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(Research Article)

Sensitivity of Viscoelastic Properties of Asphalt Concrete to the Variation in Binder Content

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Abstract

The variation of asphalt binder content from that of the job mix formula usually influence the viscoelastic properties of asphalt concrete mixture. In the present investigation, asphalt concrete mixtures for wearing course are prepared at ± 0.5 % of the optimum binder content. Asphalt concrete slab samples were prepared using roller compaction. Beam specimens were obtained from the slab samples and tested for viscoelastic properties after practicing long term ageing and moisture damage. The phase angle, and cumulative dissipated energy as a major viscoelastic properties were evaluated with the aid of four-points bending beam test at 20 ºC environment and under constant microstrain level of 750. It was noticed that the specimens prepared with lower than optimum binder content exhibit the higher phase angle after practicing moisture damage or long term ageing. The phase angle decline to a range of (35-15) ° and (10-26) ° for moisture damaged mixture and long term aged mixture at 5.3 % binder content. The phase angle increases to an optimum value of (46 and 54) ° for mixtures prepared with (4.3 and 5.3) % binder respectively. It was concluded that the viscoelastic properties of asphalt concrete in terms of phase angle, and cumulative dissipated energy, are greatly sensitive to the variation in binder content. It was recommended that a stringent control of binder content should be implemented in the field to enhance the viscoelastic properties of asphalt concrete throughout its service life.

Keywords: Asphalt binder, Ageing, Sensitivity, Phase angle, Dissipated energy.

1. Introduction

Varma et al., [1], investigated the fatigue life of asphalt concrete mixtures using the four-point bending test. Two sets of asphalt concrete specimens were subjected to repeat strain-controlled sinusoidal loading at 20°C and 10 Hz frequency. The corresponding strain and stress data were collected at 1/1000 second interval. Data were implemented to calculate the total dissipated energy. The dissipation due to damage is calculated by separating viscoelastic dissipation from the total dissipation of energy. A linear viscoelastic model was implemented. It was revealed that the discontinuity in the evolution of phase angle determined from the strain–stress plot is considered as the onset of fatigue damage. The fatigue properties were evaluated of asphalt concrete specimens by Pasetto and Baldo, [2] in strain and stress control modes. For the fatigue analysis, a dissipated energy method, based on the internal damage produced within the asphalt concretes was implemented. The damage curves, as expressed in terms of the ratio of dissipated energy change, for both the stress and strain control modes, were elaborated and statistically analysed to verify the fatigue analysis of asphalt concrete. Sarsam, [3] assessed the variations in the dissipated energy through the process of fatigue resistance of asphalt concrete mixture. Beam specimens were tested using the dynamic four-point flexure bending beam test in controlled strain mode. The dissipated energy per load cycle was monitored through the changes in the behaviour of the mixture and through the damage accumulation. The impact of strain level, asphalt content, and testing temperature on dissipated energy was discussed and compared. Rondón-Quintana et al., [4] stated that the calibration difficulty of the fatigue in asphalt mixtures models exists since the mathematical equations must be in capacity of considering that fatigue resistance of asphalt mixtures depends on the type of load (haversine or sinusoidal), the rest periods to which laboratory samples are subjected, and load mode (strain-controlled or stress-controlled). Additionally, variations with stiffness, volumetric composition, the geometry of samples and environmental conditions can affect mix durability. It was concluded that if these physical parameters are not considered, the mathematical equations will lose its reliability. Moreno-Navarro and Rubio-Gámez, [5] revealed that fatigue cracking is considered as one of the main distresses which is responsible for the decline in the service life of asphalt concrete pavements. The fatigue phenomena are important for enhancing the durability of the pavement. It was concluded that the influence that permanent deformations can exert on the mechanical response of materials and the

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reversible phenomena of the damage during the development of fatigue processes should be assessed. Bessa et al., [6] addressed that predicting asphalt pavements fatigue performance in relation to the main distresses can be monitored through laboratory characterisation and field evaluation. Various approaches may be implemented to determine what failure criterion to be considered, what testing conditions to be used, and which specimens' geometry to be produced. Some of the most common tests are diametral compression, the four-point bending beam, and the push-pull tests. Racanel and Burlacu, [7] addressed that the asphalt binder gives an asphalt pavement waterproofing property, supports its flexibility, and binds the aggregate together. However, the binder content is a key mixture design parameter. Zou et al., [8] stated that for a viscoelastic material, such as the asphalt concrete mixture, the external work applied to the material is consumed in part by inducing cracking on the surface and in part by inducing flow deformation. The binder content plays a major part in such behavior. Mandula and Olexa, [9] assessed asphalt mixture problems which are caused by its inner properties and the behavior of material under dynamical loading. The phase angle was also studied as an indicator of viscoelastic behavior. It was stated that phase angle observation is important for better understanding of structural material behavior. It was observed that the phase angle value became stabilized after one third of the test duration while strong increase in the phase angle started slightly before failure point. It was concluded that sudden increase in the phase angle is one of the indicators of material lifespan ending. Carmo et al., [10] analyze the structural sensitivity of a flexible pavement, which exhibits variations in its mechanical properties due to the asphalt binder content. A variation of ±0.5% within the optimum asphalt binder contents was used as service tolerance during the asphalt mixture manufacturing process. The indirect tensile strength and the resilient modulus of the mixtures were used for the structure analysis. The results show that the variations in the asphalt binder content influence the mechanical properties and corresponding structural responses of the investigated pavement. Omranian et al., [11] assessed the influence of short-term ageing process on the volumetric properties and compactibility of asphalt concrete. Three different binders were utilized to prepare asphalt concrete mixtures. Volumetric properties and compactibility are considered as dependent variable, while ageing duration and ageing temperature are recognized as an independent variable. The findings revealed that there is significant impacts of ageing temperature and duration on compactibility, air voids, voids in mineral aggregate, and voids filled with asphalt. Rahmani et al., [12] revealed that the stiffness modulus of asphalt concrete may increase by four folds after the ageing process based on the binder type. However, this may cause the mixture to become stiffer and brittle so that it will be susceptible to fatigue cracking at low temperatures and disintegration. The behavior of asphalt concrete depends mainly on the rheological behavior of the asphalt binder as reported by Shafabakhsh et al., [13]. Asphalt binder behaves in a visco-elastic manner, therefore the behavior of asphalt concrete mixtures changes with the change in environment temperature. The asphalt binder exhibits visco elasto-plastic behavior at high temperature while it exhibits elastic behavior at low temperatures. Al-Khateeb and Alqudahaims, [14] assessed the impact of laboratory ageing on the fatigue-life perfor¬mance of asphalt concrete mixtures. The mixtures were subjected to short and long-term ageing then tested for fatigue using the repeated indirect tensile test at various initial strain levels. It was observed that the short-term ageing led to an increase in fatigue-life. Findings also showed that the fatigue-life of asphalt concrete increased as the testing temperature increase. Sarsam, [15] investigated the influence of ageing process on the flexural stiffness of asphalt concrete specimens through the fatigue process. It was detected that the stiffness is susceptible to ageing while the increase in microstrain level leads to a remarkable reduction in initial and failure stiffness's. It was concluded that the stiffness is susceptible to the asphalt content, higher binder content exhibit a negative impact on the stiffness. The aim of the present investigation is to assess the sensitivity of the viscoelastic properties of asphalt concrete mixtures to the variation in asphalt cement content. The assessment will be conducted based on dynamic flexural behavior throughout the fatigue life of the mixture. The phase angle, and cumulative dissipated energy, will be assessed through the fatigue process.

2. Materials and Methods

The materials implemented in the present investigation are locally available and are widely used in asphalt pavement construction.

2.1 Asphalt Cement: Asphalt cement of penetration grad 40-50 was implemented in this work. It was obtained from AL-Nasiriya Refinery. The physical properties of asphalt binder are listed in Table 1.

Table 1. Physical Properties of Asphalt Cement Binder

Physical properties	ASTM, [16] Designation	Asphalt cement	SCRB, [17]
Penetration	D5-06	42	40-50
Softening Point °C	D36-95	49	-
Ductility Cm	D113-99	100+	>100
Specific Gravity	D70	1.04	-
Flash Point °C	D92-05	269	>232
Retained Penetration of Residue	D5-06	33	<55
Loss in weight (163°C, 50g,5h) %	D-1754	0.175	---
Ductility of Residue	D113-99	130 cm	>25

2.2 Fine and Coarse Aggregates: Crushed coarse aggregates (retained on sieve No. 4) was obtained from AL-Ukhaider quarry. Crushed and natural sand mixture was implemented as fine aggregate (passing sieve No.4 and retained on sieve No.200). It was obtained from the same source. The aggregates were washed, then air dried and separated into different sizes by sieving. The physical properties of aggregates are demonstrated in Table 2.

Table 2. The Physical Properties of Coarse and Fine Aggregate as per ASTM, [16]

Property	Coarse Aggregate	Fine Aggregate
Bulk Specific Gravity (ASTM C 127 and C 128).	2.642	2.658
Percent Water Absorption (ASTM C 127 and C 128)	1.07	1.83
Percent Wear (Los-Angeles Abrasion) (ASTM C 131)	18 %	------

2.3 Mineral Filler: The mineral filler implemented in the present investigation is the limestone dust which was obtained from Karbala governorate. The filler passes sieve No.200 (0.075mm). The physical properties of the mineral filler are presented in Table 3.

Table 3. The Physical Properties of Mineral Filler

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

2.4 Selection of Aggregates Combined Gradation: The selected aggregates gradation in the present investigation follows SCRB, [17] specification for dense graded wearing course pavement layer with 12.5 mm nominal maximum size of aggregates. Table 4 shows the selected aggregate gradation.

Table 4. Aggregates Gradation implemented for Wearing Course as per SCRB, [17]

Sieve size mm	Selected gradation	SCRB, [17] Specifications
19	100	100
12.5	95	95-100
9.5	83	76-90
4.75	59	44-74
2.36	43	28-58
0.3	12	5-12
0.075	7	4-10

2.5 Preparation of Asphalt Concrete Mixture and Specimens: The fine and coarse aggregates were combined with mineral filler to meet the specified gradation for wearing course. The combined aggregates were then heated to 160 ºC before mixing with asphalt cement. The asphalt cement was heated to 150 ºC, then, the binder was added to the heated aggregate to the desired amount and mixed thoroughly by hand using a spatula for two minutes so that the aggregate particles are coated with the binder. The mixture was subjected to short-term ageing process for 4 hours at temperature of 135 ºC according to AASHTO R-30, [18]. The optimum asphalt content of 4.9% was implemented. 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 Alwan, [19]. The short-term aged mixtures were casted in a slab mold of (40 x 30 x 6) cm and subjected to roller compaction to the target bulk density for each binder percentage according to EN12697-33, [20]. The applied static load was 5 kN while the number of load passes depended on the asphalt content in the mixture and was determined based on trial-and-error process. Details of the compaction process could be referred to Sarsam, [21]. The compaction temperature was maintained to 150 °C. Slab samples were left to cool overnight. Beam specimens of 50±2 mm high, 63±2 mm wide 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 Long-term Ageing of Beam Specimens: Part of the beam specimens was subjected to oxidation ageing (long-term ageing), beams have been stored in an oven for five days (120 hours) at 85°C as per AASHTO R-30, [22] procedure. Specimens were then withdrawn from the oven and stored in the testing chamber for two hours at the required testing temperature of 20°C for the fatigue test.

2.7 Conditioning of Beam Specimens for Moisture Damage: Another group of the beam specimens was subjected to moisture damage by conditioning the beams in water bath at 25º C for two hours, the air in the voids was evacuated using a compressor with a vacuum of 3.74 kPa applied for 10 minutes to obtain 80 % saturation. The asphalt concrete beam specimens were then placed in a deep freeze at (-18°C) for 16 hours. The frozen beam specimens were then moved to a water bath and stored for 24 hours at (60ºC). Then they were dried and placed in the testing chamber for two hours at 20º C before testing for fatigue life. The only deviation of this procedure from that described in AASHTO, [18] is that the tested specimen is a beam and not a cylindrical specimen.

2.8 Repeated Flexural Bending Beam Test: The four-point repeated flexural bending beam test according to AASHTO T321, [22] was implemented to identify the influence of additives on the fatigue life and flexural stiffness of asphalt concrete beam specimens at intermediate pavement operating temperature of 20 °C and under constant microstrain level of 750. During the flexural fatigue test, the beam is subjected to repeated four-point loading. The load frequency is usually set 5 Hz, and the deflection caused by the loading is measured at the center of the beam. The test was terminated when the beam has reached a 50 percent reduction in stiffness. A repeated sinusoidal (tension-compression) load is applied to the two inner clamps on the beam specimen with the outer clamps providing a reaction load. This setup produces a constant bending moment over the center portion of the beam (between the two inside clamps). Beams were subjected to a repeated load at a constant strain level. One constant Micro strain level of 750 was tried to simulate heavy traffic mode of loading in the field. Figure 1 exhibit the dynamic flexural bending beam test setup while Figure 2 shows part of the prepared asphalt concrete beam specimens.

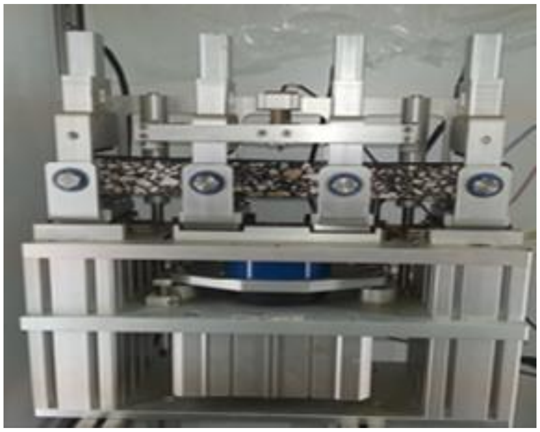

Figure 1. Dynamic flexural bending beam test

Figure 2. Part of the prepared Beam Specimens

3. Results and Discussion

3.1 Influence of Binder Content on Phase Angle: The phase angle is one of the principal measure of visco-elastic behavior of asphalt concrete mixture. It represents the phase delay between amplitude of applied strain and amplitude of corresponding stress. The phase angle is the parameter which has to be measured for calculations of the dissipated energy, and modulus and its elements. Figure 3 exhibit the influence of binder content on Phase Angle for control asphalt concrete mixture, it can be observed that higher binder content of 5.3 % shows higher phase angle as compared with lower binder content of 4.3 %. The phase angle increases to an optimum value of (46 and 54) ° for mixtures prepared with (4.3 and 5.3) % binder respectively, then decline as the flexural stiffness increases regardless of the binder content. The rate of increase in the phase angle is gentle before reaching the optimum value while the rate of decline in the phase angle after the optimum is sharp. The flexural stiffness describes a material´s dynamic response to sinusoidal loading. The measurements and calculations of complex modulus in this paper are performed according to the European standard. According to this standard, the stiffness modulus represents the numerical value of the complex modulus. If the phase angle of asphalt concrete mixture is closer to 0 °, this indicates the elastic state and the real element of the flexural stiffness is higher. However, when the phase angle is closer to 90 °, it indicates the viscous state and, the virtual element of the flexural stiffness is predominant. Such behavior agree with Mandula and Olexa, [9].

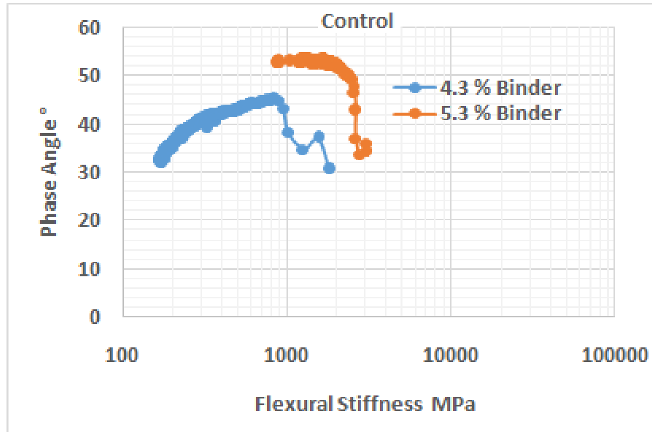

Figure 3. Influence of Binder Content on Phase Angle for Control Mixture

Figure 4 demonstrates the influence of binder content on Phase Angle for moisture damaged asphalt concrete specimens. It can be noticed that the phase angle declines sharply as the flexural stiffness increases regardless of the binder content.

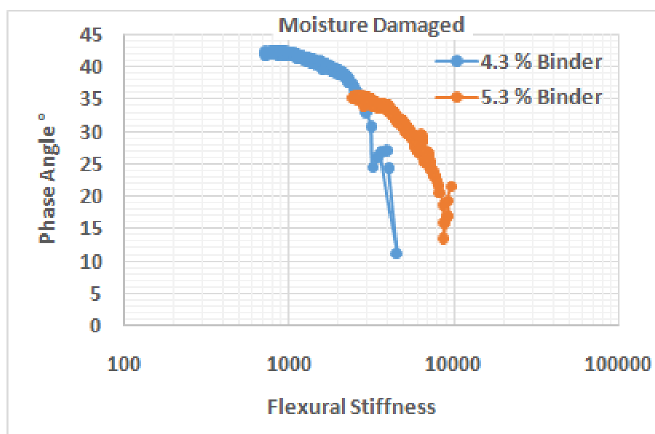

Figure 4. Influence of Binder Content on Phase Angle for Moisture Damaged Mixture

This may be attributed to the stripping of asphalt binder and the loss of strength due to the moisture damage. Lower phase angle could be noted at higher binder content for asphalt concrete mixtures practiced the moisture damage as compared with that at lower binder content. On the other hand, the phase angle decline to a range of (35-15) ° for moisture damaged mixture at 5.3 % binder content as compared with the control mixture which exhibit a phase angle range of (54 - 35) ° at 5.3 % binder content.

Figure 5 demonstrates asphalt concrete mixtures after practicing long term ageing, the phase angle increases as the flexural stiffness increase to an optimum, then declines after further increase regardless of the binder content. Aged asphalt concrete mixture prepared with 4.3 % asphalt binder content exhibit higher phase angle with a range of (10-54) ° as compared with aged asphalt concrete mixture prepared with 5.3 % binder with a range of (12-26) °. It can be noticed that the phase angle declines for asphalt concrete mixtures after practicing long term ageing process. The phase angle decline to a range of (10-26) ° for long term aged mixture at 5.3 % binder content as compared with the control mixture.

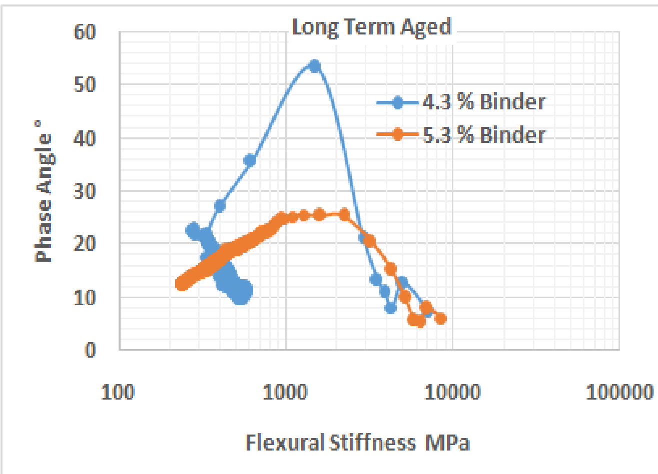

Figure 5. Influence of Binder Content on Phase Angle for Aged Mixture

3.2 Influence of Binder Content on Dissipated Energy: Asphalt concrete mixture usually dissipates the energy when practicing mechanical work which is generated from loading and relaxation. For the Visco-elastic materials like asphalt concrete mixture, energy is stored in the mixture when the load is applied. Most of the energy is recovered when the load is removed because the unloaded material exhibits a different path to that when it is loaded and the phase lag is recorded between the measured strain and the applied stress, the energy is dissipated in the form of mechanical work, or damage. Dissipated energy is measured to evaluate the fatigue life of asphalt concrete mixtures. The dissipated energy is calculated for each loading cycle, while the change in dissipated energy for different cycles indicates the start of cracking and failure of the asphalt concrete mixture. The cumulative dissipated energy is the summary of dissipated energy in every cycle until collapse of the material as addressed by Abojaradeh, [23]. Figure 6 exhibit the change of cumulative dissipated energy through the fatigue life of asphalt concrete for control and long term aged mixture. It can be detected that the control specimens exhibit higher cumulative dissipated energy than the aged specimens regardless of the binder content. However, higher binder content exhibit higher cumulative dissipated energy for control and aged specimens.

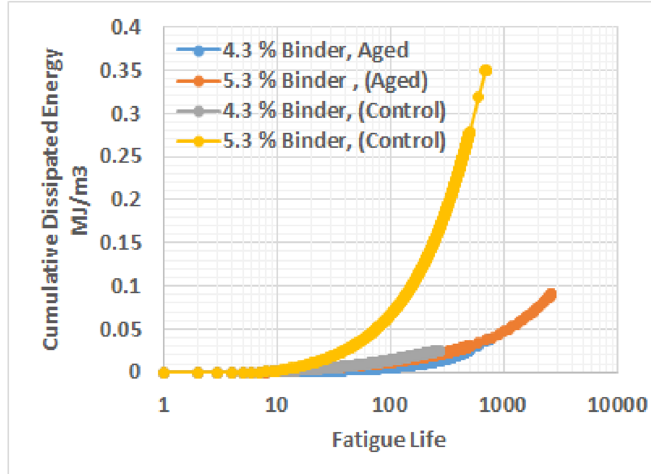

Figure 6. Influence of Binder Content and Ageing on Dissipated Energy

Figure 7 demonstrates the influence of binder content and moisture damage on the dissipated energy through the fatigue process of asphalt concrete. It can be detected that moisture damage mixtures shows higher dissipated energy than that of control mixtures regardless of the binder content. However, asphalt concrete specimens prepared with higher binder content of 5.3 % exhibit higher dissipated energy as compared with specimens prepared with low binder content of 4.3 %. The test results agree with Tauste et al., 2018.

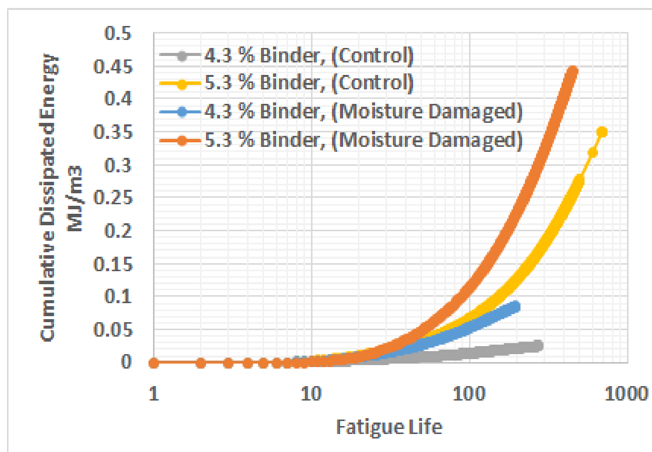

Figure 7. Influence of Binder Content and Moisture Damage on Dissipated Energy

4. Conclusions

Based on the limitation of the testing and the materials, the following conclusions may be addressed.

- The phase angle increases to an optimum value of (46 and 54) ° for mixtures prepared with (4.3 and 5.3) % binder respectively, then decline as the flexural stiffness increases regardless of the binder content.

- The phase angle decline to a range of (35-15) ° for moisture damaged mixture at 5.3 % binder content as compared with the control mixture which exhibit a phase angle range of (54 - 35) ° at 5.3 % binder content.
- The phase angle decline to a range of (10-26) ° for long term aged mixture at 5.3 % binder content as compared with the control mixture.
- Higher binder content exhibit higher cumulative dissipated energy for control, moisture damaged, and long term aged specimens.

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