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Research Article

Environmental Influence on Visco-Elastic and Visco-Plastic Behavior of Asphalt Concrete

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Keywords

Visco-Plastic, Environment, Asphalt concrete, Visco-Elastic, Dissipated energy, Phase angle, Deformation, Stiffness.

Abstract

The asphalt concrete behavior through the Visco-plastic and Visco-elastic stages of failure is highly susceptible to the variation in the temperature of the pavement. In the present work, slab samples of asphalt concrete were prepared with the optimum asphalt binder requirement with the aid of laboratory roller compactor. Beam specimens of asphalt concrete were obtained from the prepared slab samples and tested under the influence of dynamic flexural stresses for fatigue life at constant strain level of 750 microstrain. Specimens were tested at three testing temperatures of (30, 20, and 5) ℃. The variations of the behavior through Visco-plastic and Visco-elastic modes in terms of phase angle, permanent deformation, flexural stiffness, and cumulative dissipated energy with the testing temperatures have been assessed. It was verified that at the end of the Visco-plastic stage of failure, the energy dissipation of the mixture increased by (2, 1.5, and 29) folds at the testing temperatures of (5, 20, and 30) °C respectively as compared with the energy dissipation at the end of the Visco-elastic stage of failure. The phase angle declined to (55, 20, and 30) ° at (5, 20, and 30) °C testing temperatures respectively at the end of Visco-plastic stage of failure as compared with that at the end of Visco-elastic stage of failure. The flexural stiffness at the Visco-plastic stage of failure declined by (60, 80, and 92) % at (5, 20, and 30) °C testing temperature respectively as compared with the flexural stiffness at the Visco-elastic stage of failure.

1. Introduction

Selecting reliable material properties for construction of flexible pavement is vital in the design and structural analysis. The appropriate material properties can enable us to evaluate the expected state of stresses and deformation in the pavement layer. The selection of suitable properties of Asphalt concrete mixtures changes when considering loading time, rheological characteristics, and thermal conditions. Fatigue life of asphalt concrete pavement depends mainly on the durability of the mixture constitutes. Mackiewicz and Szydło, 2019 [1] addressed two methods for identifying the visco-elastic parameters of asphalt concrete mixtures. The dynamic test and the static creep test have been implemented with the aid of the four-point bending beam test. The course of the creep curve (for static creep) and fatigue hysteresis (for dynamic test) have been included in the prepared model. The analysis of test results indicated that the creep and fatigue parameters are dependent on the loading time, testing temperature, asphalt content, and the methods used for testing. The viscoelastic behavior of asphalt concrete mixture can present its prevailing mechanical properties as addressed by Alam and Hammoum, 2015 [2].

Micro-mechanical modeling has been implemented to investigate the macroscopic behavior and properties of asphalt concrete mixtures. The relationship between interaction within the microstructure and the individual constituent material properties was monitored. The developed model allows the calculation of the complex modulus and phase angle of asphalt concrete mixtures from the mechanical properties of its constituents. Alamnie and Hoff, 2022 [3] stated that significant progress was made to predict the damage in asphalt concrete. The fundamental theories of visco-plasticity, visco-elasticity, micromechanics, and continuum mechanics were applied to develop the material models through the mechanistic approach. The permanent deformation advancement models have been reviewed. Liu et al., 2022 [4] assessed the influence of annual average ground temperature and the temperature annual range on the asphalt pavement layer thickness. The variations in the thermal parameters of the asphalt concrete pavement layer were investigated. It was concluded that the experimentally obtained temperature fields data of the pavement were compared with the

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numerical calculation data for verification, and that the test results were in close agreement. Xiang et al., 2024 [5] characterized the visco-plastic deformation of aged rubberized reclaimed asphalt mixture with the aid of Hamburg Wheel-Track test. The work focused on the analysis of overall deformation and visco-plastic deformation.

The influence of material compositions on visco-plastic deformation was analyzed. The dynamic stability, which was derived from fitting curve of visco-plastic deformation, could accurately evaluate visco-plastic deformation characteristics of asphalt concrete. Chen et al., 2021 [6] presented a tendency of stiffness change which can be used in evaluation of the fatigue failure points in the laboratory and can model the stiffness of the asphalt concrete mixture. The variation in the measured stiffness of asphalt concrete mixture through its fatigue life was investigated by implementing the test at various strain levels and testing temperatures. It was revealed that the obtained model of development of stiffness could be implemented to simulate pavement deterioration. Mandula and Olexa, 2017 [7] stated that the asphalt concrete mixture is described with specific deformation parameters which are negatively influenced by temperature. Increasing the temperature can affect the behavior of asphalt-bonded materials from elastic to viscous state. It was observed that the phase angle is affected by the temperature change during dynamic bending tests. Mazurek and Iwański,2017 [8] reported that the stiffness modulus of asphalt concrete mixture is considered as a fundamental parameter used in the modelling of the viscoelastic behavior of asphalt concrete mixtures when it is assessed through the range of linear viscoelasticity. The test results from the fitting of relaxation functions in mechanical and mathematical models are fitted based on the constructed master curves from those models. It was concluded that the results of the modelling process can provide a view of the importance of implementation of each relaxation function. Ahmad et al.,2020 [9] evaluated the impact of testing environment on the dynamic complex modulus and phase angle of the asphalt concrete mixtures under various environment ranges of (35 to 50) °C using variable frequencies. It was observed that the dynamic modulus of the mixtures shows its highest at 30°C and gradually decreases at other testing temperatures. However, the high testing temperature exhibits low viscosity which refers to low phase angle values of the asphalt cement binder. Hernandez-Fernandez et al.,2022 [10] stated that the asphalt concrete behaves as a linear viscoelastic solid at small strain levels and exhibits time and temperature-dependent properties. However, Variation in the loading mechanisms, strain level, and the damage evolution will change the behavior from the linear viscoelasticity. It was concluded that the interaction of aggregate particles and energy dissipation characteristics exhibits the essential mechanisms that influenced deviations in the viscoelastic properties at high temperature. Quan et al.,2022 [11] implemented the fractional viscoelastic model for characterizing the viscoelasticity of asphalt concrete. The viscoelastic parameters of asphalt concrete were identified based on the phase angle data, and dynamic modulus obtained through laboratory testing. Stefańczyk, and Mieczkowski,2008 [12] addressed that the structural design of the flexible pavement requires the implementation of advanced models of rheology of asphalt concrete ingredients.

The prediction of the variation in the stiffness modulus of asphalt concrete with variable temperature is vital for providing the pavement structural layers with the required durability. The most implemented model for the flexible pavements design is the elastic constitutive model which assumes linear stress-strain relationship. Keshavarzi et al.,2021 [13] addressed that thermal cracking in asphalt concrete pavement is one of the most popular types of flexible pavement distress. The associated stresses of the thermal damage have great influence on the thermal contraction coefficient of the mixture. A mathematical model was presented for prediction of the coefficient values when the temperature drops. It requires the mixture's volumetric properties, elastic modulus, and the coefficient of thermal contraction of the aggregate. The aim of the present investigation is to determine the thermal influence on the Visco-plastic and Visco-elastic stages of failure and behavior of asphalt concrete. Beam specimens of asphalt concrete will be obtained from prepared slab samples and tested for fatigue life under dynamic flexural stress using three testing temperatures of (5, 20, and 30) °C. The variation in the flexural stiffness, phase angle, cumulative dissipated energy, and permanent deformation will be assessed and compared during the visco-elastic and visco-plastic stages of failure of asphalt concrete.

2. Materials and Methods

2.1. Asphalt cement

Asphalt cement with a ductility of 136 Cm, penetration grade of 42, and softening point of 49℃ was obtained from AL-Nasiriya oil Refinery for conducting the laboratory part of this work. The ductility and penetration declined to 83 Cm and 33 respectively while the softening point increases to 53℃ after conducting of the thin film oven test. The physical properties testing of the binder was conducted as per the ASTM, 2015 [14].

2.2. Fine and coarse aggregate

Crushed coarse aggregates and a mixture of natural and crushed fine aggregates were obtained from AL-Ukhaider quarry. The bulk specific gravity of the coarse and fine aggregates is (2.542 and 2.558) respectively while the water absorption was (1.076 and 1.83) % for coarse and fine aggregates respectively. The testing of aggregates properties was implemented according to the ASTM, 2015 [14].

2.3. Mineral filler

Limestone dust was implemented as mineral filler. It was obtained from Karbala quarry. The bulk specific gravity of the limestone dust was 2.617, while 94 % of the filler passes 75-micron sieve.

2.4. Selection of the combined aggregate gradation

Dense aggregates gradation which is usually implemented for wearing course pavement layer with 12.5 mm of nominal maximum size of aggregates as per SCRB, 2003 [15] specifications were selected in the present assessment. Figure 1 demonstrates the gradation of aggregates.

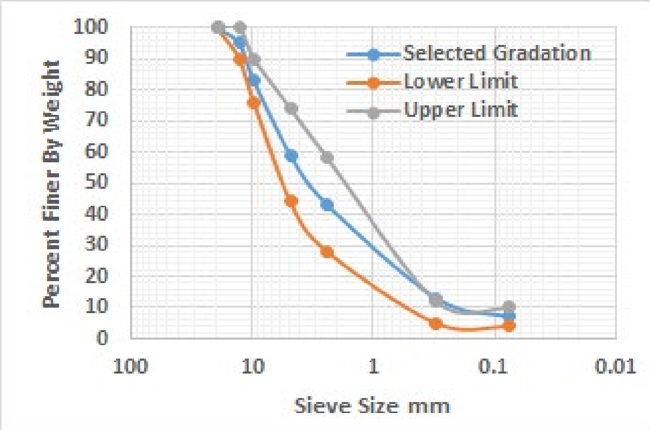

Figure 1. The Combined Aggregates Gradation

2.5. Preparation of asphalt concrete mixture

The asphalt cement was heated to 150 °C and then mixed with the combination of the coarse and fine aggregates and mineral filler which was heated to 160 °C. The 4.9 % asphalt cement binder was the optimum content which was obtained based on Marshall Test trials. More details of the optimum binder requirement may be found in Sarsam, 2021 [16]. The asphalt concrete mixtures were compacted in a slab mold of (300 × 400) mm while the depth of the mold was 60 mm. Laboratory roller compaction was implemented until a target bulk density was reached according to procedure details by EN12697-33, 2007 [17]. More details of the compaction process may be found in Sarsam and AL Nuaimi,2020 [18]. Three Beam specimens of 56 mm height, 400 mm length, and 62 mm width, were obtained from each of 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 asphalt concrete beam specimens was eighteen; three beam specimens were tested for each testing temperature. The accepted standard deviation between the maximum and minimum values was 5 % and the average value of a minimum duplicate specimens was considered for the analysis for each testing temperature.

2.6. Testing for fatigue life with the aid of dynamic flexural bending beam test

The fatigue life in the present work was monitored as the elapsed time consumed for initiation of failure. It may also be monitored through the number of loading cycles which cause failure or cause a reduction in the flexural stiffness to 50 % of its original value. The four-point dynamic flexural bending beam test was conducted according to AASHTO T321, 2010 [19]. Figure 2 exhibits the test setup. The constant strain level of 750 microstrain was implemented. The influence of testing temperature on controlling the failure of asphalt concrete mixture was monitored at (5, 20, and 30) ℃ environments in terms of the changes in phase angle, cumulative dissipated energy, flexural microstrain, and flexural stiffness. The beam specimens were stored in the testing chamber for three hours at the specific testing temperature before practicing the dynamic flexural stresses. Beams were tested sequentially at various testing temperatures. A similar testing procedure using dynamic stresses, various constant strain levels, and various testing temperatures was adopted by Chen et al., 2021 [6].

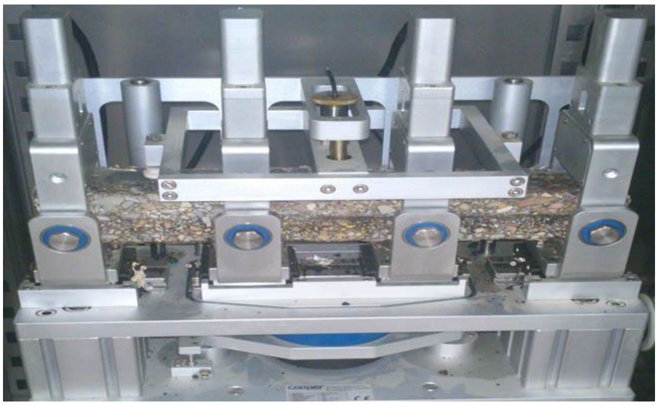

Figure 2. Four-point flexural bending beam test setup

3. Results and Discussions

3.1. Variation in cumulative dissipated energy

Asphalt concrete mixtures usually store and dissipate the kinetic energy through repetitions of loading and relaxation processes. For a pure elastic material, the kinetic energy is stored in the mixture when the load is applied. Maggiore et al., 2014 [20] stated that all the kinetic energy is recovered when the load is removed; in this case the curves of loading and the unloading coincide. However, Visco-elastic materials trace a different path during unloading to that when it is loaded, usually referred to as phase lag which is recorded between the measured strain and the applied stress. In this case, the energy is dissipated in the form of mechanical work, damage, or heat generation. Dissipated energy can be used to evaluate and measure the fatigue life of asphalt concrete mixtures. It is calculated by the software of the testing machine for each loading cycle. The variation in the dissipated energy as the load cycles proceeds can refers to the visco-elastic and visco-plastic stages of failure by initiation and propagation of microcracks and macrocracks in the asphalt concrete mixture. Abojaradeh, 2013 [21] reported that the cumulative dissipated energy is defined as the summary of the dissipated energy in every cycle until reaching the failure stage of the mixture. Figure 3 demonstrates the variation in the cumulative dissipated energy among the Visco-elastic and Visco-plastic stages of failure under environment influence. It can be detected that through the Visco-elastic stage, no significant variation in the dissipated energy among the testing environment could be observed up to 2 seconds of loading time. However, the energy dissipation increases gently up to 20 seconds of elapsed loading time, then the visco-plastic stage of failure starts, and the energy dissipation increases significantly. At the visco-plastic stage, it can be observed that as the testing temperature rises, the energy dissipation increases. At the end of the Visco-plastic stage of failure, the energy dissipation increases by (29, 1.5, and 2) folds for the testing environments of (30, 20, and 5) °C respectively as compared with the cumulative dissipated energy at the end of the Visco-elastic stage of failure. Such behavior could be related to viscos nature of the mixture at low temperature. The increment of flexibility of asphalt concrete at 30 °C can allow more dissipation of energy rather than the case at lower temperature.

Higher testing environment exhibited longer fatigue life from the dissipated energy point of view. The fatigue life increased by (83, and 230) % to (20, and 30) °C as compared with the case at 5° C.

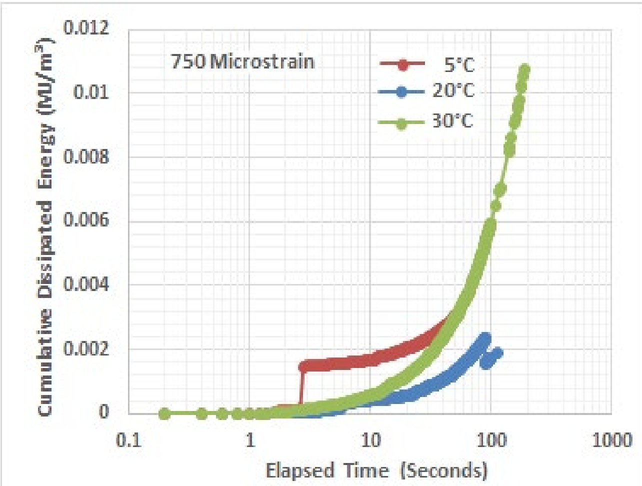

Figure 3. Variation in dissipated energy

3.2. Variation in the phase angle

Figure 4 exhibits the variation in the phase angle through the Visco-plastic and Visco-elastic stages of failure of asphalt concrete. It can be noticed that the fluctuation in the phase angle ranges between (5 to 80) °, (5 to 15) °, and (5 to 50) ° for the testing temperature of (5, 20, and 30) °C respectively regardless of the stage of failure. However, such high fluctuation in the phase angle occurs at early stages of failure in a colder testing environment, while no significant variation in the fluctuation in the phase angle could be noted at higher testing temperature.

No significant variation in the fluctuation of the phase angle for each testing environment could be detected throughout the failure stages of asphalt concrete. Through the Visco-elastic stage of failure and up to 20 seconds of elapsed time of loading, the phase angle was (65, 25, and 40) ° for (5, 20, and 30) °C testing environment respectively. However, at the end of the Visco-plastic stage of failure, the phase angle declined to (30, 20, and 55) ° for (30, 20, and 5) °C testing environment respectively. Under the dynamic flexural stresses, the behavior of the asphalt concrete mixture is elastic at the start of loading.

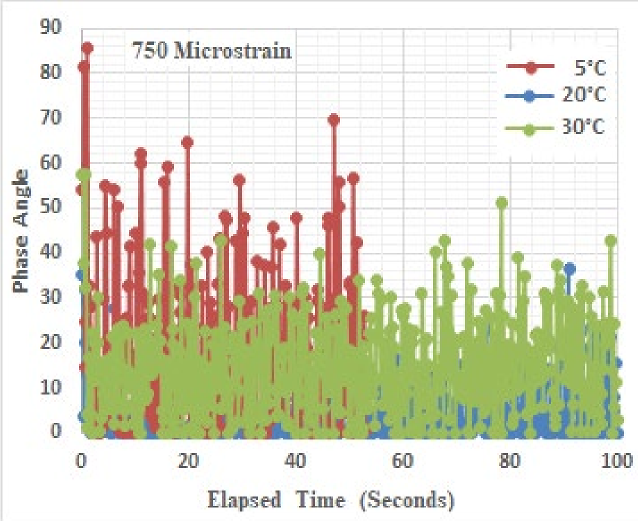

Figure 4. Variation in the phase angle

However, the behavior of the mixture under variation of testing temperature is significant over the entire range of the testing temperatures. The phase angle declines as the testing temperature increases. At higher testing temperatures and lower phase angles, the asphalt concrete mixture will exhibit a larger influence on Visco-plastic rather than Visco-elastic behavior. On the other hand, the higher the phase angle, the more elastic the material is. Higher testing temperature exhibited longer fatigue life of asphalt concrete from the phase angle point of view. The fatigue life of asphalt concrete mixture increases by 100 % at (20, and 30) °C as compared with that at 5° C. Similar behavior was reported by Karimi et al., 2017 [22]; Sarsam, 2022 [23].

3.3. Variation in flexural stiffness

Figure 5 exhibits the influence of testing temperature on the variation in the flexural stiffness of asphalt concrete through the failure stages. It can be noticed that flexural stiffness declines in general as the testing temperature increases. This may be related to the fact that the asphalt concrete mixture behaves as an elastic material at low testing temperature, which is mainly related to the viscosity of the asphalt cement binder, thus exhibits a higher stiffness. When the testing temperature rises, the asphalt binder becomes soft and exhibits lower viscous nature, leading to the decline in the flexural stiffness. At high testing temperature, the influence of the interlocking force between aggregates on mixture is significantly reduced asphalt concrete mixture behaves as a low viscous material. This will lead to a decline in flexural stiffness. At the end point of the Visco-elastic stage of failure, (point when the behavior of asphalt concrete changes from Visco-elastic to Visco-plastic), the flexural stiffness declines by (50, 81.2, and 99.3) % at (30, 20, and 5) ˚C testing temperature respectively as compared with the flexural stiffness at the start point of dynamic loading. However, the flexural stiffness at the Visco-plastic stage of failure declined by (92, 80, and 60) % at (30, 20, and 5) ˚C testing temperature respectively as compared with the flexural stiffness at the start point of Visco-plastic stage of failure. It can be observed that the fatigue life of asphalt concrete declined by (50, and 20) % at (20, and 5) °C as compared with that at 30 ° C. This may be attributed to the reduced stiffness and more flexible nature of the asphalt concrete mixture at 30 ° C environment. Such behavior of asphalt concrete mixture could be attributed to the more flexible nature of the mixture obtained due to the increase of testing temperature. Similar findings were reported by Wang et al., 2019 [24].

The viscosity of the asphalt cement binder declines as the temperature increases. This will make the asphalt concrete mixture more flexible and susceptible to flow under the dynamic flexural stresses. Similar behavior was reported by Sarsam, [23]. It can be revealed that through the visco-elastic behavior of asphalt concrete, the stiffness of the asphalt concrete mixture is higher, while the mixture exhibits possible screen cracks because of the fragility of the material regardless of the testing environment. However, through the Visco-plastic behavior of asphalt concrete, rutting could be detected of the asphalt concrete specimens. The stiffness of asphalt concrete can describe the dynamic response of the mixture to sinusoidal loading as stated by Shen and Carpenter, 2007 [25].

3.4. Variation in the permanent deformation

Figure 6 exhibits the variation in the permanent deformation in terms of flexural microstrain through the failure stages of asphalt concrete under environment influence. It can be observed that there is no significant variation in the flexural strain among the testing environment throughout the visco-plastic stage of failure. However, more elapsed time is consumed under the cold environment of the 5 ˚C test as compared with higher testing temperatures of (20 and 30) ˚C throughout the Visco-elastic stage of failure of asphalt concrete. On the other hand, the flexural strain increases in a sharp trend after the first second of loading. This may be attributed to the decline in the binder viscosity as the testing temperature rises and the reduction of the stiffness of the mixture at higher testing temperature. Similar behavior was addressed by Blab and Harvey, 2002 [26].

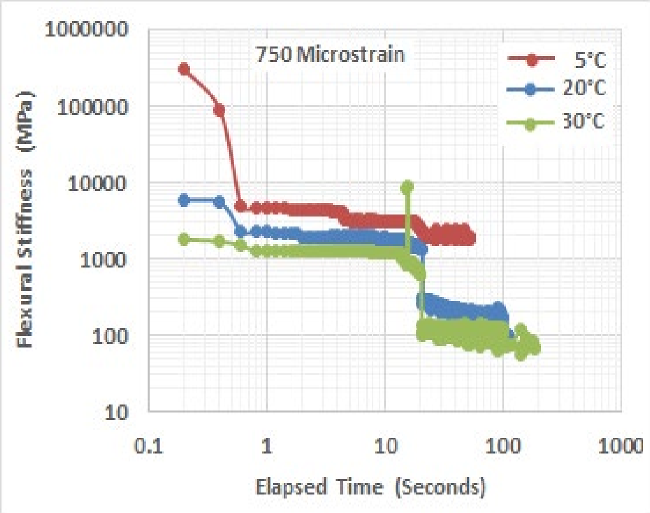

Figure 5. Variation in flexural stiffness

Table 1 summarizes the effect of testing temperatures on the fatigue parameters of asphalt concrete throughout the Visco-elastic stage of failure, while Table 2 summarizes the effect of testing temperatures on the fatigue parameters of asphalt concrete throughout the Visco-plastic stage of failure.

Table 1. Impact of testing environment on Visco-elastic failure stage of asphalt concrete

Testing temperature	5 °C	20 °C	30 °C
Fatigue parameter at Visco-elastic stage of failure			
Cumulative dissipated energy (MJ/M^3)	0.0020	0.0016	0.0015
Phase angle °	50	35	30
Flexural stiffness (MPa)	8000	2000	1000
Permanent deformation (microstrain)	700	750	810

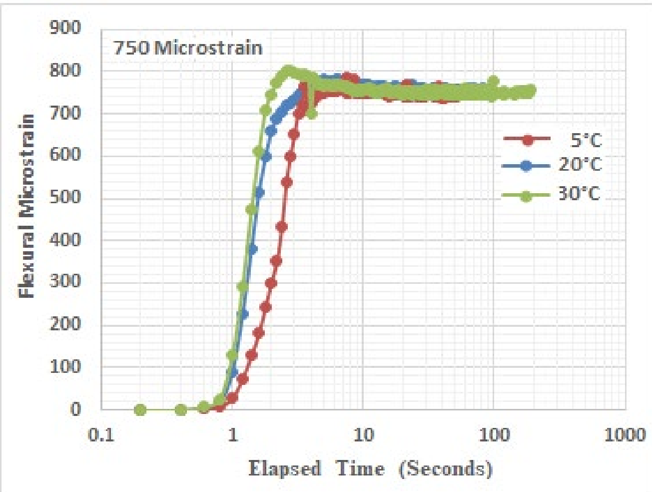

Figure 6. Variation in the permanent deformation

Table 2. Impact of testing environment on Visco-plastic failure stage of asphalt concrete

Testing temperature	5 °C	20 °C	30 °C
Fatigue parameter at Visco-plastic stage of failure			
Cumulative dissipated energy (MJ/M^3)	0.003	0.0025	0.011
Phase angle °	30	20	55
Flexural stiffness (MPa)	2000	200	100
Permanent deformation (microstrain)	750	755	750

4. Conclusion

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

- At the Visco-plastic stage of failure, the energy dissipation increases by (92, 1.5, and 2) folds for the testing environments of (30 20, and 5) °C respectively as compared with the cumulative energy dissipated at the Visco-elastic stage of failure.
- Through the Visco-elastic stage of failure and up to 20 seconds of elapsed time of loading, the phase angle was (40, 25, and 65) ° for (30, 20, and 5) °C testing environment respectively. However, at the Visco-plastic stage of failure, the phase angle declined to (30, 20, and 55) ° for (30, 20, and 5) °C testing environment respectively.
- At the end of Visco-elastic stage of failure, the flexural stiffness declines by (50, 81.2, and 99.3) % at (30, 20, and 5) °C testing temperature respectively as compared with the flexural stiffness at the start point of dynamic loading. However, the flexural stiffness at the Visco-plastic stage of failure declined by (92, 80, and 60) % at (30, 20, and 5) °C testing temperature respectively as compared with the flexural stiffness at the start point of Visco-plastic stage of failure.
- No significant variation in the flexural strain among the testing environment throughout the visco-plastic stage of failure is observed. However, more elapsed time is consumed under the cold environment of the 5 °C test as compared with higher testing temperatures of (20 and 30) °C throughout the Visco-elastic stage of failure of asphalt concrete.

Recommendations

The study was limited to the loading frequency, aggregates properties, microstrain level and optimum binder content. Other loading frequency, asphalt binder content, and aggregate properties may be studied in future work to extend the limitations of this work.

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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