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(Research Article)

Micro and Nano Size Additives for Enhancing the Sustainability of Asphalt Concrete

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Abstract

Asphalt concrete mixture practices loading and environmental impacts which can render the distresses formation. Implication of micro and nano additives to the mixture as partial substitute of the filler can extend the fatigue life of the pavement and control the initiation of distresses. An attempt has been made in this assessment to implement micro and nano additives such as fly ash and fumed silica to enhance the sustainability of asphalt concrete mixture. The influence of such additives on the stiffness, permanent deformation, and dissipated energy was investigated. It was revealed that the modified mixtures with silica fumes and fly ash exhibits higher flexural stiffness of (7500 and 8000) MPa, (2000 and 3000) MPa, and (1600 and 1800) MPa as compared to that of the control mixture under 250, 400, and 750 microstrain levels respectively. Significant loss of energy could be detected at the initial stages of loading. For the control mixture, the flexural stiffness exhibits almost constant stiffness while it increases after 0.00001 MJ/m^3 loss of energy. When the silica fumes additive are implemented, the stiffness increase sharply as the loss of energy reaches 0.0001 MJ/m^3, then increases gently. When the fly ash was introduced, a sharp increase in the flexural stiffness could be observed up to 0.00001 MJ/m^3 loss of energy, and then the increment in the stiffness was almost constant. It was concluded that the micro size additive (fly ash) exhibits superior behavior in supporting the flexural stiffness of asphalt concrete when compared with the Nano size additive (silica fumes).

Keywords: Asphalt concrete, Deformation, Flexural Stiffness, Dissipated energy, Nano size additives, Micro size additives

1. Introduction

Adding Nanotechnology assessment is the control of material particles on an atomic and molecular scale, it usually deals with the structure of the size 100 nm or smaller and involves developing new material combination within that size as stated by Buzea et al., [1]. Yanga and Tigheb, [2] revealed that adding nano particles like nano tubes, nano-silica, nano-clay in asphalts can normally improves the rutting and fatigue resistance of asphalt mixtures. The physical properties and chemical behavior of nano-sized particles differ from those of conventional materials due to the increased surface area-to-volume ratio of nano-sized particles, and because of the quantum effects resulting from spatial confinement as stated by Jochen et al., [3]. Raufi et al., [4] investigated the influence of implementing three different types of nano materials, including Zyco Therm, nano-Bentonite, and nano-$CaCO_3$ on modification of the properties of asphalt concrete.

Two design methods including modified Lottman test and Marshall design method have been implemented on laboratory prepared specimens to verify the impact of nano modification. It was revealed that nano materials can decrease the binder content, and the Marshall stability was slightly improved with nano modification. Fuscoet al., [5] presented a comparative review of the most used nano-additives for asphalt concrete mixtures; nano-silica, nano-clay, nano-calcium oxide. The mechanical behavior of the additive modified mixture was evaluated. A potential improvement of resistance to permanent deformation and rutting was achieved due to the improvement in the viscosity after implication of nano additives. It was reported that the nano particles can prolong the service life of asphalt concrete mixture by means of various interdependent chemical–physical mechanisms that can influence the resistance to fatigue failure. According to Steyn, [6], several studies have been carried out on the capability of nano-sized particles to improve rheological characteristics of asphalt binder. However, limited work has focused on the effects on fatigue life to enhance the mechanical characteristics and healing properties of asphalt concrete. Khattak et al. [7] revealed that carbon nano fibers could enhance the fatigue resistance of asphalt concrete by means of pull-out mechanisms and crack bridging. In another study conducted by Azarhoosh, et al. [8], the impact of two types of Nanomaterial (nano- TiO_2 and nano-ZnO) on fatigue behavior of asphalt concrete mixture was assessed. The test results

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indicated that Nano materials modified asphalt exhibit better resistance to fatigue failure due to improved adhesion and cohesion in the asphalt binder systems. Hamedi and Esmaeili, [9] assessed the influence of two nano anti-stripping additives (nano iron oxide and nano aluminum oxide) on the moisture susceptibility of hot mix asphalt mixtures. The test results revealed that the implication of nano materials had improved the adhesive force between aggregates and asphalt binders by reducing the acidic and increasing the basic properties of the modified asphalt binder. The influence of three types of Nano materials on resistance to moisture damage in terms of stripping potential of asphalt concrete was assessed by Sarsam and AL-Azzawi, [10]. Test results indicated positive impact of nano additives on the resistance to moisture distress. The impact of implementing various percentages of nano zinc oxide on the fatigue cracking of asphalt mixtures have been evaluated by Azarhoosh, et al. [11]. It was revealed that the mechanism that affects the cohesion and the adhesive bond between aggregate and binder were determined using the surface free energy method. The test results showed that implementation of nano Zink oxide leads to decrease the acid component of surface free energy and increase of the basic component of the binder which enhances the adhesion between the aggregate and binder. Lotfi-Eghlim and Karimi, [12] focused on the potential benefits of nano particles for modification of asphalt concrete mixtures. It was reported that Nano Al_2O_3 can improve the dynamic characteristics of hot mix asphalt. The test results show that fatigue life of nano-modified asphalt mixtures is significantly increased as compared with conventional mix. A new model was presented for prediction the fatigue behavior of asphalt mixtures modified with nano Al_2O_3. Such model can characterize the fatigue performance of modified asphalt concrete under dynamic loading conditions. Ghaffarpour et al. [13] carried out comparative mechanical tests on asphalt mixtures containing unmodified and nano-clay modified binder. Results showed that nano-clay could improve the stability, resilient modulus, and indirect tensile strength of asphalt concrete. Sarsam, [14] investigated the influence of Nano additives (coal fly ash and silica fumes) on the dissipated energy through the fatigue resistance process in asphalt pavement. It was concluded that implementation of Nano material exhibit lowering of the dissipated energy at various micro strain levels. However, the increase in micro strain level leads into a remarkable reduction in the fatigue life of asphalt concrete and increases the dissipated energy value. Silica fumes exhibits minor impact on the dissipated energy during fatigue as compared to coal fly ash, while it shows lower fatigue life. Yao and You, [15] investigated the use of micro and nano materials (carbon microfiber, Nanomer material, nano silica, non modified nano clay) to modify and evaluate the asphalt concrete mixture. Test results indicate that the dynamic modulus of micro- and nano modified asphalt concrete had improved significantly, while the rutting susceptibility was reduced. The impact of Nano-SiO_2 on the cracking incidence in the asphalt concrete mixtures was investigated through laboratory experiment by Shafabakhsh et al., [16]. The semicircular bending test was implemented for assessing the influence of Nano-SiO_2 on initiating angular and vertical cracks in asphalt at different temperatures. Results show that the all of the tested specimens that exhibited both angular and vertical cracks are significantly improved by the addition of 1.2% of Nano-SiO_2 regardless of all of the testing temperatures. The stiffness of asphalt concrete decreases throughout the crack developing process in pavements as it was addressed by Wu et al., [17]. Generally, the (stiffness versus loading cycle) plot of an asphalt concrete during fatigue testing exhibits three regimes of evolution, as shown in Figure 1. In Phase I, rapid decreases in stiffness can be observed. Phase II corresponds to a linear decrease in stiffness. However, in Phase III, fracture cracking occurs due to the damage acceleration of micro cracks which turn to macro cracks and cause the failure of the specimen.

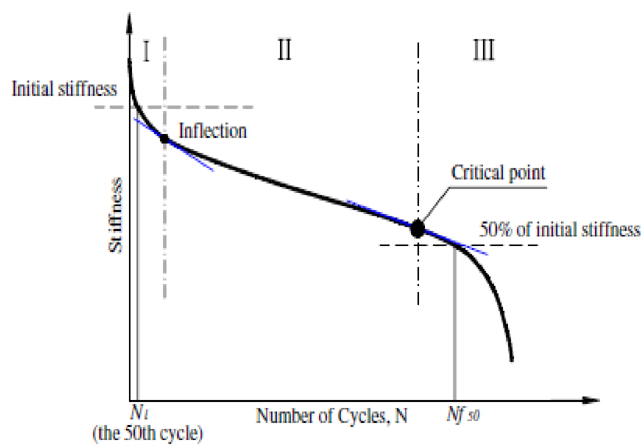

Figure 1. Typical stiffness-load cycles in fatigue test, Wu et al., [17]

The aim of this present assessment is to figure the influence of nano and micro size additives (silica fumes and coal fly ash) on the sustainability of asphalt concrete in terms of flexural stiffness, dissipated energy, permanent microstrain, and phase angle. Roller compacted beam specimens of asphalt concrete will be tested under repeated flexural stresses with the aid of Nottingham four point bending beam chamber. The influence of the additives will be evaluated and compared. The fatigue life of an asphalt concrete is defined in this study as the number of loading cycles when the stiffness decreases to 50% of its initial value measured at the 50th load cycle.

2. The Implemented Materials and the Testing Methods

The implemented materials in this are currently used for asphalt pavement construction in Iraq while they are locally available.

2.1 Asphalt cement: Asphalt cement binder having a penetration of 42 was implemented in this work. It is provided by AL-Nasiriya oil Refinery; the softening point is 49˚C, while the ductility is 136 cm. more details of the physical properties of the binder could be found at Sarsam, [14].

2.2 Micro and Nano size additives: In this investigation, two types of additives were implemented in different percentages as partial substitute of filler, Fly ash which have a micro size and Silica fumes which has a Nano size.

2.3 Fly ash: The coal fly ash, with class F which was prepared as a by-product of coal combustion, was obtained from local market, the specific gravity of fly ash is 2.016 while the specific area is 600 m^2 /kg which are considered to have a micro size. Detailed physical properties and chemical composition of the fly ash may be referred to Sarsam, [14].

2.4 Silica fumes: The implemented densified silica fumes exhibits an ultra-fine powder of very fine spherical particles having a high content of amorphous silicon dioxide and gray color. The specific surface area is 200000m^2/kg, while the specific gravity is 2.134. Silica fumes have a Nano size. Details of the physical properties and chemical composition of the silica fumes may be referred to Sarsam, [14]. Figure 3 exhibit the Silica Fumes.

Figure 2. The implemented nano and micro size additives

2.5 Coarse and fine aggregate: The implemented coarse aggregates are crushed and retained on sieve No.4. The aggregates were obtained from AL-Ukhaydir quarry. A mixture of natural and crushed sand passing sieve No.4 and retained on sieve No.200 was implemented as fine aggregates. The abrasion resistance of coarse aggregates is 18 % while the bulk specific gravity of coarse and fine aggregates was 2.542 and 2.558 respectively. The details of the physical properties of both aggregates type may be referred to Sarsam, [14].

2.6 Mineral filler: The limestone dust was implemented as mineral filler, it was obtained from lime plant at Karbala. The bulk specific gravity of the filler is 2.617, while 94 % of the filler is finer than 0.075 mm size.

2.7 Selection of combined aggregate gradation: The selected combined aggregation gradation follows SCRB, [19] for wearing course asphalt concrete. It has 12.5 (mm) nominal maximum size. Figure 3 exhibits the selected aggregate gradation.

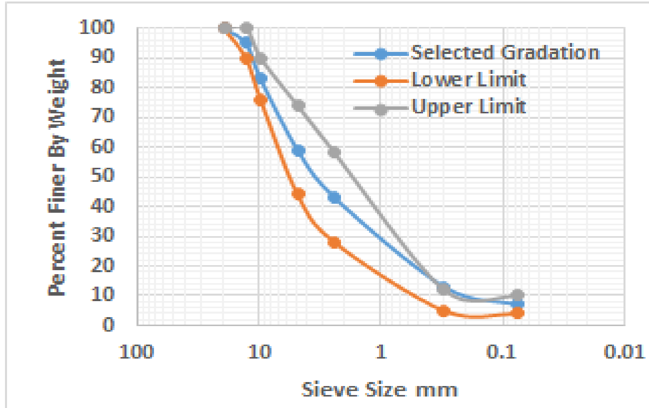

Figure 3. Selected gradation of aggregates

2.8 Preparation of reference asphalt concrete mixture: The fine and coarse aggregates were washed thoroughly to remove any type of the deleterious materials, then dried to constant weight at 110ºC, and separated to different sizes by sieving. Aggregates were combined with the mineral filler to meet the specified gradation of wearing course layer. The asphalt cement was heated to a temperature of (150ºC) while the combined aggregates mixture was heated to a temperature of (160ºC) before mixing with asphalt cement. Then, the predetermined amount of asphalt cement was added to the heated aggregates and mixed thoroughly by hand using a spatula for two minutes until a homogenous mixture was obtained and all aggregate particles were coated with thin film of the asphalt cement binder.

2.9 Preparation of modified asphalt concrete mixture: The first type of modified asphalt concrete mixture was prepared by heating the Asphalt cement to a 150 °C, and the Silica Fumes modifier was added gradually and blended. Different percentages (1, 2 and 3%) by weight of asphalt cement were tried and the optimum percentage of 2% was implemented based on the changes in the rheological and physical properties of the asphalt cement binder. The blending speed of 1300 rpm, at elevated temperature of 170°C for 20 minutes was adopted to promote the possible physical and chemical bonding of the components. On the other hand, the second type of modified asphalt concrete mixture was prepared by the addition of Fly Ash to the aggregate mixture as partial replacement of filler. Four percentage of Fly Ash were implemented, (0, 2, 4, 6) %. The optimum percentage of fly ash of 4% was implemented based on the workability and changes in bulk specific gravity. Details of the mixing and testing procedures and choice of optimum asphalt content of 4.9 % could be found at Sarsam, [20].

2.10 Preparation of asphalt concrete slab samples and obtaining beam specimens: The asphalt concrete mixtures were subjected to roller compaction as per EN12697-33, [21] to achieve the target bulk density for 4.9 % asphalt content. A slab of (300 mm x 400 mm x 60 mm) size was prepared using the control mixture of asphalt concrete and the modified asphalt concrete mixtures. The static load applied was 5 kN. The compacted slab was left to cool overnight, and then beam specimens of 50 mm x60 mm x 400 mm were obtained from the slab using Diamond-cutter according to ASTM, [18]. Six slab samples were prepared while 36 beam specimens were obtained. The prepared beams the control mixture prepared without additives and the modified asphalt concrete prepared using each of the micro and Nano size additives.

2.11 Testing of beams for repeated flexural fatigue stresses: The Flexural Fatigue Beam Test procedure as per AASHTO T 321, [22] was implemented to determine the Fatigue Life of Asphalt concrete Subjected to Repeated Flexural Bending. The fatigue life of asphalt concrete mixtures was evaluated at three constant strain level of 750µƐ, 400µƐ, and 250µƐ; a testing temperature of 20°C, and a frequency level of 5 Hz. Figure 4 demonstrates the four points bending beam test. Such load assembly produces a constant bending moment over the central portion of the beam and applies flexural stresses on the beam specimen. Test results were recorded and monitored at the selected load cycle intervals and the test was terminated when the beam exhibits 50 percent reduction in its flexural stiffness. The main test variables, namely flexural stress, permanent strain, phase angle and dissipated energy, have been determined and recorded automatically by the testing apparatus.

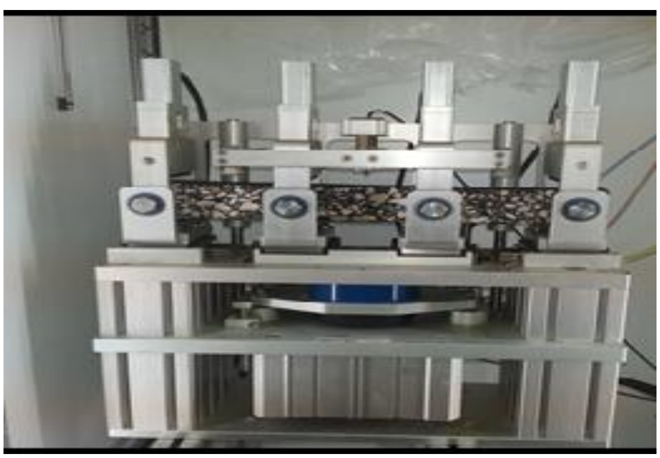

Figure 4. Four points bending beam test

3. Results and Discussions

3.1 Influence of additives on flexural stiffness of asphalt concrete: As demonstrated in Figure 5, the flexural stiffness declines as the loading repetitions proceeds under 250 constant microstrain. Similar behavior was reported by Shen and Carpenter, 2007.When the micro size additive (fly ash) was implicated, significant improvement in the flexural stiffness could be observed.

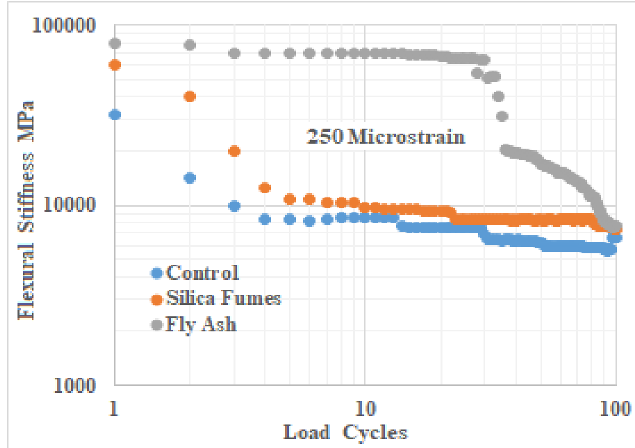

Figure 5. Initial flexural stiffness under 250 constant microstrain level

However, the stiffness declines dramatically after 30 load repetitions. On the other hand, when the Nano size additive (silica fumes) was introduced into the asphalt concrete mixture, it also exhibits higher flexural stiffness as compared with the control mixture and it declines as the loading proceeds. At the start of loading, the control mixture exhibits a flexural stiffness of 32000 MPa while the silica fumes and the fly ash treated mixtures exhibits a flexural stiffness of (70000 and 81000) MPa respectively. After 100 loading repetitions, the modified mixtures with silica fumes and fly ash exhibits higher flexural stiffness of (7500 and 8000) MPa as compared with 6000 MPa of the control mixture. Such behavior may be attributed to the stiffening of asphalt concrete after implementation of additives. Such stiffening could be attributed to the possible chemical reaction occurred between the components of the asphalt binder and the silica fumes and the physical reaction between the binder and the fly ash.

Figure 6 demonstrates the impact of additives on the variation in flexural stiffness under 400 constant microstrain level. It can be noticed that the flexural stiffness under 400 microstrain is lower than that under 250 microstrain. At the start of loading, the control mixture exhibits a flexural stiffness of 9000 MPa while the silica fumes and the fly ash treated mixtures exhibits a flexural stiffness of (10000 and 70000) MPa respectively. After 100 loading repetitions, the modified mixtures with silica fumes and fly ash exhibits higher flexural stiffness of (2000 and 3000) MPa as compared to 1800 MPa of the control mixture. Raufi et al., [4] addressed similar findings.

Figure 7 demonstrates the impact of additives on the variation in flexural stiffness under 750 constant microstrain level. It can be noticed that the flexural stiffness under 750 microstrain is lower than that under 250 or 400 microstrain. At the start of loading, the control mixture exhibits a flexural stiffness of 4000 MPa while the silica fumes and the fly ash treated mixtures exhibits a flexural stiffness of (7000 and 50000) MPa respectively. After 100 loading repetitions, the modified mixtures with silica fumes and fly ash exhibits higher flexural stiffness of (1600 and 1800) MPa as compared to 1400 MPa of the control mixture.

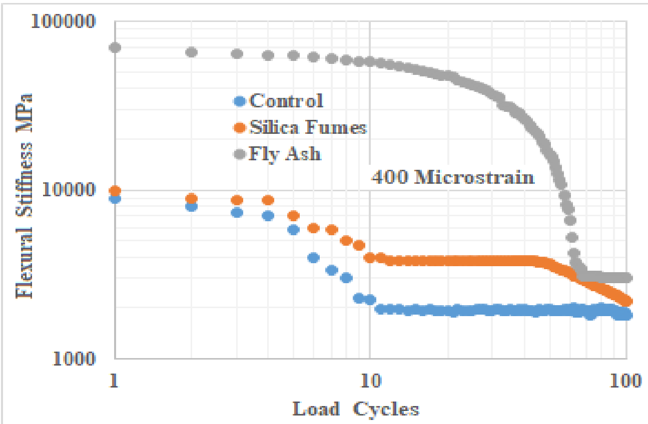

Figure 6. Initial flexural stiffness under 400 constant microstrain level

It can be revealed that implication of micro and Nano additives (fly ash and silica fumes) into the asphalt concrete mixture had exhibited an increment in the initial flexural stiffness of (119, 153) %, (11.1, 677) %, (75, 1150) % for mixtures practicing (250, 400, and 750) microstrain levels respectively. On the other hand, after 100 repetitions of flexural stresses, the flexural strength of asphalt concrete mixtures after implication of micro and Nano additives (fly ash and silica fumes) increases by (25, 33.3) %, (11.1, 66.6) %, (14.2, 28.5) % for mixtures practicing (250, 400, and 750) microstrain levels respectively.

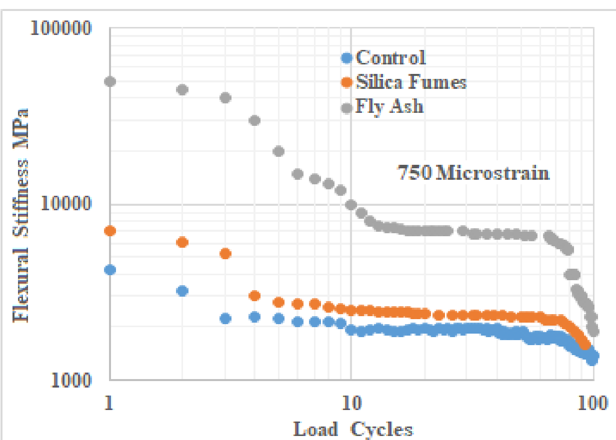

Figure 7. Initial flexural stiffness under 750 constant microstrain level

It can be stated that implication of the micro size additive (fly ash) exhibits superior behavior in supporting the flexural stiffness of asphalt concrete when compared to the Nano size additive (silica fumes). This may be attributed to the ability of fly ash to fill more voids between the aggregates structure and shows effective modification by physical reaction rather than the expected chemical reaction made by silica fumes and the asphalt binder. Such behavior agrees with the work reported by Fusco et al., [5].

3.2 Influence of additives on energy dissipation and phase angle: Dissipated energy is a sound measure of the lost energy through the mechanical work. It is considered as a proper engineering parameter, and representative of the internal damage developed within the asphalt concrete mixture during repeated flexural stresses loading. Figure 8 demonstrates the stiffness-dissipated energy relationship under 400 constant microstrain. The flexural stiffness of asphalt concrete is directly proportional to the cumulative dissipated energy. Significant loss of energy could be detected at the initial stages of loading, however, after 0.00001 MJ/m^{3}of energy losses, the rate decreases indicating the start of distress in the asphalt concrete. For the control mixture, the flexural stiffness exhibits almost a straight-line indicating constant stiffness while it increases after 0.00001 MJ/m^3 loss of energy. When the Nano size additive (silica fumes) was implemented in the mixture, the stiffness increases sharply as the loss of energy reaches 0.0001 MJ/m^3 then the rate of increases changes to gentle. When the micro size additive (fly ash) was introduced as partial substitute of the filler, a sharp increase in the flexural stiffness could be observed up to 0.00001 MJ/m^3 loss of energy, and then the increment in the stiffness was almost constant. Similar behavior was reported by Shen and Carpenter, [23].

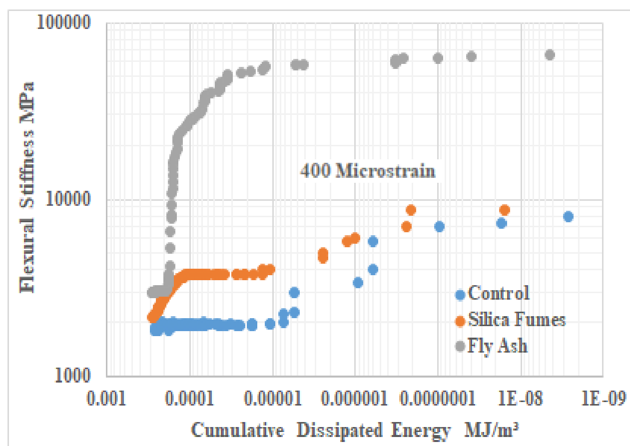

Figure 8. Stiffness-dissipated energy relationships

Figure 9 exhibit the permanent microstrain-cumulative dissipated energy relationship under constant 400 microstrains. A constant dissipated energy can be noticed at the initial loading causing almost constant permanent microstrain as indicated by the straight-line portion of the relationship up to 0.00001 MJ/m^3. However, as the dissipated energy vanishes, the permanent microstrain declines regardless of the micro or Nano additives implemented. Such behavior is in agreement with Pasetto and Baldo, [24] work.

Figure 10 exhibit the influence of additives on Phase Angle under constant 400 microstrains, it can be noted that the phase angle increases after implication of micro or Nano size additives.

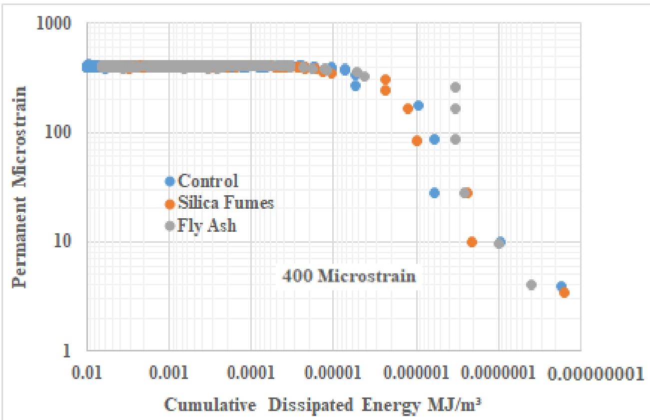

Figure 9. Deformation-dissipated energy relationship

However, the influence of micro size additive is more pronounced. The phase angle after a rapid increase, tends to have almost a constant behavior during the test. Similar behavior was reported by Maggiore et al., [25]. The phase angle values range between (16 to 25)°. The phase angle increases by (12.5 and 43.7) % when silica fumes and fly ash were implemented respectively. On the other hand, asphalt concrete mixture treated with fly ash was able to sustain more repeated flexural stresses as compared with control or silica fumes treated mixtures. Such improvement in load sustain potential could be attributed to the control of flexibility of asphalt concrete by implication of the additives. The load sustaining potential increases by (84.3 and 175) % for silica fumes and fly ash treated mixtures respectively.

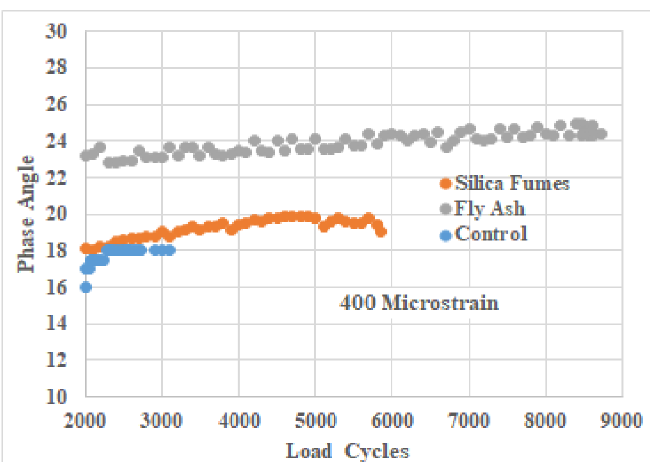

Figure 10. Influence of additives on phase angle

4. Conclusions

Based on the implemented testing and limitation of materials, conclusions can be addressed.

- After 100 loading repetitions, the modified mixtures with silica fumes and fly ash exhibits flexural stiffness of (7500 and 8000) MPa, (2000 and 3000) MPa, and (1600 and 1800) MPa under (250, 400, and 750) microstrain levels respectively.
- Implication of micro and Nano additives (fly ash and silica fumes) into the asphalt concrete mixture had exhibited an increment in the initial flexural stiffness of (119, 153) %, (11.1, 677) %, (75, 1150) % for mixtures practicing (250, 400, and 750) microstrain levels respectively.
- Implication of the micro size additive (fly ash) exhibits superior behavior in supporting the flexural stiffness of asphalt concrete when compared to the Nano size additive (silica fumes).
- For the control mixture, the flexural stiffness increases after 0.00001 MJ/m^3 loss of energy. When the silica fumes additive was implemented, the stiffness increases sharply when the loss of energy reaches 0.0001 MJ/m^3 then increases gently. When the fly ash was introduced, a sharp increase in the flexural stiffness could be observed up to 0.00001 MJ/m^3 loss of energy.
- As the dissipated energy vanishes, the permanent microstrain declines regardless of the micro or Nano additives implemented.

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Biographical notes

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