (40-50) binder by 21 %. The creep stiffness of (60-70), and (40-50) green asphalt binders treated with fumed silica is higher than that of control binder by (12.5 and 25) % at failure respectively. While the creep stiffness of (60-70), and (40-50) green asphalt binders treated with silica fumes is higher than that of control binder by (17.8 and 35) % at failure respectively. For (60-70) and (40-50) binders, the creep stiffness increased by (25, and 6.2) % and (32.5, and 5) % after modification with hydrated lime and coal fly ash respectively. It was concluded that modification of asphalt binder with Micro or Nano additives exhibited a reasonable control on the creep stiffness of the binder of the sol and gel types. Additives are recommended to control the cracking of the binder at low temperatures.

1. Introduction

The green asphalt cement binder refers to the modification of asphalt cement by implication of some industrial waste additives which can improve its overall physical and chemical properties. Green asphalt could be used for paving work. Using such waste material additives is beneficial in reserving the resources and prevention of uncontrolled disposal of waste materials which exhibit pollution to the soil or water. Environmental factors exhibit negative influence on the behavior of asphalt binder from the physical and rheological points of view. Such properties are mainly related to the chemical composition of the asphalt cement binder, and more specifically to the intramolecular interactions. Raufi et al.,2020 [1] assessed the modification of asphalt binder with Nano materials and evaluated its impact on asphalt concrete through the testing of mechanical properties. It was stated that Nano additives had improved slightly Marshall stability while decreased the asphalt binder percentages after Nano modification. The influence of digestion of asphalt binder with Nano material and its impact on the rheological properties of the binder was investigated by Sarsam,2023 [2]. Modified binders were tested for the rheological properties. It was noticed that the viscosity increased while the penetration- viscosity number declined after modification. It was concluded that modification with Nano additives exhibits lower temperature susceptibility as compared with the control binder. The modification of asphalt binder with various percentages of coal fly ash was addressed by Sarsam and AL-Azzawi, 2013, [3]. It was reported that such modification exhibits poor wetting, poor adhesiveness, and the behavior of the modified binder changes from hydrophilic to hydrophobic. One of the most common techniques for enhancing the strength properties and performance of asphalt concrete in a cold environment is the implementation of modified asphalt binder as stated by Celauro et al.,2012 [4]. Cheng et al., 2023 [5] implemented the multiple stress creep recovery test to assess the rheological property of asphalt cement binder under freeze-thaw cycles. The results indicated that the recovery of asphalt cement binder increased as freeze-thaw cycle increased, while the non-recoverable creep of asphalt binder declined. The low-temperature creep stiffness of asphalt binder increased as the freeze-thaw cycle increased. Zhao and Yang,2023 [6] addressed that implementation of by-product and industrial solid waste such as fly ash, and other materials with pozzolanic reaction, such as SiO_2, hydrated lime, carbonates, blast furnace slag, and steel slag, for modification of asphalt binder are globally accepted in the construction of green pavement. Huang et al., 2023 [7] assessed the rheological behavior of a modified asphalt binder using low-temperature creep stiffness test. The unrecoverable creep compliance and the creep recovery rate were calculated and measured, while the creep stiffness and speed are used as technical indexes. It was concluded that the implication of modifiers into asphalt binder reduces the unrecoverable creep and increases the creep recovery rate of the asphalt binder. Zeiada et al., 2024 [8] predicted the m-value and flexural creep stiffness of asphalt binder with the aid of the Frequency sweep tests at temperatures of 0 °C. It was addressed that the evaluation of the ability of asphalt cement binder to relieve the thermal stress accumulated due to a drop in temperature depends on predicted values of (s and m) (60). Büchner et al., 2022 [9] stated that creep deformation of asphalt cement binder could be evaluated through cyclic or static compression tests at freezing temperature. However, Creep tests can be conducted with the aid of a bending beam rheometer or dynamic Shear Rheometer. Conventional and modified asphalt cement binders were tested while their creep properties were correlated. It was stated that the additive has a significant positive influence on the creep property of the asphalt mixture. Fusco et al.,2020 [10] reviewed of the most popular Nano additives for implication into asphalt concrete mixtures. The physical properties of the modified mixture with additives were assessed. It was revealed that the resistance of the modified mixture to permanent deformation was improved due to the increment in the viscosity of the binder after modification. It was concluded that the Nano additives can increase the service life of the flexible pavement due to

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various chemical-physical mechanisms which can control fatigue resistance. Wu et al.,2021 [11] reviewed existing work on binder-filler interaction mechanisms. It was revealed that such interaction is physicochemical which can be explained by the rheological theory for evaluation. The main factors that influence the binder-filler interaction are the physical properties and the chemical composition of filler and asphalt binder. Wang, 2023 [12] assessed the interface models of three additives and asphalt binder through molecular dynamic simulation process. The impact of temperature variation on the strength was studied based on service temperature of asphalt concrete pavement. It was concluded that due to the increment of temperature, the polar components of asphalt moved toward the surface of Al2O3 and CaO crystals while the non-polar components moved away from their surface, particularly saturate molecules. Wang et al.,2022 [13] stated that to select a proper binder for pavement design, the rheology of asphalt cement binder is an important consideration which is related to its microstructure and chemical composition. The chemical functionality of the asphalt cement binder was described and the behavior of asphalt cement binder in terms of molecular interactions was explained. It was revealed that asphalt cement binder mainly comprises carbon (80–88) %, nitrogen (0–2) %, hydrogen (8–12) %, and few heteroatoms including sulfur (0–9) %, oxygen (0–2) %, and traces of nickel vanadium as well as manganese. Li et al., 2017, [14] stated that nano additives provide specific characteristics due to their small particle size and large surface area as compared with the common filler material applied in the preparation of asphalt concrete mixture. The Rheological properties test was employed to evaluate the performances of the modified asphalts binder. It was concluded that the addition of Nano material additives could dramatically enhance the physical properties of asphalt material such as visco-elasticity, the resistance to aging, and performance at high temperature. Azarhoosh, et al. 2019 [15] implicated Nano zinc oxide as an additive in the asphalt concrete mixture and assessed its influence on the cracking due to fatigue. It was revealed that the cohesive and adhesive bonds between the aggregates and the asphalt binder was evaluated with the aid of surface free energy concept. The test results declared that the implication of Nano Zink oxide showed an increment of the basic component of the binder which controls the adhesion between the binder and aggregate and decline in the acid component of surface free energy. Hamedi and Esmaeili, 2019 [16] assessed the impact of implicating Nano iron oxide and Nano aluminum oxide on the resistance to moisture damage of asphalt concrete mixtures. It was found that implementation of such Nano materials was able to enhance the adhesive forces between the binder and aggregates by lowering the acidic property of the treated asphalt binder and increasing the basic properties. A recent investigation by Farag et al., 2014, [17] revealed that the addition of lime to asphalt cement binder can exhibit a decline of the penetration value, which is directly related to its resistance to deformation at high temperature, and an increase in the softening point and the resilience modulus value as compared with that of the control binder. Sarsam, 2016 [18] investigated the impact of Nano additive (silica fumes) on the energy dissipation of asphalt concrete mixture through the fatigue process. It was revealed that the Nano material in asphalt binder shows lower energy dissipation at variable micro strain levels. It was concluded that the implication of Silica fumes into the asphalt binder exhibited shorter fatigue life and minimal influence on energy dissipation. Kommidi and Kim, 2021,[19] reported that transverse cracks formation in asphalt concrete pavement become visible when the thermal stress which was generated in the restrained asphalt pavement under cold environment exceeds the tensile strength of the asphalt cement binder. It was revealed that improvement of stress relaxation ability and the tensile strength of asphalt cement binder is recommended by implication of additives to reduce the risk of thermal cracking in asphalt pavements. Hischke, 2019,[20] stated that the creep behavior of asphalt concrete can influence the formation of rutting in the pavement structures. The creep and recovery behavior of asphalt binder can be modelled using different rheological and mathematical models. Various viscoelastic and visco-plastic characteristics could be considered in the models mostly for modified binders. Shafabakhshet al., 2020, [21] stated that the modification of asphalt binder with Nano silica can increase elastic modulus, reduced ductility, increased softening point and viscosity. The impact of the implication of Nano silica into the asphalt concrete mixture on the ability to crack in asphalt concrete mixtures was experimentally investigated by Shafabakhsh et al.,2021 [22]. Nahar, 2016 [23] stated that the chemical composition of asphalt binder influences the microstructure properties. The wax component of the binder has been found to induce the phase separation of asphalt materials, while the asphaltene fraction of the binder is responsible for most of the structuring observed. The environmental conditions during construction of the pavement and its variation throughout the service life can also influence the properties of asphalt binder to a great extent. Implementing additives into the binder can improve its performance by making the rate of deterioration slower and may offer fast, efficient, and cost-effective repair methods. Sarsam, 2015, [24] assessed the possibilities of improving physical and mechanical properties of the asphalt binder by digesting asphalt cement binder with fly ash and silica fumes additives. It was revealed that such additives exhibited a positive effect on the asphalt cement by reducing its temperature susceptibility, while it exhibited variable impact on the viscosity of the binder. Silica fumes increased the viscosity and softening point significantly. Tarefder et al., 2018, [25] studied the effect of freeze-thaw cycles on asphalt cement binder samples in the laboratory using the bending beam rheometer. It was reported that the freeze-thaw cycles can damage the binder's structure, which can be noticed in the decline of the stiffness with increasing the freeze-thaw cycles. Sun et al., 2016 [26] reported that previous investigations on creep issue of asphalt cement binder provide satisfactory predictions of the m-value and flexural creep stiffness. Lu et al., 2017, [27] reported that thermal cracking of asphalt concrete is considered as a major mode of failure of asphalt pavement particularly in cold environment regions. The rheology of asphalt cement binder at low temperature has been found to be the major factor influencing the thermal cracking of asphalt pavements. Sayadi and Hesami, 2017, [28] reported that after practicing the process of freeze-thaw cycles, the asphalt cement binder becomes hard. However, the implication of additive can influence the fatigue property and the self-healing capability and of the treated asphalt binder with additives after practicing the freeze-thaw cycles. It was revealed that the asphalt additive-binder interaction is responsible to influence the rheological property. It was concluded that the asphalt additive-binder interaction may be evaluated effectively by the interaction indexes. Lotfi-Eghlim and Karimi,2016, [29] evaluated the main benefits of implementation of Nano materials for modification of the asphalt concrete mixtures. It was reported that the Nano material was able to improve the dynamic characteristics of the asphalt concrete, and the fatigue life is significantly extended as compared with control asphalt mixture. Abedali et al., 2020, [30] developed an apparatus for simulating the behavior of asphalt binder in the asphalt concrete mixture by measuring the deformation values at different testing temperatures and measuring the flexural-creep stiffness properties of asphalt binder.

The aim of the present assessment is to verify the influence of Nano and Micro additives (silica fumes, fumed silica, coal fly ash, and hydrated lime) on the flexural creep stiffness of two penetration grades of asphalt cement binder with (60-70, and 40-50). The bending beam rheometer (BBR) test will be implemented to measure the flexural creep stiffness of the prepared green asphalt cement binder.

2. Materials and Methods

Two types of Nano additives have been implemented in the present investigation using different percentages for modification of asphalt cement binder and preparation of the green asphalt binder, Silica fumes and fumed silica. Such additives represent industrial waste which can have beneficial effect by its possible physical and chemical reactions with asphalt cement binder. However, two types of Micro additives with different percentages were used for preparation of the green binder, coal fly ash and hydrated lime. The physical properties of each additive are mentioned as below, while Table 1 demonstrates the important chemical composition of the implemented additives.

2.1. Silica fumes

Silica fumes are an ultra-fine powder, gray colored. The specific surface area of silica fumes is 200000 m2/kg. It is considered to have a Nano size. It was obtained from the local market. Details of chemical composition and physical properties of the silica fumes can be obtained from Sarsam, 2023, [2].

2.2. Fumed silica

Fumed silica is supplied as a fluffy, white powder. It has a specific surface area of 100000 m2/kg and is considered to have a Nano size. The physical properties of fumed silica can be obtained from Sarsam,2023, [2].

2.3. Hydrated lime

Hydrated lime is a derivative of burnt lime, it is light and fluffy with a chemical formula of Ca (OH)2 and has a 4404 m^2/kg specific surface area. This material was obtained from the local market and the portion used is 75-micron maximum size. Its physical properties and chemical compositions can be obtained from Sarsam, 2023, [2].

2.4. Coal fly ash

The coal fly ash of class F is obtained as a by-product of coal combustion from local market, this fly ash has specific surface area of 600 m^2/Kg. The portion used is 75-micron maximum size. The chemical components of fly ash can be obtained from Sarsam, 2023, [2]. Figure 1 demonstrates Nano additives while Figure 2 exhibits Micro additives.

Figure.1 The Implemented Nano Additives

Figure.2 The Implemented Micro Additives

Table 1. Chemical Components of Nano size additives

Oxide type	Percentage			
	Fumed silica	Silica fumes	Coal fly ash	lime
SiO_2	99.1	90	0.74	61.9
Fe_2O_3	35.0 ppm	1.0	0.19	2.67
Al_2O_3	< 0.035	3.0	0.5	28.8
CaO	0.03	1.2	64.2	0.88
MgO	52.0 ppm	< 6%	1.17	0.34
Loss on ignition	0.7	1.0	29.9	0.86

2.5. Asphalt cement binder

Asphalt cement binder of two penetration grades of (60-70) and (40-50) were obtained from Durah oil refinery, south of Baghdad. Such types of binder are usually implemented in asphalt paving work in Iraq. Table 2 presents the physical properties of asphalt binders, and Table 3 exhibits the rheological properties of the tested asphalt binders.

Table 2. Physical Properties of Asphalt Cement Binders

Property	ASTM, 2016, [31] specification	Asphalt cement (40-50) Test results	Asphalt cement (60-70) Test results
Penetration at 25˚C,100gm, 5sec, (0.1mm)	D-5	44	66
Softening Point, ˚C	D-36	50	48
Ductility at 25 ˚C, 5cm/min, (Cm)	D-113	+100	+100
Resilience (ball strain recovery) %	D-5329	98	99
Specific gravity	D-70	1.042	1.030
After thin film oven test			
Penetration at 25°C,100gm,5sec, (0.1mm)	D-5	33	51
Loss in weight	D-1754	0.17	0.24
Ductility at 25 °C, 5cm/min, (Cm)	D-113	73	90
Softening Point, ˚C	D-36	54	51

Table 3. Rheological Properties of Asphalt Cement Binders

Asphalt cement type	Penetration grade (40-50)	Penetration grade (60-70)
Penetration-index (PI)	-1.474	-1.370
Penetration viscosity number (PVN)	6.09	6.204
Temperature of equivalent stiffness (TES)	-22	-25
Viscosity (poises)	3690	2123

2.6. Preparation of green asphalt cement binder

The green asphalt binders were prepared in the laboratory by implementing the wet process. In the wet process, asphalt cement of each type was heated to 150°C and then the fumed silica, hydrated lime, coal fly ash, or silica fumes were added in powder form using various percentages of each additive. The mixture was blended in a mixer at a blending speed of about 1300 rpm and the mixing temperature of 160°C was maintained for 20 minutes to promote the chemical and physical bonding of the components. The range of treatment with micro additives was (5-20) % with a 3 % increment. However, the range of treatment with Nano additives was (1-4) % with a 1 % increment. Details of the preparation process can be referred to Sarsam, 2016, [18]. The optimum additives content was selected based on the significant change in the physical and rheological properties of the prepared green binder specimens. Details of mixing and obtaining optimum additives can be found in Sarsam and Lafta, 2014 [32]; Sarsam, 2013, [33]. The summary of the optimum additives content is shown in Table 4.

Table 4. Optimum Additives Content

Fumed silica	Silica fumes	Hydrated lime	Coal fly ash
3 %	2 %	10 %	5 %

2.7. Testing of green asphalt cement binder

The viscoelastic behavior of asphalt cement and the green asphalt binder was characterized through the creep test with the Bending Beam Rheometer. In this test, flexural stresses are applied instantaneously to the prepared asphalt cement binder specimen and maintained constantly for the entire duration of the test. The prepared asphalt binder samples were subjected to the creep stiffness determination with the aid of bending beam rheometer apparatus as per the testing procedure recommended by AASHTO, 2016 [34]. Figure 3 exhibits the bending beam rheometer test apparatus. Specimens were tested in triplicate for each case, and the average value of the flexural creep stiffness was considered in the analysis. The accepted standard deviation was 5 % for the accepted testing results for such a limited testing program.

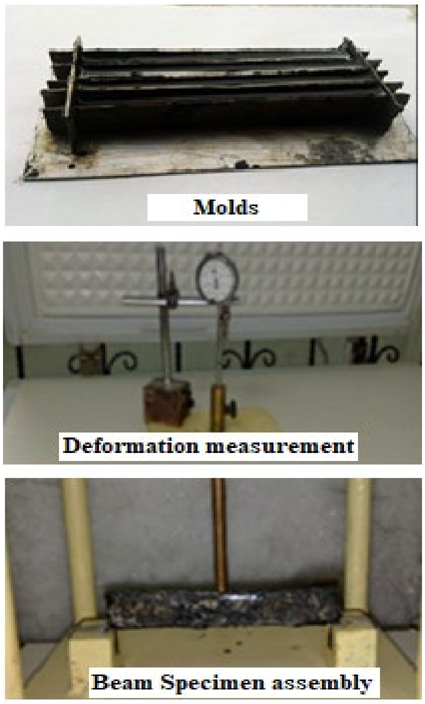

Figure 3. Bending beam rheometer (BBR) test apparatus

3. Test Results and Discussions

3.1. Creep Stiffness of conventional binder

Based on the chemical composition, Asphalt cement binders can be divided into two major fractions: maltenes and asphaltenes and as reported by Farhan et al., 2021 [35]. The maltenes consist of aromatics, saturates, and resins, while the asphaltenes fraction controls the physical characteristics of the binder. High asphaltene content exhibits more sticky and stiffer asphalt binder. Based on the percentages of the four fractions, Saturates, Aromatics, Resins, and Asphaltene (SARA), asphalt cement is divided into gel and a sol type as stated by Siroma et al., 2023 [36]. In the gel type, the resin and aromatic fractions are not presented in adequate amounts to peptize the micelles, or have not sufficient solvating power, whereas the asphaltenes associate and form irregular structures. The sol type has an adequate quantity of resins and aromatics of sufficient solvating power, while the asphaltenes are completely peptized and the subsequent micelles have free movements inside the asphalt cement. However, as presented in Figure 4. Sol type asphalt cement binder is more ductile and less elastic than the gel type. Most asphalt cements have intermediate character between sol and gel types as revealed by Lesueur et al.,2021 [37].

The assessed conventional Asphalt cement binder’s composition can be divided into four parts as demonstrated in Table 5. It shows that the asphaltene ratio represents (8,7 and 19) % of the overall asphalt composition for (60-70, and 40-50) grade binders respectively. Gastel index is defined as the dispersing capability of maltene to asphaltene and noted as the peptizing power, the growth of the Gastel index leads to decline in colloidal stability.

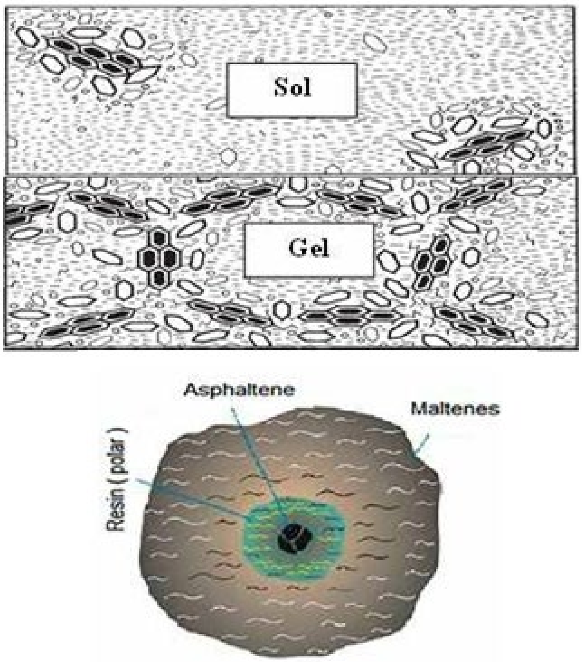

Figure 4. Variation between sol and gel types of asphalt binder, Lesueur et al., 2021 [37]

Table 5. Major chemical composition SARA of Durah (40-50) asphalt binder, as per Saad and Ahmed,2018 [41]; Al Jafari and Ismael,2020 [42]

SARA Fractions	Content (%) by weight	
	Penetration grade 40-50	Penetration grade 60-70
Saturates	19.53	6.5
Aromatics	26.8	58.5
Resins	29.47	26.4
Asphaltenes	19.0	8.7
Gastel index	0.684	0.179
Aromatic/asphaltenes	1.41	6.72

The decline in Gastel index indicates a growing of sol character of the asphalt cement. Oyekunle, 2006 [38] demonstrated that such an index is implemented in addition to (SARA) in distinguishing the variation in asphalt binder behavior based on the chemical composition. Another indicator of asphalt binder behavior is the ratio of aromatic to asphaltene, which exhibits an assessment of the solvation capacity of the asphalt cement. The lower ratio indicates fewer peptized asphaltenes, and results in increasing the gel character and the softening point of the asphalt cement as reported by Weigel and Stephan, 2017 [39]. Hermadi, and Pravianto, 2019 [40] revealed that the rise of saturates lead to the decline in the rheological properties of the asphalt cement binder, and the asphalt exhibit viscous, less elastic, more resistant to fatigue cracking, and to plastic failure. It can be noticed that the chemical composition of the asphalt cement binders is variable among the penetration grade which will have an influence on the rheological and physical properties. Higher asphaltene content cause reduction in penetration, which is a measure of the consistency of asphalt cement and exhibits stiffer structure and higher viscosity and change the physical and rheological properties. It can be stated that the penetration grade (60-70) asphalt cement is of sol type while the penetration grade (40-50) asphalt cement binder is of gel type. Figure 5 exhibits the impact of binder penetration grade on creep stiffness of conventional asphalt cement. Higher creep stiffness is noticed for penetration grade (40-50) binder throughout the testing period when compared with the penetration grade (60-70) binder. This could be attributed to the gel type of penetration grade (40-50) binder when compared to the sol type of penetration grade (60-70) binder. The creep stiffness of penetration grade (60-70) binder is lower than that of penetration grade (40-50) binder by (21.5 and 20) % at the initial point of loading and at failure respectively. However, the decline in creep stiffness throughout the testing period is (21.5 and 20) % for penetration grade (40-50) and (60-70) binders respectively. A similar trend of decline in the creep stiffness is observed through the loading period regardless of the binder penetration grade. Such behavior could be attributed to the higher asphaltenes and saturates and lower aromatics content in the composition of (40-50) binder. Such behavior is further supported by the obtained models. Similar findings were reported by Raufi et al.,2020 [1]; Wang et al.,2022 [13]; Nahar, [23]; and Moon et al.,2014 [43].

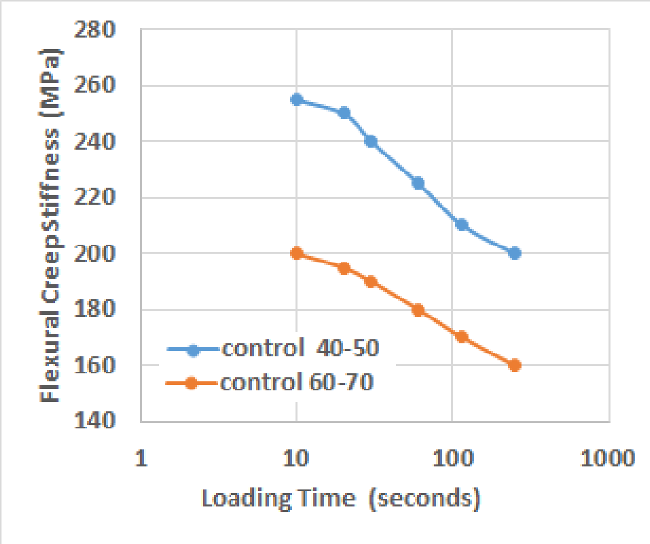

Figure 5. Influence of binder penetration grade on creep stiffness

3.2. Behavior of the green binder with Nano additive in the creep test

Figure 6 exhibits the impact of implicating Nano additives on the creep stiffness of green asphalt binder. Higher flexural creep stiffness is noticed when the asphalt cement was treated with silica fumes as compared with the case of modification with fumed silica. A significant increment in creep stiffness is detected when Nano additives were implicated into the (40-50) penetration grade binder as compared with the control or the (60-70) penetration grade binder. This is attributed to the chemical reaction with the binder ingredient which was possible to change the conventional asphalt binder to a stiffer green binder. The creep stiffness of penetration grade (40-50) green asphalt binder treated with fumed silica is higher than that of penetration grade (40-50) control binder by (17.6 and 25) % at the start point of loading and at failure respectively. When the binder was treated with silica fumes, the creep stiffness of penetration grade (40-50) green asphalt binder treated with silica fumes is higher than that of penetration grade (40-50) control binder by (25.5 and 35) % at the initial point of loading and at failure respectively. However, the creep stiffness of penetration grade (60-70) green asphalt binder treated with fumed silica is higher than that of penetration grade (60-70) control binder by (10 and 12.5) % at the initial point of loading and at failure respectively. When the binder was treated with silica fumes, the creep stiffness of penetration grade (60-70) green asphalt binder treated with silica fumes is higher than that of penetration grade penetration grade (60-70) control binder by (15 and 18.7) % at the initial point of loading and at failure respectively. It can be revealed that a significant variation in the creep stiffness exists between the sol and gel type binders after modification with Nano additives. Such performance agrees well with the reported work by Sarsam,2024 [44]; and Lin et al., 2018 [45].

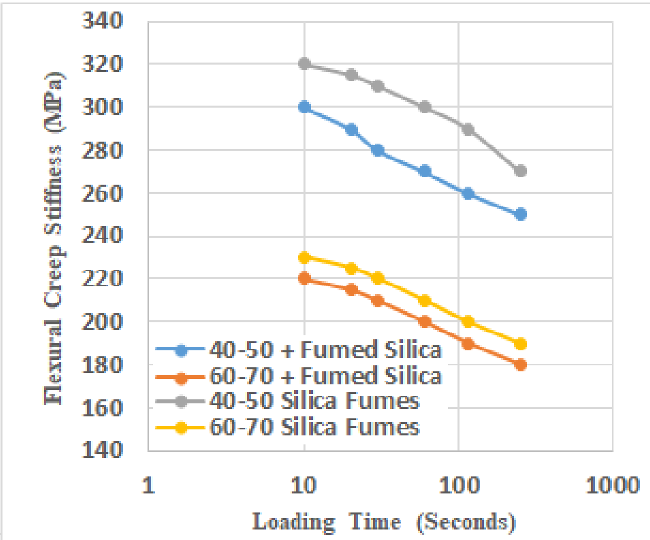

Figure 6. Influence of Nano additives on the creep stiffness of green asphalt binder

3.3. Behavior of the green binder with Micro additive in the creep test

Creep stiffness measures the impact of thermal stresses in the asphalt binder resulting from thermal contraction. If these stresses are significant, cracking will occur. A higher creep stiffness value indicates higher thermal stresses. To determine the stress relaxation properties of an asphalt binder, creep stiffness calculations are made after 8, 15, 30, 60, 120 and 240 seconds of loading with the aid of bending beam rheometer BBR. These loading periods were chosen because they are equally spaced on a logarithmic time scale. For each time, the asphalt binder creep stiffness is calculated and plotted. The creep stiffness measured at 60 seconds should be equal to or less than 300 MPa for regular asphalt binder. As demonstrated in Figure 7, creep stiffness declines with the loading period regardless of the binder or additives type. For penetration grade (40-50) binder type, implications of additives into asphalt binder exhibit an increment in the creep stiffness compared to the control binder. A sharp reduction in the creep stiffness could be noticed after the start of loading, while the rate of reduction changes to gentle after 120 seconds. The creep stiffness increases by (5, and 32.5) % when coal fly ash, and hydrated lime are implemented. For penetration grade (60-70) binder type, implementation of additives also exhibits an increment in the creep stiffness compared to the control binder. A sharp reduction in the creep stiffness could be noticed after the start of loading while the rate of reduction changes to gentle after 120 seconds. The creep stiffness increases by (6.2, and 25) % when coal fly ash, and hydrated lime were implemented. It can be stated that implementation of such additives exhibits higher creep stiffness when compared with the control binder. Similar findings were reported by Sarsam and Lafta, 2014, [32]; Ashish and Singh, 2019, [46].

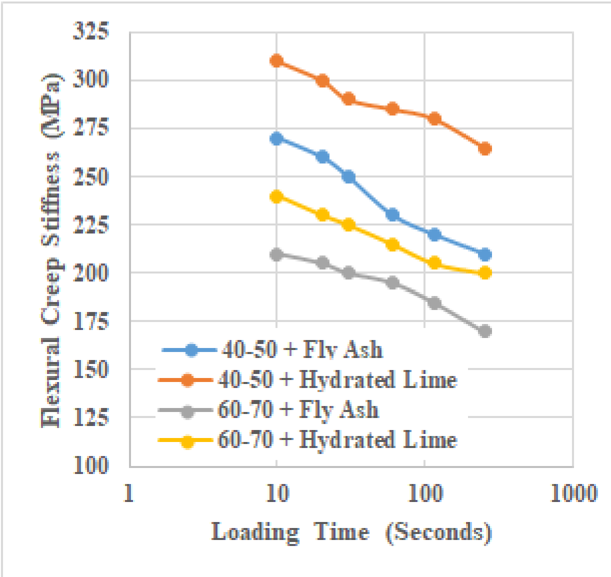

Figure 7. Influence of Micro additives on the creep stiffness of green asphalt binder

4. Conclusions

Based on the limitations of materials and the conducted testing, the following concluding remarks may be addressed.

- The penetration grade (60-70) asphalt cement is of sol type while the penetration grade (40-50) asphalt cement binder is of gel type.
- The creep stiffness of penetration grade (60-70) binder is less than that of penetration grade (40-50) binder by (21.5 and 20) % at the initial point of loading and at failure respectively.
- The creep stiffness of penetration grade (40-50), and (60-70) green asphalt binders treated with fumed silica is higher than that of control binder by (25 and 12.5) % at failure respectively. While the creep stiffness of penetration grade (40-50), and (60-70) green asphalt binders treated with silica fumes is higher than that of control binder by (35 and 17.8) % at failure respectively.
- Nano additives are recommended to control the creep stiffness of green asphalt binder regardless of the sol and gel types of the conventional (60-70) and (40-50) binders.
- For penetration grade (40-50) and (60-70) binders, the creep stiffness increases by (5, and 32.5) % and (6.2, and 25) % when coal fly ash, and hydrated lime were implemented respectively.

Declaration of Conflict of Interests

The author declares that there is no conflict of interest. They have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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