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Modeling the Thermal Behavior of the Viscoelastic Properties of Asphalt Concrete

Saad I. Sarsam[*]
Professor, Sarsam and Associates Consult Bureau (SACB), Baghdad-IRAQ. Former Head, Department of Civil Engineering, College of Engineering, University of Baghdad, Iraq
*Corresponding Author Email: saadisasarsam@coeng.uobaghdad.edu.iq

Abstract:

The viscoelastic properties of asphalt concrete are susceptible to the variation in the pavement temperature. In the present work, asphalt concrete beam specimens were prepared at optimum binder content and tested under repeated flexural stresses for fatigue life. Three testing temperature were implemented (5, 20, and 30) °C. The variation in the phase angle, dissipated energy, flexural stiffness, and permanent deformation due to the testing temperatures were monitored and modeled. It was concluded that the viscoelastic properties of asphalt concrete are highly sensitive to the variation in testing temperature. The phase angle and the permanent deformation increases sharply as the testing temperature rises. However, the dissipated energy and the flexural stiffness declines as the testing temperature rise. Mathematical models were obtained which can be implemented in identifying the thermal behavior of the viscoelastic properties of asphalt concrete.

Keywords:
thermal behavior; asphalt concrete; viscoelastic; modeling; phase angle; deformation; stiffness

I. Introduction

The selection of reliable asphalt pavement material properties is essential in the structural analysis. The appropriate material parameters enable to determine the state of deformation and stresses in the pavement layer. Asphalt concrete mixtures changes their properties under thermal conditions and load time. Under various conditions of loading, such mixtures reveal their rheological characteristics. Fatigue of asphalt concrete depends on the durability of the mixture. Chen et al., (2021) developed a stiffness change tendency method, it was revealed that it may be implemented to determine the critical laboratory fatigue failure points and model the stiffness in asphalt concrete. The change in the measured stiffness through fatigue life was determined by testing at various temperatures and strain levels. Different mixtures were subjected to the four-point bending fatigue test. It was concluded that the model of stiffness development, obtained different fatigue failure criteria and characterize different fatigue damage stages, which could be useful in a simulation of pavement deterioration.

The viscoelastic behavior of asphalt concrete can characterize the mechanical properties of mixture as revealed by Alam and Hammoum, (2015). Micromechanical modeling was implemented to study the macroscopic properties of the mixture, the relationship between individual material properties, and their interaction within the microstructure. The model based allows calculating the phase angle and complex modulus of asphalt concrete mixtures from the mechanical properties of its constituents. Mazurek and Iwański, (2017) stated that the Stiffness modulus is considered as a fundamental parameter used in the

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modelling of the viscoelastic behavior of asphalt concrete mixtures. The stiffness modulus of asphalt concrete under steady-state strain was measured using axial tensile-compression test under controlled strain mode and tested in a linear viscoelasticity range.

Keshavarzi et al., (2021) reported that the thermal cracking is considered as one of the most prevalent types of asphalt concrete pavement distress. Thermal damage and associated stress are greatly affected by the coefficient of thermal contraction of the mixture. A model was suggested to predict the coefficient values as the temperature drops which require the elastic modulus, mixture's volumetric properties, and coefficient of thermal contraction of the aggregate. Stefańczyk, and Mieczkowski, (2008) revealed that the design of flexible pavement structures requires the use of advanced rheological models for asphalt concrete materials. The ability to predict the variation of the stiffness modulus with temperature is critical for providing pavement structural layers with adequate durability. The most used model in the design of pavements is the elastic constitutive model. It assumes linear strain-stress relationship. Mazurek and Iwański, (2017) compares the results from the fitting of relaxation functions in mathematical and mechanical models in conjunction with master curves constructed based on those models. It was concluded that the modelling results will provide an overarching view on the effectiveness of use of each relaxation function.

Mackiewicz and Szydło, (2019) presented two methods for the identification of viscoelastic parameters of asphalt mixtures. The dynamic test and the static creep test were carried out based on the four-point bending beam. The fatigue hysteresis (for dynamic test), and course of a creeping curve (for static creep) were included in the model. The analysis shows that these parameters depend significantly on the methods used, load time, asphalt content, and temperature. Ahmad et al., (2020) determined the influence of temperature on the phase angle and dynamic complex modulus of the asphalt concrete mixtures tested at a temperature range of (30, 35, 40, 45 and 50) °C at various frequencies. The dynamic modulus test the mixtures is highest at 30°C and gradually decrease at (35, 40, 45 and 50) °C respectively. However, the low phase angle values indicate low viscosity of the asphalt binder due to increase in temperature. Liu et al., (2022) investigated the effects of annual range temperature on the layer thickness, and annual average ground temperature. The thermal parameters of the asphalt concrete layer were analyzed. The test results indicated that the temperature fields of the pavement obtained by the experimental data were compared with the numerical calculation results for verification, and the conclusions were in close agreement. The aim of this investigation is to assess and model the thermal behavior of the viscoelastic properties of asphalt concrete. Beam specimens will be tested for fatigue life under repeated flexural stress. The variation in the phase angle, dissipated energy, flexural stiffness, and permanent deformation will be assessed and modeled.

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II. Material Characteristics and Testing Methods

Materials which are implemented in this investigation are locally available and usually used for asphalt concrete paving work.

2.1 Asphalt Cement Binder

Asphalt cement with a penetration grade of 40-50 was obtained from AL-Nasiriya oil refinery. The Physical properties of the asphalt cement binder are listed in Table 1.

Table 1. The Physical properties of asphalt cement

Property	Testing condition	ASTM, (2015) Designation No.	Value	SCRB, (2003) Specifications
Penetration	100 gm, 25˚C, 5 seconds	D5-06	42	40-50
Softening Point	(Ring and Ball)	D36-895	49	-
Ductility	25˚C,5cm/minutes	D113-99	100 +	>100
Specific Gravity	25˚C	D70	1.04	-
After thin film oven test properties according to ASTM D1754-97				
Penetration	100 gm, 25˚C, 5 seconds	D5-06	33	-
Ductility of Residue	25˚C,5cm/mi	D113-99	83	-

2.2 Fine and Coarse Aggregates

Crushed coarse aggregates and crushed sand have been implemented as Fine aggregate. The aggregates were obtained from AL-Ukhaider quarry. The physical properties of aggregates are listed in Table 2.

Table 2. Physical Properties of Fine and Coarse Aggregate

Property	Value	ASTM, (2015) Designation No.
Coarse Aggregate		
Bulk specific gravity	2.542	C127-01
Water absorption %	1.076%	C127-01
Wear % (lose Angeles's abrasion)	18%	C131-03
Fine Aggregate		
Bulk specific gravity	2.558	C128-01
Water absorption %	1.83%	C128-01

2.3 Mineral Filler

Limestone dust filer was obtained from Karbala quarry. The physical properties of the mineral filler are presented in Table 3.

Table 3. The Physical Properties of limestone dust (Mineral Filler)

Bulk specific gravity	% Passing Sieve 0.075 mm	Specific surface area (m^2/Kg)
2.617	94	312.5

2.4 Selection of Aggregate Gradation for Asphalt Concrete

The selected aggregates gradation in the present work follows SCRB, (2003) limitations for dense graded wearing course pavement layer. It has 12.5 mm nominal maximum size of aggregates. Table 4 shows the implemented aggregate gradation.

Table 4. The Combined Gradation Implemented for Wearing Course as per SCRB, 2003

Sieve size (mm)	19	12.5	9.5	4.75	2.36	0.3	0.75
Implemented gradation	100	95	83	59	43	13	7
SCRB, (2003) limitations	100	90-100	76-90	44-74	28-58	5-12	4-10

2.5 Preparation of Asphalt Concrete Mixture and Specimens

The fine and coarse aggregates were combined with the mineral filler to meet the specified gradation for wearing course. The combined aggregates were then heated to 160 ºC. The asphalt cement binder was heated to 150 ºC, then, it was added to the heated aggregates mixture to achieve the desired amount and mixed thoroughly for two minutes until all aggregate particles were coated with a binder thin film. The optimum binder percentage was determined based on Marshall Trial mixes using various asphalt percentages. Details of obtaining the optimum binder content could be found in Sarsam and Al-Lamy, (2015). The mixture was subjected to the short-term ageing process for 4 hours at temperature of 135 ºC according to AASHTO R-30, (2002). The short-term aged mixtures were casted in a slab mold of (300 x 400 x 60) mm and subjected to roller compaction to the target bulk density according to EN12697-33, (2007). The applied static load was 5 kN. Details of the compaction process could be referred to Sarsam, 2016. The compaction temperature was maintained to 150 °C. Slab samples were left to cool overnight. Beam specimens of 63±2 mm width and 50±2 mm height, and 400 mm length were obtained from the compacted slab sample using the Diamond-saw. The total number of beam specimens obtained was twelve, while the number of casted slabs was three.

2.6 Four-Points Repeated Flexural Bending Beam Test

The four-points repeated flexural bending beam test was implemented according to AASHTO T321, (2010) to verify the influence of testing condition on the flexural stiffness of asphalt concrete beam specimens at various pavement operating temperature of (5, 20, and 30) °C and under constant strain level of (250, 400, and 750) micro strain. During the flexural fatigue test, the asphalt concrete beam is subjected to repeated four-point bending. The load frequency is set to 5 Hz, and the vertical deformation caused by the loading is detected at the center of the beam. A repeated sinusoidal load (tension-compression) is applied to the two inner clamps on the asphalt concrete beam specimen while the outer clamps are providing a reaction load. The loading produces a uniform tension state and a constant bending moment along the central part of the beam. Thus, in this region, there are no shear stresses. The asphalt concrete beam specimens were subjected to a repeated load at a constant strain level of 400. The test was terminated when the stiffness of asphalt concrete beam specimens was declined to 50 % of its original value. The test results presented are the average of three specimens. Figure 1 exhibit the test setup.

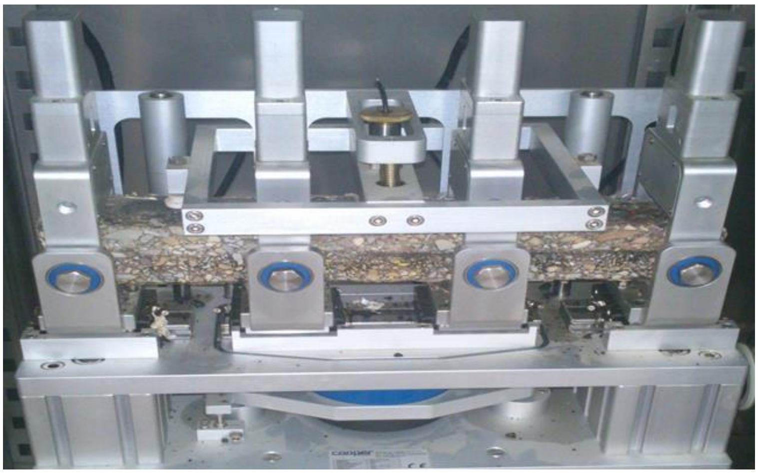

Figure 1. *Four-Point Flexural Bending Beam Test Setup*

III. Results and Discussion

3.1 Impact of Testing Temperature on Phase Angle

Figure 2 demonstrates the impact of testing temperature on the phase angle of asphalt concrete mixture. It can be noticed that the phase angle increases sharply as the testing temperature rises at the early stages of load repetitions. The power model exhibits high coefficient of determination of 0.999. Under the repeated flexural stresses, the response of the asphalt concrete mixture is influenced by the short-variable load which was more elastic. However, the thermal behavior through the rheological features is visible over the entire range of the tested temperatures. The value of the phase angle increases with increasing temperature.

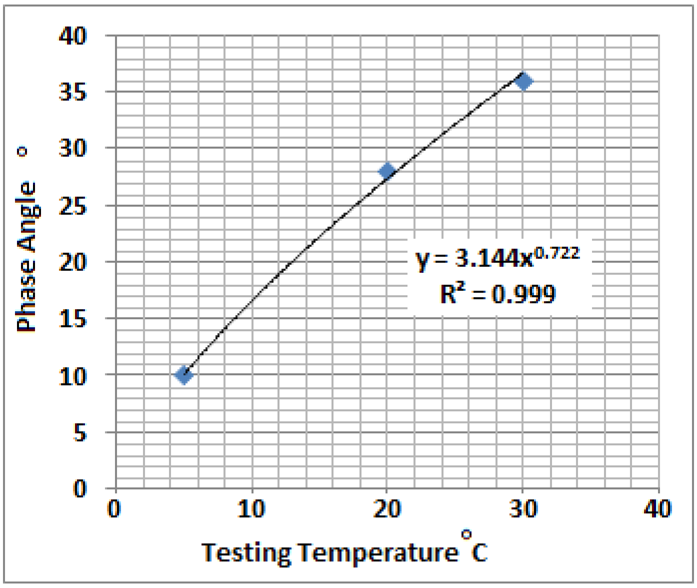

Figure 2. *Impact of Testing Temperature on Phase Angle*

However, the change in the phase angle in the low temperature range is practically linear. At higher testing temperatures and higher angles, the asphalt concrete mixture will have a larger contribution of viscous rather than elastic behavior. On the other hand, the lower the phase angle, the more elastic is the material. Similar behavior was reported by Karimi et al., (2017).

3.2 Impact of Testing Temperature on Cumulative Dissipated Energy

Asphalt mixture dissipates energy through loading and relaxation. For an elastic material, the energy is stored in the system when the load is applied. Maggiore et al., (2014) reported that all the energy is recovered when the load is removed; in this case the loading and the unloading curves coincide. However, viscoelastic materials are known by a hysteresis loop because the unloaded material traces a different path to that when it is loaded, usually referred as phase lag is recorded between the applied stress and the measured strain. In this case, the energy is dissipated in the form of damage, heat generation, or mechanical work. Dissipated energy is implemented to measure and evaluate the fatigue life of asphalt concrete mixtures. It is calculated by the software for each loading cycle. The change in the dissipated energy for different load cycles refers to the failure by initiation of micro cracks in the asphalt concrete mixture. The cumulative dissipated energy is the summary of dissipated energy in every cycle until failure of the mixture as revealed by Abojaradeh, (2013). As demonstrated in Figure 3, the cumulative dissipated energy of asphalt concrete mixture declines as the testing temperature increase. A sharp rate of decrease could be noticed at lower testing temperature. The power model exhibits high coefficient of determination of 0.997.

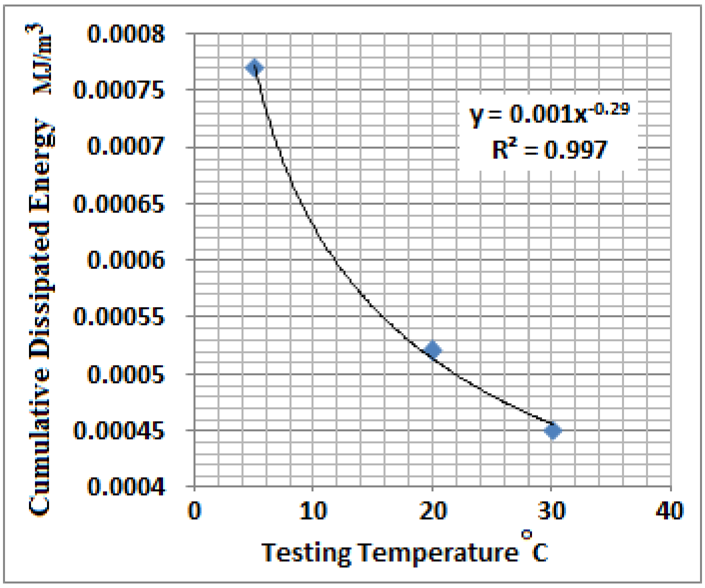

Figure 3. *Impact of Testing Temperature on Cumulative Dissipated Energy*

3.3 Impact of Testing Temperature on Flexural Stiffness

Through the elastic behavior of asphalt concrete, the stiffness of the asphalt concrete mixture is higher, while the mixture shows screen cracks because of the fragility of the material. On the other hand, through the viscous behavior of asphalt concrete, permanent deformation is noticed of the asphalt concrete mixture on the top road surface. Stiffness of asphalt concrete describes the dynamic response of the mixture to sinusoidal loading as revealed by Shen and Carpenter, (2007). Figure 4 demonstrates the influence of testing temperature on the flexural stiffness of asphalt concrete. It can be noticed that as the testing temperature increases, the flexural stiffness decline. This could be attributed to the fact that at low testing temperature, the asphalt concrete mixture behaves as an elastic material which is mainly related to asphalt cement binder, thus exhibits a higher stiffness and smaller phase angle. When decreasing the testing temperature, the asphalt binder becomes soft and viscous, leading to the decreased stiffness and increased phase angle. At high testing temperature, asphalt concrete mixture behaves as a viscous material, and the influence of the interlocking force between aggregates on mixture becomes distinct, while the asphalt cement binder of the mixture becomes weak. This will lead to the decline in the flexural stiffness and increase in the phase angle. With the further increase in temperature, the phenomenon where the aggregates skeleton mainly bears the loading stress becomes more obvious, then leading to a lower stiffness and smaller phase angle. The power mathematical model exhibits high coefficient of determination of 0.994 which indicates high sensitivity of the flexural stiffness to the testing environment.

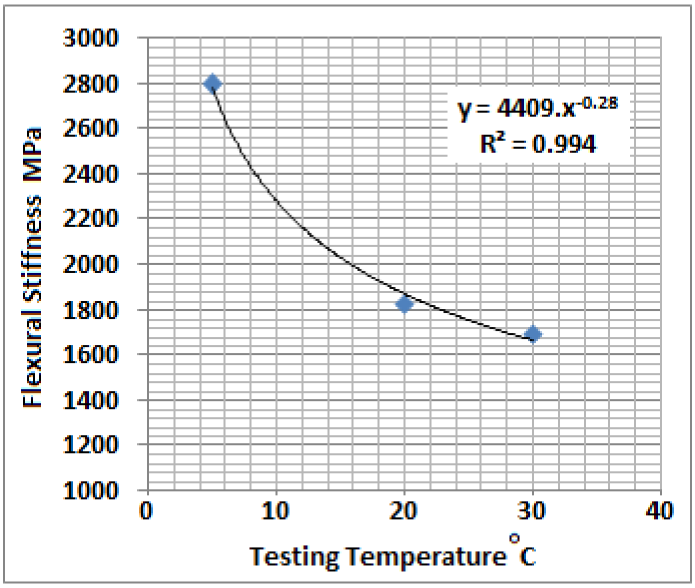

Figure 4. *Impact of Testing Temperature on Flexural Stiffness*

Such behavior may be attributed to the more flexible mixture obtained due to the rise of temperature. Similar findings were addressed by Wang et al., (2019). The viscosity of the asphalt cement binder decreases as the temperature rises which make the asphalt concrete mixture more susceptible to flow under the repeated flexural stresses. Similar behavior was reported by Sarsam, (2022).

3.4 Impact of Testing Temperature on Permanent Deformation

Figure 5 exhibit the variation in the permanent deformation of asphalt concrete with the testing temperature.

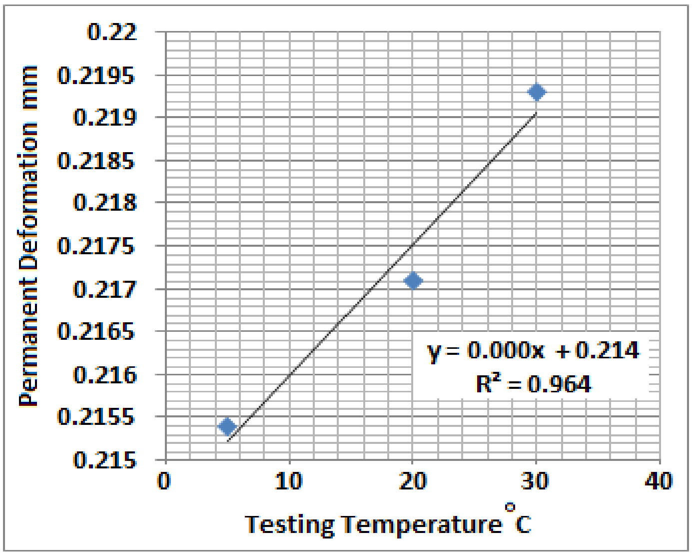

Figure 5. *Impact of Testing Temperature on Permanent Deformation*

It can be observed that as the testing temperature increases, the viscosity of the binder decreases and the mixture will be susceptible to deformation as the stiffness declines. A sharp increase in the permanent deformation could be noticed as the testing temperature increases. Such behavior agrees with the work reported by Sarsam, (2021).

3.5 Modeling the Thermal Behavior of Phase Angle

Figure 6 exhibit the variation in the phase angle through the fatigue life of asphalt concrete under various testing temperatures. The phase angle declines throughout the fatigue life. It can be noticed that asphalt concrete practices higher fatigue and lower phase angle as the testing temperature increases. This may be attributed to the increase in the flexibility of the mixture as the testing temperature increases. Similar findings were reported by Ahmad et al., (2020). Modeling the behavior of asphalt concrete under various testing conditions was reported by Sarsam and Hamdan, (2020). Table 5 demonstrates the phase angle parameters after implementation of power models. The intercept represents the phase angle at various testing temperatures, while the slope represents the rate of change of the phase angle through the fatigue life. High coefficients of determination could be observed for the power mathematical models obtained regardless of the testing temperature.

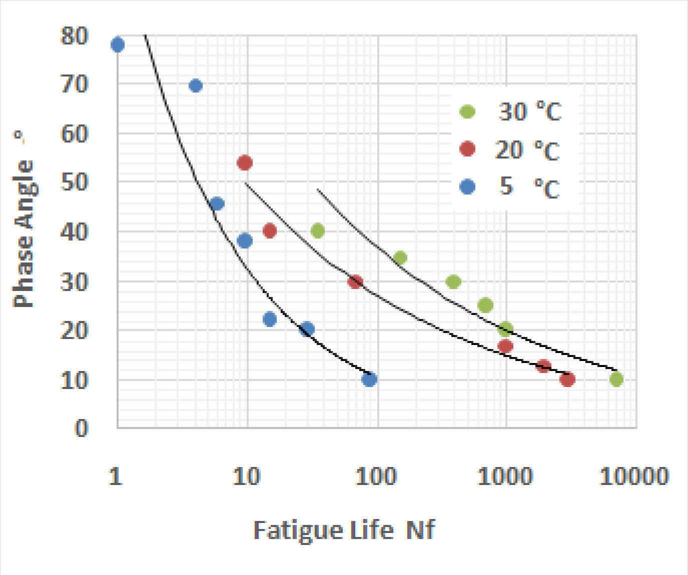

Figure 6. *Impact of Testing Temperature on Phase Angle-Fatigue Life Relationship*

The fatigue life increases from (100 to 3000 and 9000) as the testing environment changes from (5 to 20, and 30) ° C respectively at a phase angle of 10°. However, at a fatigue life of 100, the phase angle rises from (10, to 28, and 36) ° when the testing temperature rises from (5 to 20, and 30) ° C respectively. The intercept represents the phase angle while the slope represents the rate of decline in the phase angle throughout the fatigue life. Such findings agree with the work reported by Sarsam, (2022).

Table 5. Phase Angle Parameters

Testing Temperature °C	**Intercept**	**Slope**	**Mathematical Model**	**Coefficient of Determination**
30	124.8	- 0.26	Y= 124.8 $X^{-0.26}$	0.907
20	90.66	- 0.26	Y= 90.66 $X^{-0.26}$	0.977
5	101.6	- 0.49	Y= 101.6 $X^{-0.49}$	0.924
Y= Phase angle X= Fatigue life				

3.6 Modeling the Thermal behavior of Flexural Stiffness

The sensitivity of the flexural stiffness to the implementation of additives or to the testing temperature was reported by Nurmaidah and Pradana, (2019). However, modeling the influence of ageing on the flexural stiffness was reported by Sarsam and AL Nuaimi (2020).

Figure 7 exhibit that the flexural stiffness of asphalt concrete declines through the fatigue life regardless of the testing environment. However, higher flexural stiffness could be noticed at lower testing temperatures. This may be attributed to the fact that high viscosity of the binder is created as the testing temperature decline.

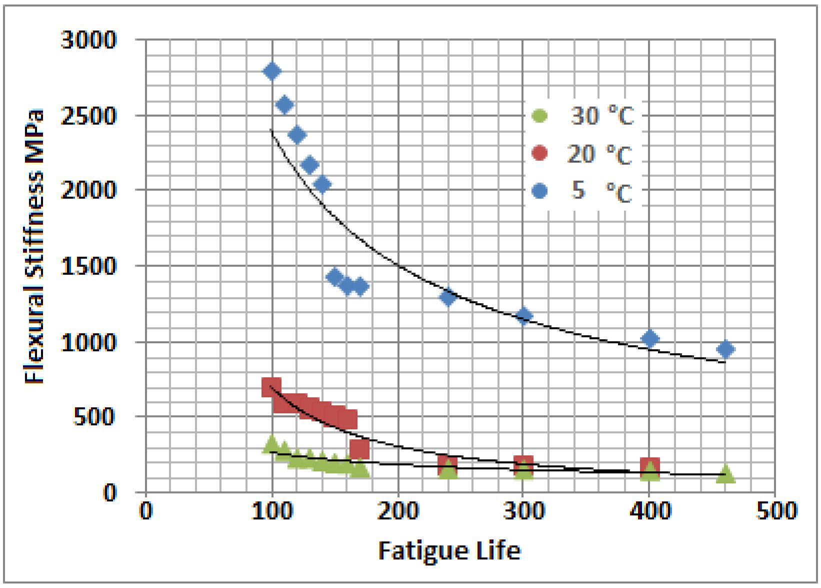

Figure 7. *Variation of the Flexural Stiffness through the Fatigue Life*

A significant influence of the testing temperature on the flexural stiffness is observed. After 100 repetitions of flexural stresses, the flexural stiffness decline by (75, and 89.2) % when the beam specimens were tested at (20, and 30) °C respectively as compared with that at 5°C. However, after 460 repetitions of flexural stresses (almost failure limit), the flexural stiffness decline by (85, and 99) % when the beam specimens were tested at (20, and 30) °C respectively as compared with that at 5°C. Table 6 demonstrates the power mathematical models obtained. The intercept represents the flexural stiffness in (MPa) of asphalt concrete while the slope represents the rate of decline in the flexural stiffness throughout the fatigue life. An acceptable coefficient of determination is exhibited by the power models obtained.

Table 6. Flexural Stiffness Parameters

Testing Temperature °C	**Intercept**	**Slope**	**Mathematical Model**	**Coefficient of Determination**
30	2638	- 0.49	$Y= 2638\ X^{-0.49}$	0.849
20	16011	-1.17	$Y= 16011\ X^{-1.17}$	0.894
5	52966	-0.67	$Y= 52966\ X^{-0.67}$	0.839
Y= Flexural Stiffness (MPa) X= Fatigue life				

3.7 Modeling the Thermal behavior of Dissipated Energy

Changing the viscoelastic dissipated energy is important in fatigue behavior of asphalt concrete mixtures. This change significantly affects the fatigue destruction of the material. As demonstrated in Figure 8, the cumulative dissipated energy of asphalt concrete decline as the testing temperature increases. However, the cumulative dissipated energy increases as the flexural stresses application increase. On the other hand, the rate of increase of the dissipated energy changes to gentler trend as the testing temperature rises. This may be attributed to the fact that stiffer mixture created at low testing temperature exhibit higher dissipation of energy. At higher testing temperature of (20 and 30) °C, the asphalt concrete mixture exhibit more flexibility due to the decline in the viscosity of the binder and dissipates lesser energy. Such behavior agrees with Maggiore et al., (2014). After 300 repetitions of flexural stresses, the cumulative dissipated energy decline by (50 and 66.6) % at (20 and 30) °C as compared with the mixture tested at 5 °C respectively. Table 7 present the cumulative dissipated energy parameters, the intercept represents the cumulative dissipated energy in MJ/m^3 while the slope represent the rate of increase of the dissipated energy through the fatigue life of asphalt concrete. The obtained power mathematical models exhibit very high coefficients of determination which indicates higher sensitivity of dissipated energy to the testing environment.

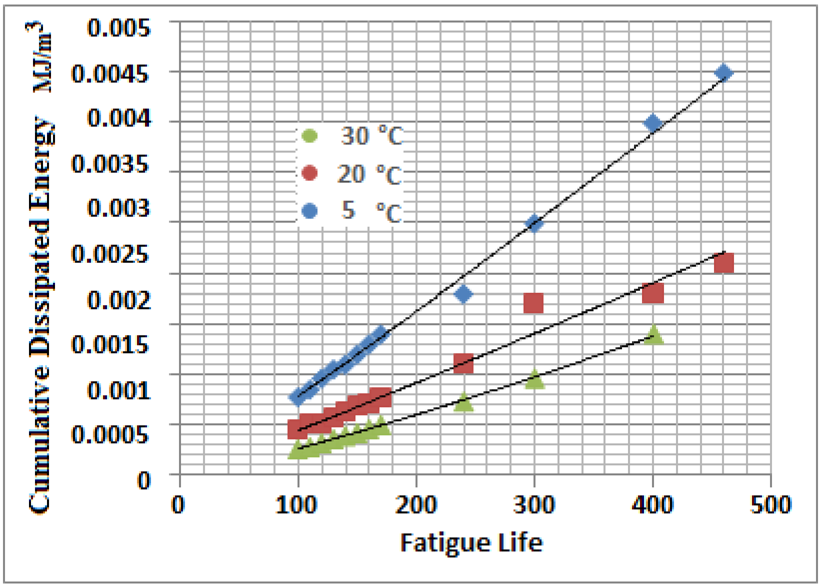

***Figure** 8. Variation of the Cumulative Dissipated Energy through the Fatigue Life*

Table 7. Cumulative Dissipated Energy Parameters

Testing Temperature °C	Intercept	Slope	Mathematical Model	Coefficient of Determination
30	0.0000001	1.211	$Y= 0.0000001 X^{1.211}$	0.999
20	0.0000003	1.061	$Y= 0.0000003 X^{1.061}$	0.985
5	0.0000006	1.065	$Y= 0.0000006 X^{1.065}$	0.996
X= Cumulative Dissipated Energy (MJ/m^3) Y= Fatigue life				

3.8 Modeling the Thermal behavior of Permanent Deformation

Figure 9 exhibit the variation of permanent deformation of asphalt concrete mixture at various testing temperature while practicing repeated flexural stresses. In general, lower testing temperature exhibits lower permanent deformation. The asphalt concrete pavement layers exhibit both viscous and elastic features. The viscous behavior is typical of the higher temperatures. However, the elastic properties are shown at the lower temperatures, and are responsible for irreversible deformations of the asphalt pavement. Both static and repetitive loads with short-term impact exist in the field as revealed by Blab and Harvey, (2002). The asphalt concrete mixtures become viscous over time in high temperatures for a long-term static load, whereas the accumulation of permanent deformations resulting in permanent deformation occurs under dynamic loading. After practicing 300 of flexural stress repetitions, the permanent deformation increases to (0.5 and 1.4) % when the asphalt concrete mixture was tested at (20 and 30) °C respectively as compared with a testing temperature of 5°C. Table 8 exhibit the permanent deformation parameters, the power mathematical models with a suitable coefficient of determination indicates a significant sensitivity of permanent deformation to the variation of testing temperature through the fatigue life of asphalt concrete. The intercept represents the permanent deformation in (mm), while the slope represent the rate of deformation through the fatigue life of asphalt concrete.

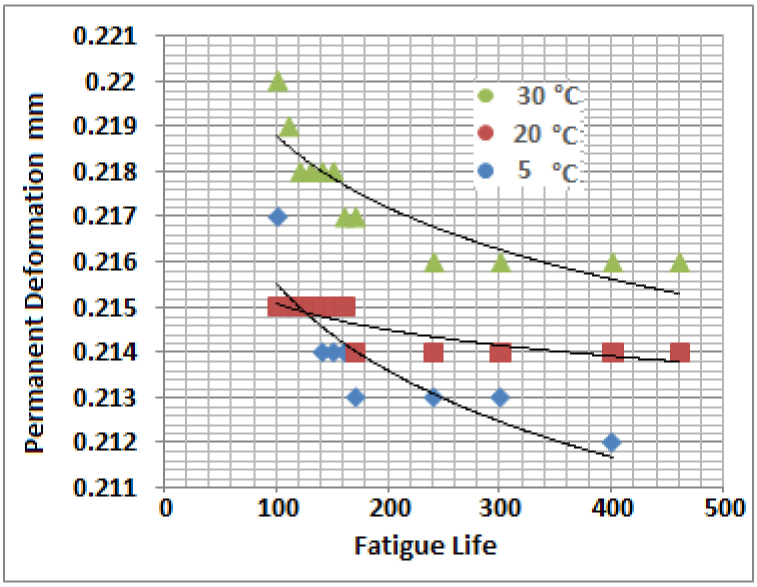

Figure 9. *Variation of the Permanent Deformation through the Fatigue Life*

Table 8. Permanent Deformation Parameters

Testing Temperature °C	**Intercept**	**Slope**	**Mathematical Model**	**Coefficient of Determination**
30	0.229	-0.01	$Y= 0.229\ X^{-0.01}$	0.789
20	0.219	-0.01	$Y= 0.219\ X^{-0.01}$	0.714
5	0.228	-0.01	$Y= 0.228X^{-0.01}$	0.773
X= Permanent Deformation (mm) Y= Fatigue life				

IV. Conclusions

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

1- The phase angle and the permanent deformation of asphalt concrete increases as the testing temperature while the flexural stiffness and the cumulative dissipated energy declines.

2- The fatigue life increases from (100 to 3000 and 9000) as the testing environment changes from (5 to 20, and 30) ° C respectively at a phase angle of 10°. However, at a fatigue life of 100, the phase angle rises from (10, to 28, and 36) ° when the testing temperature rises from (5 to 20, and 30) ° C respectively.

3- After 460 repetitions of flexural stresses (almost failure limit), the flexural stiffness decline by (85, and 99) % when the beam specimens were tested at (20, and 30) °C respectively as compared with that at 5°C.

4- After 300 repetitions of flexural stresses, the cumulative dissipated energy decline by (50 and 66.6) % at (20 and 30) ℃ as compared with the mixture tested at 5 ℃ respectively.

5- After practicing 300 of flexural stress repetitions, the permanent deformation increases to (0.5 and 1.4) % when the asphalt concrete mixture was tested at (20 and 30) ℃ respectively as compared with a testing temperature of 5℃.

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