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Variation in asphalt concrete properties with testing mode

Saad Issa Sarsam*

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Author Affiliation:
Professor, Sarsam and Associates Consult Bureau (SACB), Former Head, Department of Civil Engineering, College of Engineering, University of Baghdad–Iraq

***Corresponding author**
Professor, Sarsam and Associates Consult Bureau (SACB), Former Head, Department of Civil Engineering, College of Engineering, University of Baghdad,
Iraq
Email: saadisasarsam@coeng.uobaghdad.edu.iq

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ABSTRACT

Asphalt concrete beam specimens were tested under controlled strain and stress conditions for dissipated energy, phase angle, flexural stiffness and permanent deformation. It was observed that higher permanent deformation, flexural stiffness and cumulative dissipated energy is achieved under constant strain mode. However, lower phase angle could be observed under constant strain mode. The fatigue life of constant strain mode of testing is longer by 128.5 % and the permanent deformation is higher by 733 % than that of constant stress mode of testing respectively. After the first load repetition, the constant stress mode exhibits a high phase angle of 47° as compared with 17° for constant strain mode. It was concluded that higher dissipated energy is required in case of constant stress while lower dissipated energy is required in case of constant strain to exhibit a permanent deformation than that required for the constant stress mode. Choice of the testing mode of asphalt concrete is essential in the evaluation of asphalt concrete properties and the variation in such properties is significant among the testing mode.

Keywords: Asphalt Concrete, Fatigue, Strain, Stress, Dissipated Energy, Phase Angle, Flexural Stiffness

1. INTRODUCTION

The stress control mode of testing the fatigue behaviour of asphalt concrete is commonly adopted to evaluate the fatigue resistance of stiff materials and thick pavements, while the strain control mode is used in case of conventional bituminous mixtures and flexible paving as revealed by Artamendi and Khalid, (2005). Fatigue testing has been conducted using both constant stress and constant strain load applications. In constant strain mode, the strain is maintained constant and the stress is allowed to vary. However, in constant stress mode, the load is maintained the same and the strain is allowed to vary. Experts has shown that thick asphalt pavements with more than (125 mm) generally perform closer to a constant stress mode in the field, while thin asphalt pavements with less than (125 mm) generally perform closer to a constant strain mode in the field. On the other hand, the constant strain mode is suitable for more flexible mixtures and the constant stress mode is recommended for stiffer materials as reported by Ghuzlan and Carpenter, (2000). Pasetto and Baldo, (2017) conducted an experimental study on the stiffness and the fatigue performance of asphalt concrete. The flexural fatigue tests were performed in stress and strain control mode to describe completely the fatigue properties of the mixes.

A dissipated energy approach, based on the internal damage produced within the asphalt concretes, was implemented for the fatigue analysis. Yu and Zou, (2013) developed a transfer function for considering the fatigue life transition from constant strain mode to constant stress testing mode. Such transfer function was combined with the laboratory fatigue prediction model which was developed using 618 constant microstrain and four points bending fatigue tests to form a new asphalt pavement fatigue cracking prediction model. Rajbongshi, (2009) revealed that the possible modes of loading the asphalt concrete is bounded by two well-defined test methods, namely, constant strain testing and constant stress testing, which are generally applied in the laboratory for evaluation of fatigue characterization of asphalt pavement. The constant stress type of loading is generally considered applicable to 200 mm thick asphalt pavement layers and over, while the constant strain type of loading is considered more applicable to 50 mm thin asphalt pavement layers or lower. The fatigue characteristics of asphalt mixtures have been investigated by Shen et al., (2006) using the dissipated energy concept. It was reported that the cumulative dissipated energy of an asphalt mixture can be related to its failure life significantly. Strong relationship exists between the total dissipated energy and the number of loading cycles to failure and such relationship is not affected by loading mode, temperature, frequency, temperature, but it is highly dependent on material type.

Laboratory fatigue tests and full-scale field studies conducted by Hosseini et al., (2009) indicated that the effective stiffness modulus of asphalt mixtures is reduced significantly under repeated loading without the presence of visible cracks. It was revealed that this indicates that damage is accumulating in the material, thus, reducing the effective volume able to carry the applied loads by cracking while the effective stiffness modulus is reduced. Shafabakhsh et al., (2020) assessed the fatigue life of asphalt concrete with four-point bending beam fatigue test at constant strain conditions and the strain levels of (900, 700 and 500) microstrain and a testing temperature of 20°C. The adopted condition to reach the failure was assumed to be equivalent to a 50 % reduction in the stiffness throughout the load repetition and the load was applied semisinusoidal at a frequency of 10 Hz without rest period. The implemented loading waveform was sinusoidal in a controlled stress testing mode and sinusoidal and semisinusoidal in a controlled strain mode. The simplest fatigue prediction models are based on either controlled strain mode or controlled stress mode as revealed by Adhikari and You, (2010). Equation 1 exhibits the simplest fatigue models of controlled strain mode while Equation 2 exhibits the simplest fatigue models of controlled stress mode. It must be mentioned that such simplest fatigue model does not consider the temperature, modulus and loading frequency of the asphalt pavement.

$$Nf = k1\left(\frac{1}{\epsilon t}\right)^{K2} \quad (1)$$

$$Nf = k1\left(\frac{1}{\sigma t}\right)^{K2} \quad (2)$$

Where:
Nf = cycle of load to failure
$\in t$ = tensile strain at bottom of specimen
σt = applied tensile stress
k_1, k_2 = experimental determined coefficient

The constant strain and constant stress equations developed by Bonnaure et al., (1980) are presented in Equation (3) and Equation (4) respectively.

$$Nf = Af(0.17\, PI - 0.0085\, PI.Vb + 0.0454\, Vb - 0.112)^{s} \varepsilon t^{-s} Sm^{-1.8} \quad (3)$$

$$Nf = Af(0.0252\, PI - 0.00126 PI.Vb + 0.0067 Vb - 0.067)^{s} \varepsilon t^{-s} Sm^{-1.4} \quad (4)$$

Where:
PI is the penetration index of the binder in the mix,
Vb is the volumetric bitumen content of the mix,
Af is the laboratory to field adjustment factor,
Nf is the number of repetitions to failure,
εt is the magnitude of the tensile strain repeatedly applied,
Sm is the stiffness modulus of asphalt mixture.

The major role of these fatigue life models is to provide a relation between mixture properties, load repetitions to failure and pavement response (strain). The parameters of these models are mainly based on a repeated loading sequence and the coefficients are determined from empirical data regression. The aim of the present investigation is to assess the influence of testing mode (constant stress and constant strain) on the fatigue, flexural stiffness, dissipated energy, permanent deformation and phase angle of asphalt concrete through the four-point bending beam test.

2. MATERIALS AND METHODS

The materials implemented in the present study are locally available and are currently used for asphalt concrete pavement construction in Iraq.

Asphalt Cement

Asphalt cement of (40-50) penetration graded was implemented in this investigation. It is obtained from AL-Nasiriyah oil Refinery. Table 1 presents the physical properties of asphalt cement.

Table 1 Physical Properties of Asphalt Cement

Property	Test Conditions	ASTM, 2015 Designation	Test Value
Penetration	25˚C , 5 sec.,100gm	D5-06	42
Softening Point	(ring &ball)	D36-895	49
Ductility	5cm/minutes, 25˚C	D113-99	136
Specific Gravity	25˚C	D70	1.04
Flash Point	Cleave land open cup	D92-05	256
Binder properties after thin film oven test according to ASTM D-1754, 2015			
Penetration	25˚C , 5 sec.,100gm	D5-06	33
Ductility of Residue	5cm/minutes, 25˚C	D113-99	83
Loss on Weight	163ºC, 50g, 5 hours	----	0.35

Coarse and Fine Aggregates

Crushed coarse aggregates which retained on sieve No.4 was obtained from AL-Ukhaydir quarry. Crushed sand and natural sand which passes sieve No.4 and retained on sieve No.200 are combined and used as Fine aggregates. The physical properties of aggregates are listed in Table 2.

Table 2 Physical Properties of Course and Fine Aggregate

Property	Value	ASTM, 2015 Designation No.
Coarse Aggregate		
Bulk specific gravity	2.542	C127-01
Apparent specific gravity	2.554	C127-01
Water absorption %	1.076	C127-01
Wear %(los Angeles abrasion)	18	C131-03
Fine Aggregate		
Bulk specific gravity	2.558	C128-01
Apparent specific gravity	2.563	C128-01
Water absorption %	1.83	C128-01

Mineral Filler

Limestone dust was obtained from the lime plant at Karbala and implemented as mineral filler in this work; the physical properties of the filler are presented in Table 3.

Table 3 Physical Properties of Mineral Filler (Lime stone dust).

Property	Value
Bulk specific gravity	2.617
% Passing Sieve No.200	94

Selection of Combined Aggregates Gradation

The selected combined aggregates gradation follows SCRB, 2003 for wearing course asphalt concrete. It has 12.5 (mm) nominal maximum size of aggregate. Table 4 exhibits the selected aggregate gradation.

Table 4 Selected Gradation of Aggregates

Sieve size (mm)	19	12.5	9.5	4.75	2.36	0.3	0.075
Selected limit	100	95	83	59	43	13	7
SCRB, 2003 Specification	100	90-100	76-90	44-74	25-58	5-21	4-10

Preparation of Asphalt Concrete Mixture

The aggregates were washed, dried to constant weight at 110ºC and sieved to different sizes. Aggregates were combined with mineral filler to meet the specified gradation. The combined aggregates mixture was heated to a temperature of (160ºC) before mixing with asphalt cement. The asphalt cement was also heated to a temperature of 150 ºC to produce a kinematic viscosity of (170±20) centistokes. Then, the predetermined amount of asphalt cement was added to the heated aggregates and mixed thoroughly in mixing bowl by hand using a spatula for two minutes until all aggregate particles were coated with thin film of asphalt cement.

Preparation of Asphalt Concrete Slab Samples

The asphalt concrete mixtures were subjected to roller compaction as per EN12697-33, (2007) 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 mixture of asphalt concrete. 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, 2015. Three slab samples were prepared while 18 beam specimens were obtained. The prepared beams were tested for fatigue with the aid of four point bending beam technique by the application of repeated flexural stress as per AASHTO T 321, (2007). The first part of the beams was tested at a constant strain level of 250 microstrains, a frequency level of 5 Hz and testing temperature of 20°C. The second part of the beam specimens was tested at constant stress level of 100 kPa, a frequency level of 5 Hz, under 20°C environment. The test results were monitored and recorded, while it was terminated when the stiffness of the asphalt concrete mixture declines to 50 % of its original value. All tests were run in the constant strain or stress modes of successive haversine cycles. The constant maximum strain level was monitored by measuring deflection at the middle of the beam. Figure 1 exhibit the roller compactor while Figure 2 exhibits the four-point bending beam test setup.

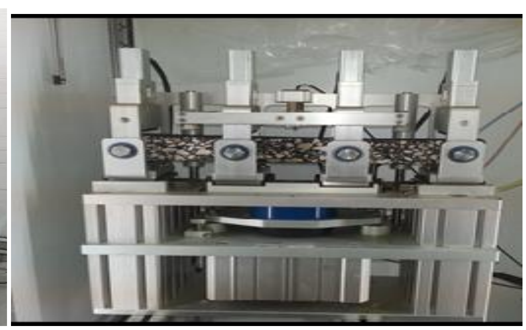

Figure 1 The Roller Compactor **Figure 2** Four points bending beam test

3. RESULTS AND DISCUSSIONS

Influence of Testing Mode on Permanent Deformation and Fatigue Life

Figure 3 demonstrates the influence of testing mode on permanent deformation, it can be observed that the constant strain mode exhibits higher permanent microstrain as compared with the constant stress mode of testing after 4 load repetitions.

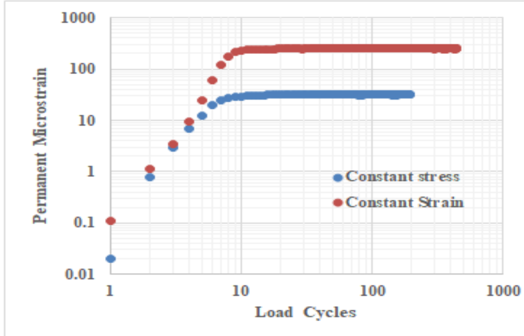

Figure 3 Influence of testing mode on permanent deformation

However, the permanent deformation exhibits a constant trend after 10 load repetitions regardless of the testing mode. The fatigue life as expressed by the reduction of the stiffness of asphalt concrete is (480 and 210) load cycles for constant strain and constant stress mode of testing respectively. The permanent deformation at the fatigue life (Nf) was (250 and 30) microstrain for constant strain and constant stress mode of testing respectively. It can be revealed that the fatigue life of constant strain mode of testing is longer by 128.5 % and the permanent deformation is higher by 733 % than that of constant stress mode of testing respectively.

Influence of Testing Mode on Flexural Stiffness

Figure 4 exhibit the variation of flexural stiffness of asphalt concrete with load cycles due to the testing mode. It can be noticed that the first stage of loading is characterized by the rapid reduction of the flexural stiffness and only accounts for approximately 1% of the total fatigue life. The second stage of loading is characterized by an approximate linear reduction in the flexural stiffness with the number of the loading cycles. This could represent the flexural stiffness of the beam specimen. This implies that, during this period, the rate of damage accumulation is, approximately constant. This part of the relationship accounts for approximately 95% of the total fatigue life and it is considered as the stage where the possible micro cracks are initiated. The third stage of loading characterizes a sudden decrease in the flexural stiffness as the specimen approaches failure. This stage was not reached since the test was terminated when the stiffness declines to 50 % of its original value. It can be noticed that higher flexural strength could be noticed when the test was conducted under constant strain. The flexural stiffness declines as the repeated flexural stresses proceeds regardless of the testing mode. The reduction of stiffness can be related to the micro crack that appeared in asphalt concrete. After the first load repetition, the flexural stiffness was 28.5 % higher when the asphalt concrete beam specimens were tested at constant strain mode as compared with that at constant stress mode. However, such variation in flexural stiffness is almost maintained throughout the test. Similar behavior was reported by Hosseini et al., (2009).

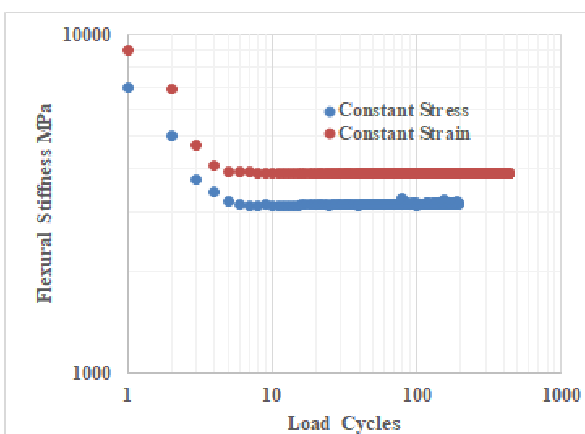

Figure 4 Influence of testing mode on flexural stiffness

Influence of Testing Mode on cumulative dissipated energy

Figure 5 demonstrates the influence of testing mode on cumulative dissipated energy of asphalt concrete. The dissipated energy increases as the flexural stresses repetitions proceeds regardless of the testing mode. However, after the first load repetition, the dissipated energy increased from (10^{-10} to 10^{-9}) MJ/m^3. Sharp increase in the energy dissipation is observed as the loading proceed up to almost 4 to 5 load cycles when it reaches (10^{-7} to 10^{-4}) MJ/m³ for constant strain and constant stress respectively, while it exhibits a constant trend throughout the rest of the test. Similar behavior was reported by Shen et al., (2006).

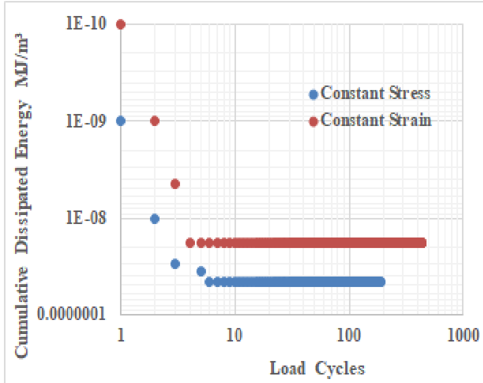

Figure 5 Influence of testing mode on cumulative dissipated energy

Influence of Testing Mode on Phase Angle

Figure 6 exhibit the influence of testing mode on the change in phase angle of asphalt concrete with initial loading cycles. It can be noticed that after the first load repetition (N=1), the constant stress mode exhibits a high phase angle of 47° as compared with 17° for constant strain mode. It can be observed that the phase angle declines as the repeated flexural stresses proceeds regardless of the testing mode. However, the phase angle vanishes after (7 and 5) load repetitions for constant stress and constant strain modes respectively.

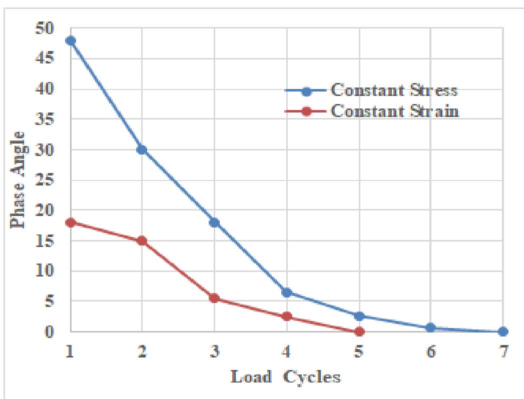

Figure 6 Influence of testing mode on phase angle

Influence of Testing Mode on Microstrain-Dissipated Energy Relationship

Figure 7 demonstrates the influence of testing mode on permanent deformation- dissipated energy relationship. It can be detected that as the energy dissipation increases, the permanent deformation in microstrain also increases. However, higher dissipated energy is required in case of constant stress mode of testing than that for constant strain mode. Similar behavior was reported by Shu et al., (2008). On the other hand, higher permanent microstrain was achieved under constant strain mode as compared with constant stress mode. The permanent microstrain increases by 149 % when the dissipated energy increases from (1 to 950) MJ/m³ for constant stress mode while it increases by 3000 % when the dissipated energy increases from (10^{-12} to 10^{-7}) MJ/m³ for constant strain mode. Lower dissipated energy is required in case of constant strain to exhibit a permanent deformation than that required for the constant stress mode. Such finding agrees with Maggiore et al., (2014).

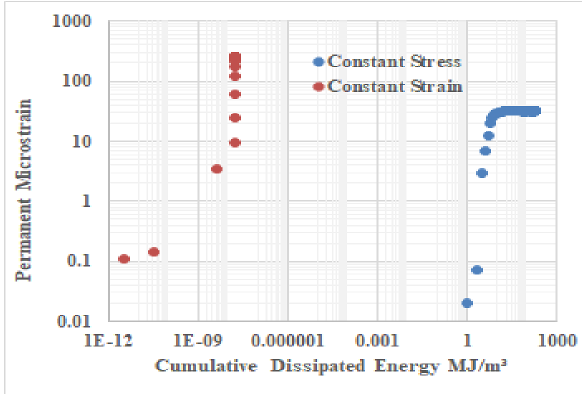

Figure 7 Influence of testing mode on permanent deformation- dissipated energy relationship

Influence of Testing Mode on Flexural Strength-Dissipated Energy Relationship

Figure 8 exhibit the influence of testing mode on flexural stiffness-dissipated energy relationship. It can be noticed that as the dissipated energy increases, the flexural stiffness of asphalt concrete declines sharply for constant stress mode of testing while it declines gently for constant strain testing mode. However, higher flexural stiffness can be observed at the start of repeated loading for constant stress mode as compared with constant strain mode.

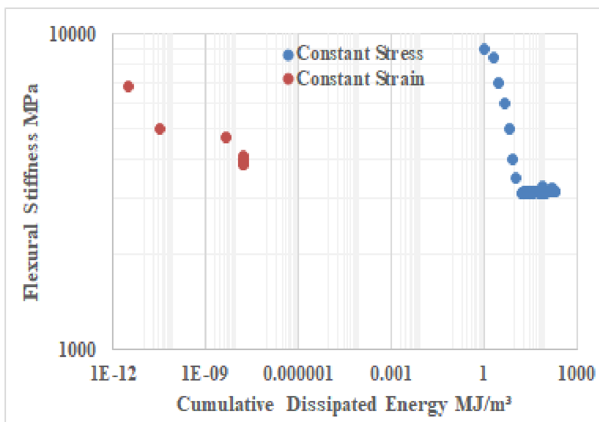

Figure 8 Influence of testing mode on flexural stiffness - dissipated energy relationship

On the other hand, the influence of increasing the energy dissipation under constant stress on flexural stiffness is more pronounced as compared with the constant strain mode. The reduction of flexural stiffness is 66.6 % when the dissipated energy increases from (1 to 950) MJ/$m^3$for constant stress mode while the reduction in flexural stiffness for constant strain mode is 47.1 % when the dissipated energy increases from (10^{-12} to 10^{-7}) MJ/m^3. However, higher dissipated energy is required in case of constant stress to exhibit a proper flexural stiffness than that required for the constant strain mode. It can also be monitored that the applied constant stress exhibit constant creep in the asphalt concrete specimen while the applied constant strain exhibit relaxation. Such behavior agrees with the work reported by Wu et al., (2014).

4. CONCLUSION

Based on the limitations of materials and the testing program, the following conclusions can be drawn. The fatigue life of constant strain mode of testing is longer by 128.5 % and the permanent deformation is higher by 733 % than that of constant stress mode of testing respectively. After the first load repetition, the flexural stiffness was 28.5 % higher when the asphalt concrete beam specimens were tested at constant strain mode as compared with that at constant stress mode. Sharp increase in the energy dissipation is observed as the loading proceed up to almost 4 to 5 load cycles when it reaches (10^{-7} to 10^{-4}) MJ/m^3 for constant strain and constant stress respectively, while it exhibits a constant trend throughout the rest of the test. The constant stress mode exhibits a high phase angle of 47° as compared with 17° for constant strain mode, the phase angle declines as the repeated flexural stresses proceeds regardless of the testing mode.

The reduction of flexural stiffness is 66.6 % when the dissipated energy increases from (1 to 950) MJ/m^3 for constant stress mode while the reduction in flexural stiffness for constant strain mode is 47.1 % when the dissipated energy increases from (10^{-12} to 10^{-7}) MJ/m^3. Higher dissipated energy is required in case of constant stress mode of testing to exhibit a proper flexural stiffness than that for constant strain mode. Lower dissipated energy is required in case of constant strain to exhibit a permanent deformation than that required for the constant stress mode. Choice of the testing mode of asphalt concrete is essential in the evaluation of asphalt concrete properties and the variation in such properties is significant among the testing mode.

Ethical approval

Not applicable.

Informed consent

Not applicable.

Conflicts of interests

The authors declare that there are no conflicts of interests.

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Data and materials availability

All data associated with this study are present in the paper.

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