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Research Article

Influence of Additives on the Visco-Elastic and Visco-Plastic Behavior of Green Asphalt Concrete under Dynamic Flexure

Saad Issa Sarsam*,[1]
[1]Professor, Sarsam and Associates Consult Bureau (SACB), Baghdad-IRAQ. Former head, Department of Civil Engineering, College of Engineering, University of Baghdad, Iraq.

Keywords

Visco-elastic,
Additives,
Visco-plastic,
Flexure,
Stiffness,
Asphalt concrete,
Constant strain.

Abstract

Asphalt concrete mixture exhibit Visco-elastic behaviour under vehicular loading. In the present work, two types of additives (silica fumes and coal fly ash) have been implemented to modify asphalt binder. Asphalt concrete mixtures were prepared and subjected to laboratory roller compaction in a slab Mold. Beam specimens were obtained from the slab samples and tested for fatigue resistance under dynamic flexural stresses at 20℃ environment using constant strain level of 750 microstrain. The variations in the failure mode from Visco-elastic to Visco-plastic was monitored. It was observed that during the Visco-elastic stage of failure, implication of additives exhibits higher flexural stiffness as compared with the control mixture. However, the flexural stiffness declined by (66.6, 99 and 97) % for (control, fly ash treated, and silica fumes treated) mixtures respectively at 20 seconds of practicing the dynamic flexural stresses. However, after the 20 seconds of loading, the Visco-plastic stage of failure starts, and the flexural stiffness declined dramatically by (91.6, 98.7, and 95.8) % for (control, fly ash treated, and silica fumes treated) mixtures respectively. The deformation during the Visco-elastic stage increased by (6.8 and 5) % for (fly ash and silica fumes) treated mixtures respectively as compared with the control mixture. Through the Visco-plastic stage of failure, it can be noticed that at failure, the cumulative dissipated energy increases by (1.72 and 1.4) folds and the phase angle increase by (1.5, 1.25) folds for mixtures treated with fly ash and silica fumes respectively as compared with the control mixture.

1. Introduction

It is obviously known that many efforts have been devoted in the development and application of the visco-elastic and visco-plastic model coupled with damage theory of asphalt concrete. Hafeez et al. 2013, [1] analyzed the fatigue failure of asphalt concrete and stated that the damage mechanism can be attributed to the reduction in the stiffness modulus. Redelius and Soenen, 2015, [2] stated that the asphalt concrete always manifests the visco-plastic and visco-elastic behavior under sustained loading due to the diffusion and relaxation of the long chain hydrocarbon in the asphalt mastic. The visco-elastic and visco-plastic behavior is an essential property of the asphalt concrete and contributes to its deformation, which declines the service life of asphalt pavement as revealed by Masad and Somadevan, 2002, [3]. Cao et al., 2022, [4] studied the three stages of creep in asphalt concrete and proposes a three-dimensional visco-elastic damage model to describe the whole stages of the creep of asphalt and asphalt concrete including the accelerated creep, decelerated creep, and equi-velocity creep stages. Hernandez-Fernandez et al., 2021, [5] stated that asphalt concrete behaves as a linear viscoelastic material at small strain levels. However, various mechanisms and the damage evolution may change its behavior from the linear viscoelasticity. Chen et al., 2021, [6] developed a stiffness change tendency method which may be used to model the stiffness variation in asphalt concrete mixture and determine the critical laboratory fatigue failure and damage stages. A selected model represents the relationship between the log of the number of loading cycles and the log of the flexural stiffness obtained from dynamic bending fatigue tests. The reduction in the stiffness was monitored through the loading process. Three transition points were identified which are associated with the fatigue progression, the first point represents the micro-crack initiation and propagation, while the second point defined the macro-crack generation point. During recent decades, the sustainability issue of asphalt concrete pavement has received much attention by road agencies and research institutes as addressed by Pouranian and Shishehbor, 2019, [7]. Evaluating the sustainability of the pavement can be conducted by addressing its environmental impact issues of using the by-product and waste materials that can be recycled and reused in the production of asphalt concrete. Utilization of industrial solid by-product and waste such as fly ash, phospho-gypsum, RAP, and those with typical chemical components related to pozzolanic reaction, such as SiO2 (silicate), CaO and Al2O3 (oxide), CaOH (carbonate), SO4 (sulfate), and related solid wastes such as red mud, blast furnace slag, desulfurization ash, and steel slag, have been widely used in the construction of green pavement as stated by Zhao and Yang, 2023, [8]. Sarsam and Mashaan, 2022, [9] studied the influence of modification of the asphalt cement binder by implementation of coal fly ash and silica fumes as partial replacement of additives on the fatigue life of asphalt concrete mixture. It was concluded that the implication of coal fly ash exhibits lower susceptibility to the ageing process, while implication of silica fumes exhibits lower susceptibility to moisture damage as compared to the control or other treated mixtures. Shafabakhsh et al., 2021, [10] assessed the impact of implementing the nano silica as a filler on the cracking behavior of asphalt concrete mixtures at different testing environments. It was concluded that implementation of the additives exhibits positive influence on controlling the vertical and angular cracking at all the testing environments. Li et al., 2022, [11] investigated the viscoelastic properties of grouting material with different content of silica fumes and fly ash. It was stated that the fly ash increases the shear stress while the silica fumes reduce the shear stress significantly. It was concluded that such behavior may be related to the fact that such additives exhibit higher chemical adhesion and higher specific surface area respectively. Shafabakhsh et al., 2020, [12] stated that the implication of Nano-silica additive to modify the asphalt cement binder can improve the dynamic modulus of asphalt concrete. Khodary, 2016, [13] investigated the influence of

*Corresponding Author: saadisasarsam@coeng.uobaghdad.edu.iq
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implementing silica fumes additive on the mechanical behavior of asphalt concrete mixture. The impact of structure and morphology of the Silica fume were assessed. Various levels of modification of asphalt binder by the silica fume have been tried. It was concluded that implementing silica fumes into asphalt concrete mixture can exhibit a positive influence on the strength and stability of asphalt concrete mixture. Sarsam, 2022, [14] reported that dynamic vehicular loading applied on the pavement surface cause various flexural strain with the same angular frequency, but it is retarded in phase by an angle which is known as phase angle. The elastic behavior of asphalt concrete is expected when the phase angle is low (closer to 0 °), and the flexural stiffness of the mixture is also high showing screen cracks due to fragility of the mixture. However, the viscous behavior of asphalt concrete is expected when the phase angle is high (closer to 90°), which causes permanent deformation of the asphalt concrete mixture. Mackiewicz and Szydło, 2019, [15] investigated many methods for identification of the viscoelastic parameters of asphalt concrete mixtures. The dynamic test which is based on the four-point bending beam was selected as it is more appropriate. It was revealed that the fatigue life of asphalt concrete mixture can be predicted with the aid of the model. Sobolev et al., 2014, [16] revealed that the implementation of fly ash in asphalt concrete mixtures as partial substitute of filler can positively improve the performance of the flexible pavement. It was reported that the crack-arresting process into the asphalt concrete can be controlled by fly ash particles. It was stated that the implication of fly ash into the asphalt concrete mixture can improve the resistance of the mixture to rutting. The energy dissipation of asphalt concrete is considered as a good approach to distinguish between the visco-elastic and visco-plastic stages of failure. Only a proportion of the energy dissipation disposing in asphalt concrete materials during the dynamic (loading–unloading) process is devoted to fatigue damage. However, by creating the plot of cumulative energy dissipation versus number of cycles, three stages which are separated by two transition points could be noticed. Such transition points are clearly separating the visco-elastic and the visco-plastic stages of failure and can be used as fatigue criteria that were defined and calculated using the energy-based approaches as presented by Zeng et al., 2013, [17].

The aim of the present work is to assess the influence of implementing additives (silica fumes and coal fly ash) for modification of asphalt binder and generating a sustainable and green asphalt concrete mixture on the Visco-elastic and Visco-plastic stages of failure of asphalt concrete mixtures. Beam specimens of asphalt concrete will be extracted from roller compacted slab samples made with optimum binder requirement and tested for fatigue resistance at constant strain level of 750 microstrain with the aid of four-point dynamic bending beam technique. The changes in the flexural stiffness, deformation, phase angle, and cumulative energy dissipation upon Visco-elastic and Visco-plastic stages of failure of asphalt concrete will be monitored for the control and the additives treated mixtures through the fatigue life of asphalt concrete.

2. Materials and Methods

2.1. Additives

In this work, two types of Additives have been implemented for modification of asphalt cement binder. Silica fumes which exhibit Nano size and Coal Fly Ash which exhibit a micro size. The coal fly ash class F is a by-product. It was obtained from the local market and was implemented as a modifier for asphalt binder. Such additives can be disposed of in the asphalt concrete industry to create a green pavement and support its sustainability. This fly ash has specific surface area of 600 m²/Kg, and specific gravity of 2.016, while 98 % of the fly ash passes sieve of 75 micron. The major Chemical components of fly ash are (61.9 % SiO_2 0.88 % of CaO, and 28.8 % Al_2O_3). Figure 1 exhibit the implemented additives.

Figure 1. The Implemented additives

The silica fumes, which are also a fluffy powder by-product, were implemented as a modifier for asphalt binder to obtain a green pavement with sustainable behavior. Such additives can be disposed of in the asphalt concrete industry. The specific surface area of silica fumes was 200000 m²/Kg, the specific gravity is 2.134, while 100 % of the silica fumes is finer than sieve of 75 micron. The major chemical composition of the silica fumes is (90 % of SiO_2, 0.03 CaO, and 3 % of Al_2O_3).

2.2. Asphalt Cement

Asphalt cement with a softening point of 49℃, penetration grade of 42, and ductility of 136 Cm, was obtained from AL-Nasiriya oil Refinery and implemented in the present work. After implementation of the thin film oven test, the penetration and ductility declined to 33 and 83 Cm respectively while the softening point increases to 53℃. The test of physical properties of binder was conducted according to the ASTM, 2015, [18] procedures.

2.3. Coarse and Fine Aggregate

The Crushed coarse aggregates have been obtained from AL-Ukhaider quarry as pebbles from river origin. A mixture of crushed and natural fine aggregates was obtained from the same quarry of aggregates. The bulk specific gravity of the fine and coarse aggregates is (2.558 and 2.542) respectively while the water absorption was (1.83 and 1.076) % for fine and coarse aggregates respectively. The test of physical properties of aggregates was conducted according to the ASTM, 2015, [18] procedures.

2.4. Mineral Filler

The limestone dust was obtained from Karbala quarry and implemented as mineral filler. Testing for physical properties shows that the bulk specific gravity of the mineral filler was 2.617. However, 94 % of the filler passes 75-micron sieve.

2.5. Selection of the Combined Aggregate Gradation for Preparation of Asphalt Concrete mixture

The dense gradation of aggregates which is usually used for wearing course pavement layer was selected in the present work. It follows SCRB, 2003, [19] specification. The aggregates gradation exhibits 12.5 mm of nominal maximum size of aggregates. Figure 2 demonstrates the implemented aggregates gradation.

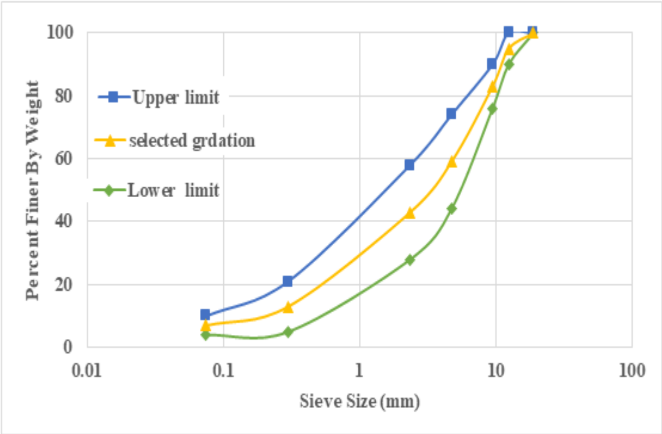

Figure 2. Gradation of Aggregate for Wearing Course as per SCRB, 2003, [19]

2.6. Preparation of Modified Asphalt Cement

Modified asphalt cement binder is prepared by using the wet process. In the wet process, asphalt cement was heated to 150°C and then the 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 possible chemical and physical bonding of the components. The optimum percentages of fly ash and Silica fumes are (4 and 2) % by weight of binder respectively were selected after trying various percentages in the laboratory. Details of the mixing procedure and selection of the optimum percentages could be found in Sarsam and Al-Lamy, 2015, [20].

2.7. Preparation of Asphalt Concrete Mixture, slab samples and beam specimens

The asphalt cement was heated to 150ºC, and then it was mixed with the combination of the fine and coarse aggregates and mineral filler which was heated to 160ºC. The 4.9 % binder was the optimum asphalt binder content and was obtained based on Marshall Test. Details of the procedure of obtaining the optimum binder requirement can be referred to Sarsam and Alwan, 2014, [21]. The prepared asphalt concrete mixtures were compacted in a rectangular slab mold of (40 × 30) Cm while the depth of the mold was 6 Cm. Laboratory roller compaction was conducted to the target bulk density according to procedure described by EN12697-33, 2007, [22]. The details of conducting the process of compaction can be referred to Sarsam, 2023, [23]. The temperature of the compaction was maintained at 150°C throughout the rolling compaction process. The asphalt concrete slab samples were left to cool overnight. Beam specimens of 5.6 Cm height, 40 Cm length, and 6.2 Cm width, were obtained from the prepared slab sample with the aid of diamond-saw. The total number of the prepared slab samples of asphalt concrete was six, while the number of the asphalt concrete beam specimens was eighteen; the average value of testing duplicate beam specimens was considered for the analysis.

2.8. Testing for Fatigue by Implementing the Dynamic Flexural Bending Beam Test

The four-point dynamic flexural beam bending test was conducted according to AASHTO T321, 2010, [24] at 20 ℃ environment as exhibited in Figure 3. The constant strain level of 750 microstrain was selected to represent the heavy traffic loading and implemented for testing. This testing technique was conducted to detect the failure stages of asphalt concrete in the form of the decline in the flexural stiffness through the fatigue life.
The influence of additives in modification of the binder and controlling the failure of asphalt concrete mixture was monitored at 20℃ environments. The beam specimens were stored in the testing chamber for three hours at the specific testing temperature before practicing the dynamic flexural stresses. A similar testing procedure using dynamic stresses, various constant strain levels, and various testing temperatures was adopted by Chen et al., 2021, [6].

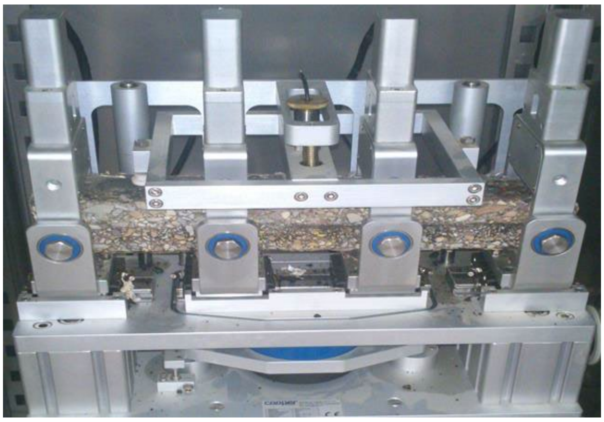

Figure 3. Four-point flexural bending test setup

3. Test Results and Discussions

3.1. Failure mode of asphalt concrete flexural stiffness

Fatigue failure of asphalt concrete is defined as the number of loading cycles which leads to a 50% decline in the flexural stiffness as reported by Abhijith and Narayan, 2020, [25]. It is realized that a typical fatigue curve (flexural stiffness versus number of load cycles under constant strain-controlled mode) is obtained and presented with four distinct regions, the first two regions are referred as the visco-elastic stage of failure which include the internal heating, and the micro-crack formation. However, the second two regions are referred to as the visco-plastic stage of failure which include the macro-crack formation and propagation, and the breakdown of the specimen. Such regions are separated by three transition points as revealed by Sarsam, 2021, [26]; and Shahsavari et al., 2016, [27]. It is then suggested that the first and second transition points are possibly associated with microcracking for visco-elastic stage and macrocracking for visco-plastic stage in the material, respectively. Figure 4 demonstrates the visco-elastic and visco-plastic mode of failure in the flexural stiffness of asphalt concrete which was prepared with optimum binder requirement of 4.9 %. It was observed that during the visco-elastic stage of failure, implication of additives for modification of the binder exhibits higher flexural stiffness as compared with the control mixture. such behavior indicates a sustainable property created in the mixture which can resist the applied dynamic stresses, while it can also refer to the creation of the green asphalt concrete mixture which make use of the waste material to improve the mixture properties. However, the flexural stiffness declined sharply by (66.6, 99 and 97) % for (control, fly ash treated, and silica fumes treated) mixtures respectively at 20 seconds of practicing the dynamic flexural stresses. On the other hand, after the 20 seconds of practicing the dynamic flexural stresses, the visco-plastic stage of failure starts, and the flexural stiffness of asphalt concrete declined dramatically by (91.6, 98.7, and 95.8) % for (control, fly ash treated, and silica fumes treated) mixtures respectively. Similar behavior was reported by Onyelowe et al., 2020, [28].

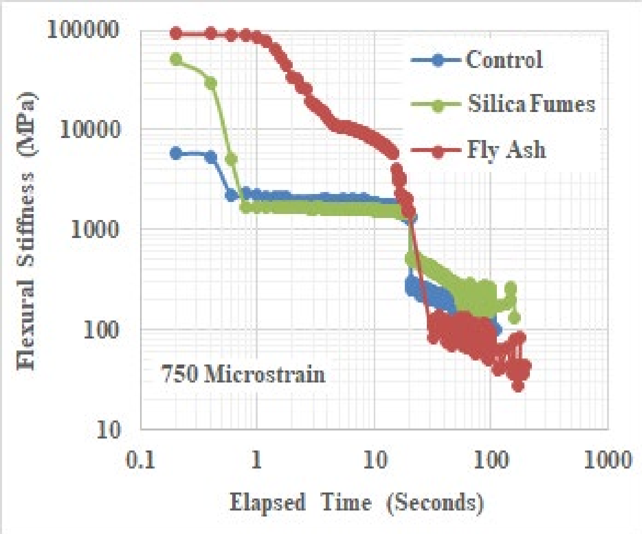

Figure 4. Mode of failure in asphalt concrete flexural stiffness

3.2. Deformation Failure mode of asphalt concrete

Figure 5 exhibits the deformation of asphalt concrete mixture in terms of flexural microstrain. No significant change in the deformation behavior at the visco-plastic stage of failure could be noticed when the additives were implemented, however, the deformation during the visco-elastic stage increased by (6.8 and 5) % for (fly ash and silica fumes) treated mixtures respectively as compared with the control mixture. However, in this stage, the mechanical properties of asphalt concrete change dramatically under external loading condition.

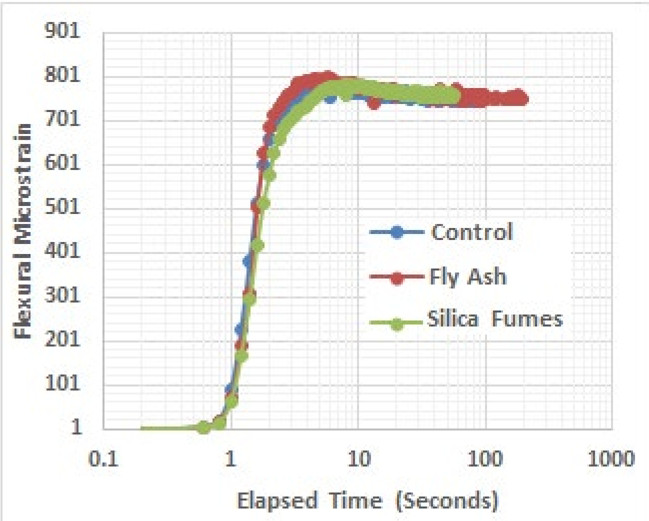

Figure 5. Deformation during the failure stages

Meanwhile, the deformation rate will increase rapidly as shown in Figure 4 and sustain to the ultimate fracture. When the asphalt concrete mixture reaches such creep stage, it can be revealed that the material will lose the load sustaining capacity immediately. Similar behavior was reported by Zhang et al., 2018, [29]; and Raufi et al., 2020, [30]. On the other hand, during the visco-plastic stage of failure, no significant variation in the deformation could be noticed regardless of the mixture type or additives implemented.

3.3. Cumulative Dissipated energy during the failure stages

Energy dissipation is initiated due to the dynamic flexural stresses and is considered as a proper engineering parameter of asphalt concrete. It exhibits a representation of the internal structural damage which can develop within the asphalt concrete mixture while practicing the dynamic flexural stresses. Wu et al., 2014, [31] stated that the energy dissipation through the fatigue life can usually be represented by a mathematical model curve, which presents three different stages. The first stage is exhibited by a gentle increase of the cumulative dissipated energy with elapsed time of loading; however, it exhibits sharp increase as the loading proceeds in the second stage. A considerable rate of input energy vanished to create internal damage to the asphalt concrete. On the other hand, the transition between the second stage of failure and the third one, which can be defined by a high rate of increment in energy dissipation with the elapsed time, can be used to identify the fatigue failure of the asphalt concrete. The energy dissipation is calculated after each load cycle by the software of the dynamic flexural stresses testing apparatus. Figure 6 exhibits the variation in the Cumulative Dissipated energy during the failure stages of asphalt concrete. It can be detected that the dissipation of energy is limited throughout the visco-elastic stage of failure, and it gradually increased as the dynamic flexure stresses proceeds. However, implementation of silica fumes exhibits higher energy dissipation as compared with the control or fly ash treated mixtures.

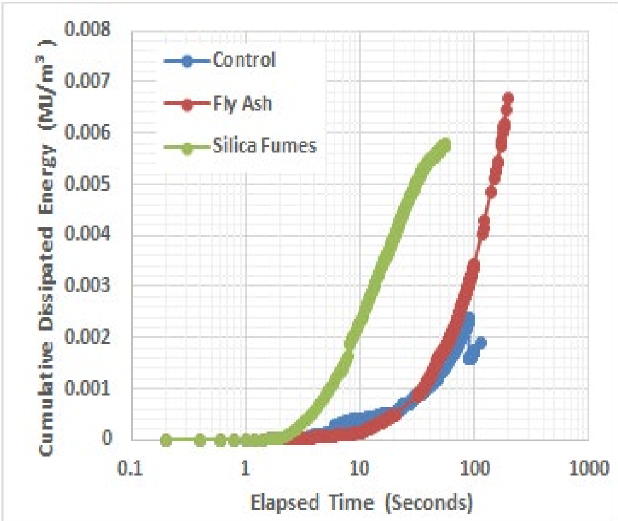

Figure 6. Dissipated energy during the failure stages

At 20 seconds of practicing the dynamic flexural stresses, the cumulative dissipated energy of silica fumes treated asphalt concrete mixture increases by seven folds as compared with the control mixture while the change in the cumulative dissipated energy was not significant for coal fly ash treated mixture. Through the visco-plastic stage of failure, it can be noticed that at failure, the cumulative dissipated energy increases by (1.72 and 1.4) folds for mixtures treated with fly ash and silica fumes respectively as compared with the control mixture. It can be revealed that implication of such additives had created stiffer asphalt concrete mixture which limits the visco-elastic stage of failure and increases the visco-plastic stage of failure. It was found that the energy dissipation characteristics are the main mechanisms that influenced deviations in the viscoelastic properties, however, they were only significant during the accumulated deformation. Similar findings were reported by Hernandez-Fernandez et al., 2021, [5]; and Sarsam, 2016, [32].

3.4. Phase angle through the failure stages

Phase angle is one of the important visco-elastic parameters, and it is the delay between the amplitudes of applied stress and the corresponding strain. Hussain et al., 2021, [33] stated that the Phase angle is considered as one of the important properties of asphalt concrete mixtures which can be implemented in the proper selection of material and can assist in evaluating various phase angle behavior for different mixture characteristics to minimize the premature failure process of flexible pavements. The phase angle characteristics of asphalt concrete mixtures can be modelled, and the model can be applied to various pavement mixtures to be used for wearing, binder, and base course layers by considering the values of phase angle as input and to predict its value for the next loading frequency. It was revealed that minimization of the phase angle is required to control the rutting, however, to resist the cracking of the pavement in cold weather, high phase angle is recommended. Figure 7 demonstrates the Phase angle through the failure stages of asphalt concrete. The phase angle is calculated after each load cycle by the software of the dynamic flexural stress testing apparatus. The phase angle fluctuates during the visco-elastic phase of failure between (20 to 15) ° regardless of the mixture type. A higher phase angle could be detected when the additives were implemented. However, it increases through the visco-plastic phase while at failure, it increases by (1.5, 1.25) folds after implementation of coal fly ash and silica fumes additives respectively. Such behavior agrees with the work reported by Shafabakhsh et al, 2021, [34]; and Khan et al., 2020, [35].

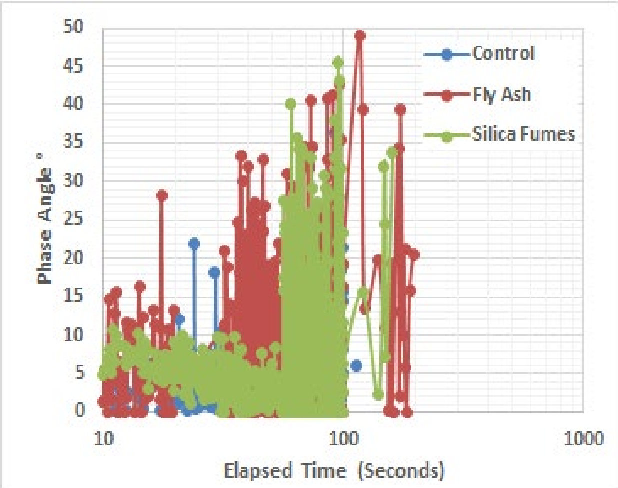

Figure 7. Phase angle through the failure stages

4. Conclusions

The following remarks may be addressed based on the testing and limitations of materials.

- During the visco-elastic stage of failure, implication of additives exhibits higher flexural stiffness as compared with the control mixture. However, the flexural stiffness declined sharply by (66.6, 99 and 97) % for (control, fly ash treated, and silica fumes treated) mixtures respectively at 20 seconds of practicing the dynamic flexural stresses.
- During the visco-plastic stage of failure, the flexural stiffness of asphalt concrete declined dramatically by (91.6, 98.7, and 95.8) % for (control, fly ash treated, and silica fumes treated) mixtures respectively.
- The deformation during the visco-elastic stage increased by (6.8 and 5) % for (fly ash and silica fumes) treated mixtures respectively as compared with the control mixture. During the visco-plastic stage of failure, no significant variation in the deformation could be noticed regardless of the mixture type or additives implemented.
- Through the visco-elastic stage of failure, the cumulative dissipated energy gradually increased as the dynamic flexure stresses proceeds. Implementation of silica fumes exhibits higher energy dissipation as compared with the control or fly ash treated mixtures.
- Through the visco-plastic stage of failure, the cumulative dissipated energy at failure increases by (1.72 and 1.4) folds for mixtures treated with fly ash and silica fumes respectively as compared with the control mixture.
- The phase angle fluctuates during the visco-elastic phase of failure between (20 to 15) ° regardless of the mixture type. A higher phase angle could be detected when the additives were implemented. However, the phase angle at failure increases by (1.5, 1.25) folds after implementation of coal fly ash and silica fumes additives respectively.
- Implication of coal fly ash and silica fumes for modification of asphalt binder was able to increase the sustainability of asphalt concrete and create a green pavement which dispose the by-product and waste materials.

Declaration of Conflict of Interests

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

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