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FATIGUE LIFE OF MALAYSIAN HOT MIX ASPHALT MIXTURES

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Abstract: Fatigue cracking is one of the major types of distress in asphalt concrete pavements. Under the action of repeated vehicle loading, the asphalt concrete deteriorates and eventually results in fatigue cracking. This study investigated the effect of temperature, aggregate gradation, nominal maximum aggregate size, and asphalt types on the fatigue life of hot mix asphalt (HMA) mixtures. Six mixtures conforming to JKR/SPJ/2008 were selected, namely asphaltic concrete with a nominal maximum aggregate size of 10 mm (AC10) and 14 mm (AC14), polymer-modified asphalt concrete 10 mm (PMA10) and 14 mm (PMA14), and stone mastic asphalt 14 mm (SMA14) and 20 mm (SMA20). Specimens were prepared with the optimum asphalt content using the Marshall Mix design procedure. An indirect tensile test for the resilient modulus was performed according to ASTM D 4123. A fatigue test was also conducted to determine the performance of the mixtures. The specimens were prepared using 80/100 penetration grade asphalt for AC10 and AC14, and PG76 asphalt for PMA10, PMA14, SMA14, and SMA20. Fatigue tests with constant stress were performed using a Universal Testing Machine at 25 ˚C and 40 ˚C at a load of 1000 N. Results show that the fatigue life of asphalt mixtures was lower at 40˚ C than at 25 ˚C. It was also observed that the mixtures with the smallest nominal maximum aggregate size had a higher fatigue life. The PMAs developed greater fatigue performance than SMAs and ACs due to the aggregate gradation and asphalt type.

Keywords: *Hot mix asphalt; polymer-modified asphalt concrete; stone mastic asphalt; Marshall mix design; indirect tensile test; fatigue test*

1.0 Introduction

Fatigue cracking of the bituminous layer is a primary structural distress mode within flexible road pavement material systems [1]. It consists of two main phases, crack initiation and crack propagation, and is caused by tensile strains generated in the pavement by not only traffic loading but also temperature variations and construction practices [2]. Much research and innovation has been done to improve the quality of the mixture; however, the problem of fatigue cracking is still persistent on asphalt roads [3]. This distress reduces the service life of the pavement and increases the maintenance cost [4].

The prediction of fatigue performance for a particular mixture traditionally required involved and specialised testing equipment. Many diverse test geometries have been developed over the past 40 years to simulate the fatigue behaviour of bituminous road construction materials, with varying success. These devices can be categorised into simple flexure (two-, three-, and four-point bending), supported flexure, uniaxial fixtures, triaxial fixtures, diametral fixtures, and wheel tracking fixtures [1]. Understanding the ability of an asphalt pavement to resist fractures from repeated loading is essential to develop superior hot-mix asphalt (HMA) pavement designs. However, reaching a better understanding of the fatigue behavior of asphalt pavements continues to challenge researchers worldwide, particularly as newer materials with more complex properties are being used in the field [5].

To reduce pavement distresses, there are different solutions such as adopting new mix designs or by using asphalt additives. Using asphalt additives in highway construction is known to give conventional bitumen better engineering properties as well as being helpful in extending the lifespan of asphalt concrete pavement [1]. Therefore, this study investigates the fatigue behavior of various mixtures, namely asphaltic concrete with a nominal maximum aggregate size of 10 mm (AC10) and 14 mm (AC14), polymer-modified asphalt concrete 10 mm (PMA10) and 14 mm (PMA14), and stone mastic asphalt 14 mm (SMA14) and 20 mm (SMA20). The effect of temperature, aggregate size and gradation type, and asphalt content and types on the resilient modulus and fatigue life of various HMA are also investigated.

2.0 Experimental Design

To satisfy the objectives of this study, HMA, PMA, and SMA specimens were prepared at the optimum asphalt content using the Marshall Mix design procedure. Two types of asphalt were used in this study: asphalt with penetration grade 80/100 for HMA, and Performance Grade (PG) 76 for PMA and SMA. Two aggregate gradations were used in preparing HMA, PMA, and SMA specimens. Fatigue tests were performed on the prepared Marshal specimens to evaluate the effect of temperature, aggregate types and gradation, and asphalt content and types on fatigue life.

2.1 Materials

2.1.1 Aggregate

Crushed limestone was used as the aggregate in this study. The aggregate was obtained from the IJM quarry ULU CHOH in Johor Bahru, South of Malaysia. The aggregate's gradations for AC10, AC14, PMA10, and PMA14 are shown in Figure 1, and those for SMA14 and SMA20 are presented in Figure 2. The physical properties of the aggregates can also be seen in Table 1. Portland cement was used as the filler material for the mix design in all mixtures in this study.

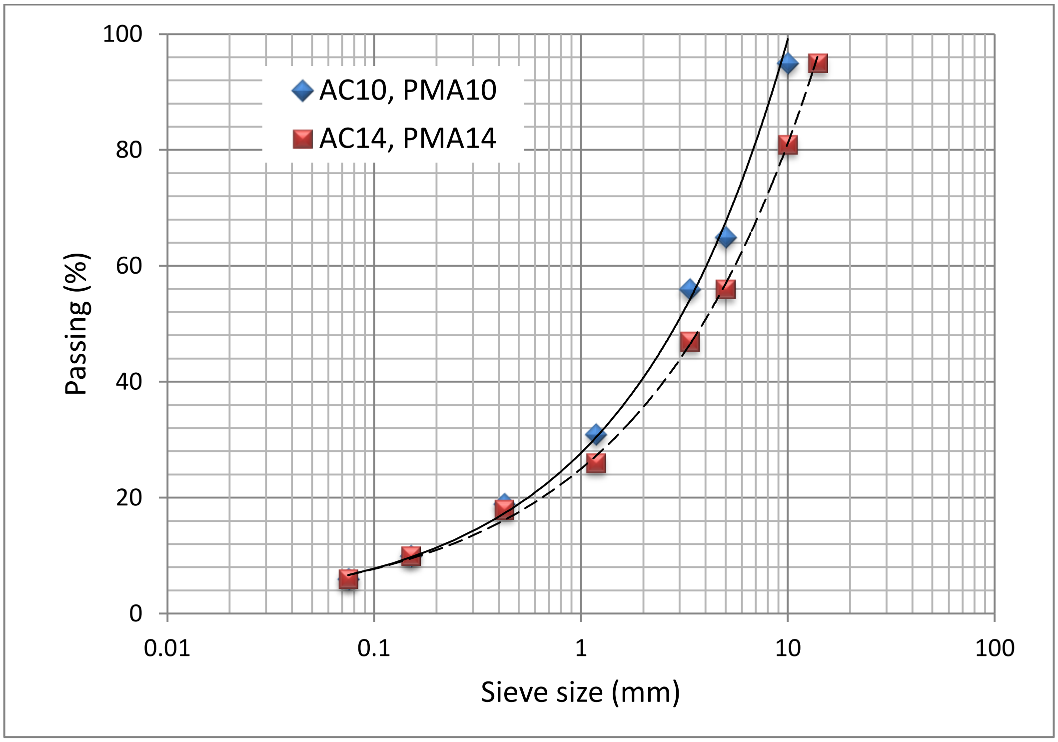

Figure 1: Gradation of used aggregate (AC10, AC14, PMA10 and PMA14)

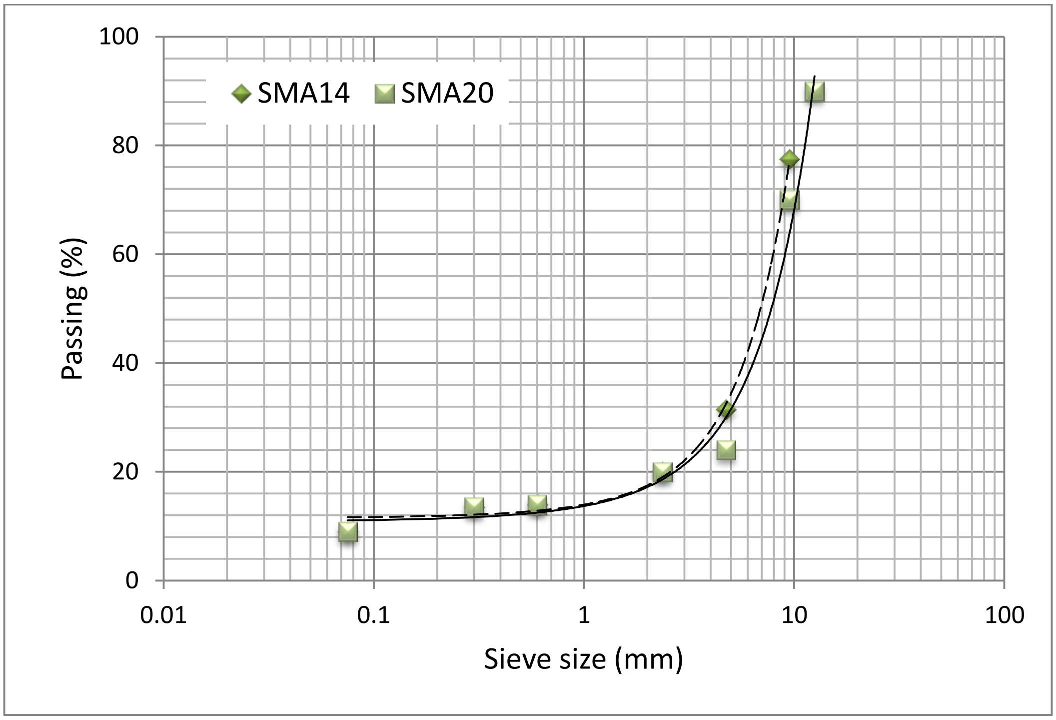

Figure 2: Gradation of used aggregate (SMA 14 and SMA 20)

Table 1: Properties of Aggregate

Mixtures	AC10 & PMA10	AC14 & PMA14	SMA14	SMA20
The aggregate Retained on 5 mm Sieve				
Bulk Specific Gravity	2.592	2.585	2.540	2.600
Apparent Specific Gravity	2.643	2.641	2.650	2.655
Water Absorption (%)	0.74	0.82	0.02	1.40
The Aggregate Passing 5 mm Sieve				
Bulk Specific Gravity	2.388	2.410	2.596	2.620
Apparent Specific Gravity	2.466	2.488	2.682	2.720
Water Absorption (%)	1.30	1.28	1.19	1.55

2.1.2 Asphalt

Two types of asphalt cement were used in this study: asphalt with 80/100 penetration for HMA, and Performance Grade (PG 76. styrene–butadiene–styrene, SBS) for PMA and SMA. Table 2 shows the asphalt test result.

Table 2: Asphalt Test Result

Type of Asphalt	Average PEN	Average Temperature (˚C)
80/100	85	45
PG 76	55	70

2.2 Optimum Asphalt Content

Six different asphalt mixture types were used through the laboratory works according to JKR/SPJ2008 (the standard specification for road works in Malaysia) – asphalt concrete (AC10, AC14), polymer-modified asphaltic concrete (PMA10, PMA14), and stone mastic asphalt (SMA14 and SMA20). The Marshall Laboratory compaction method was used to prepare all samples. Each mix gradation design was proposed in the laboratory, where three specimens were prepared for each asphalt content at increments of 0.5 percent. The optimum asphalt content (OAC) was determined for each mix. The specimens were prepared at the optimum asphalt content for the fatigue life test. The mixtures' properties are presented in Table 3.

Table 3: The Mixtures Properties

Properties	Mixtures					
	AC10	AC14	PMA10	PMA14	SMA14	SMA20
OAC (%)	6.4	5.3	7.1	6	5.8	6
Stability (N)	10250	9750	14300	13121	15800	15810
Flow (mm)	3.1	2.8	4.5	4.2	3.4	3.6
Stiffness (N/mm)	3306	3433	3136	3124	4647	4392
Air voids (%)	4.2	4.1	4	3.1	4	4.9
Voids filed with asphalt (%)	70	70	71	78	77	75
Voids in mineral aggregate (%)	12.2	12	13.5	13.9	17.2	17.8

2.3 Indirect Tensile Test

Constant stress fatigue tests were performed using the Universal Testing Machine (UTM) under a load of 1000 N at 25 °C and 40 °C. Specimens were subjected to a repeated compressive loading across the vertical cross section along the depth of the specimen using loading strips 12.5 mm in width. The UTM is an electro-hydraulic test system. The loading frame was housed in an environmental chamber to control temperature during a test.

3.0 Results and Discussion

The main objectives of this study were to evaluate the fatigue life of hot mix asphalt mixtures at different temperature (25 ˚C and 40 ˚C), different types of asphalt binder, and different gradations of aggregate. The specimens at the optimum asphalt content with different types of asphalt and different aggregate gradations were prepared according to the American Society of Testing and Materials standards (ASTM D3387-83 and 3496-79). Table 4 shows the results for the Resilient Modulus and Fatigue Life for various HMA mixtures.

Table 4: Summary of Results

Temperature (˚C)	Mix Type	Resilient Modulus (MPa)	Fatigue Life (cycle)
25	AC10	1188	39996
	AC14	1423	40000
	PMA10	2069	64000
	PMA14	2105	60000
	SMA14	1624	58000
	SMA20	1930	55000
40	AC10	314	3800
	AC14	337	1027
	PMA10	404	7860
	PMA14	410	7010
	SMA14	346	6450
	SMA20	387	6380

3.1 Indirect Resilient Modulus

The PMA mixtures have an average stiffness significantly higher than that of the SMA mixtures at any test temperature. This is because the aggregate gradation of PMA mixtures are continuously dense, which makes the mixture stiffer than the gap-graded SMA mixtures. Figure 3 indicates that increasing the asphalt content will decrease the resilient modulus, except for SMA, which could be related to the aggregate gradation. Also, as observed from the figures above, mixtures with a coarse aggregate gradation will show a better resilient modulus than those with a finer aggregate gradation; AC14 is stiffer than the AC10 mix; also, PMA14 is stiffer than PMA10, and SMA20 is stiffer than SMA14.

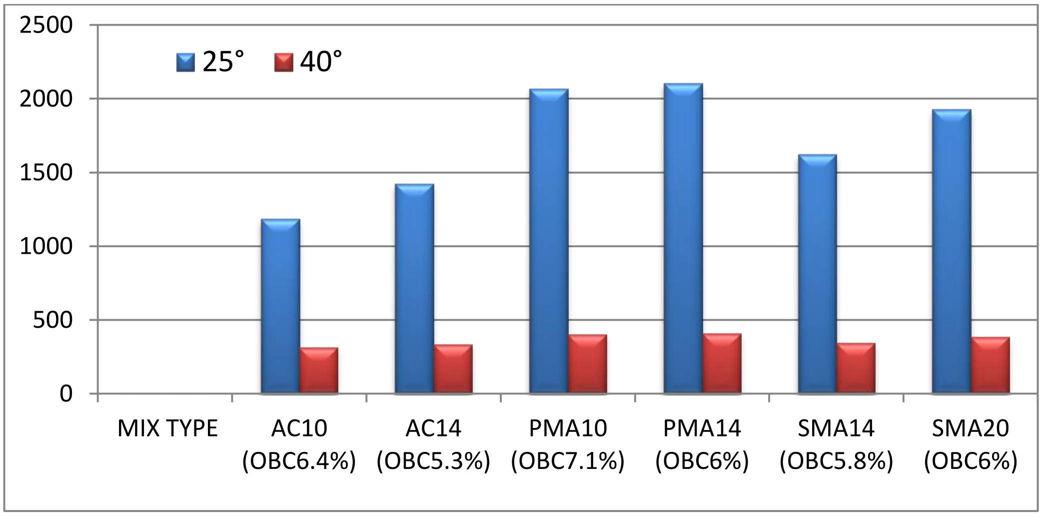

Figure 3: Indirect Tensile Modulus Test

3.2 Indirect Fatigue Life Result

3.2.1 Effect of Temperature on Fatigue Life

Fatigue cracking occurs during intermediate temperatures. Bottom-up fatigue cracking is not caused by the same mechanism that occurs in low temperature cracking. Among the factors that affect fatigue life, the temperature shows the most significant impact. In this study, two temperatures, 25ºC and 40ºC, were selected to address the fatigue condition. Regardless of the types of gradation and asphalt content, all samples tested at 25 ºC had greater fatigue resistance than the samples tested at 40 ºC. This result confirms the finding of Nejad *et al*. [3]. It is because viscosity changes with temperature. Previous studies show that an increase in temperature redistributes the high-weight molecules (asphaltenes) and rebalances the low-weight molecules (maltenes), thus decreasing viscosity. Bhattacharjee [6] illustrates that fatigue life increases with a stiffer mixture if the stress is constant.

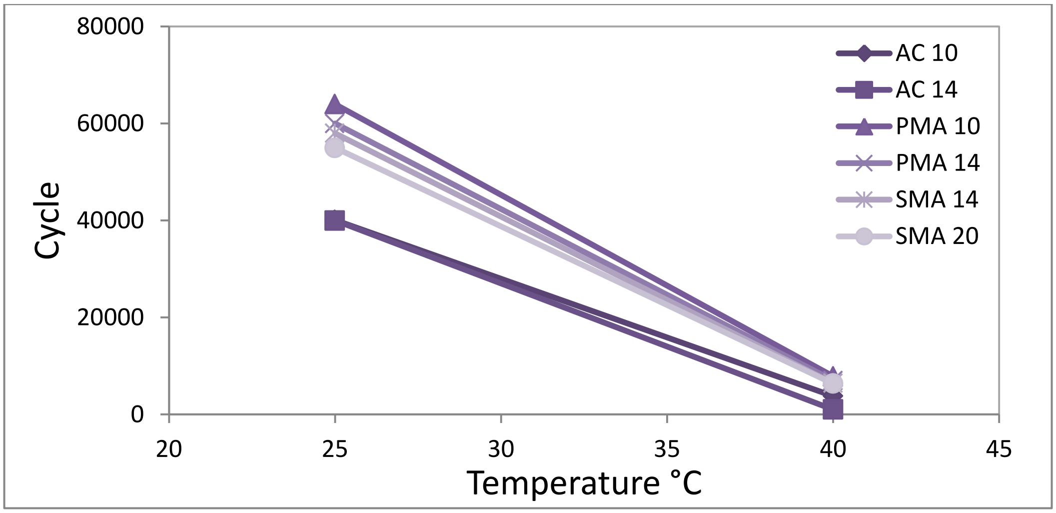

Figure 4: Influence of temperature on fatigue life

3.2.2 *Effect of Gradation Type on Fatigue Life*

The results indicate that the PMA mixtures have a greater fatigue life than SMA, even if the same type of asphalt binder is used. This could be due to the grade difference between the two mixtures. It should be mentioned that this comparison is made for mixtures with the same NMASs (between PMA14 and SMA14). SMA14 has a higher fatigue life compared to AC14, even if the grade for AC14 is the same as PMA 14; this could be due to the use of different types of asphalt.

PMA mixtures with a well-graded (dense grade) aggregate structure have greater interlocking between aggregates, which makes them more resistant to tensile stresses and therefore gives them a greater fatigue life. Gap-graded SMA mixtures have a structure that makes them very rut resistant. This might be due to its resistance against compressive stresses that is supported by its stone matrix [7]. It seems that SMA is not capable of undergoing tensile stresses that will lead to fatigue cracking [8].

3.2.3 *Effect of Aggregate Size on Fatigue Life*

Figure 5 shows that the aggregate gradation has a noticeable effect on fatigue life. At the same temperature and load magnitude, AC10 has the highest fatigue life, followed by the AC14 mix. Also, PMA10 has a longer fatigue life than PMA14, and SMA14 has a longer fatigue life than SMA 20. In other words, asphalt mixtures with a finer aggregate gradation will show a better fatigue life than those with a coarse aggregate gradation. SMA mixtures have smaller fatigue lives when compared with PMA, because SMA has about 70% coarse aggregate, which reduces adhesion, leading to less fatigue resistance. Asphalt mixtures with a finer gradation have a better fatigue life because of better interlocking between the aggregates, making it a denser mixture.

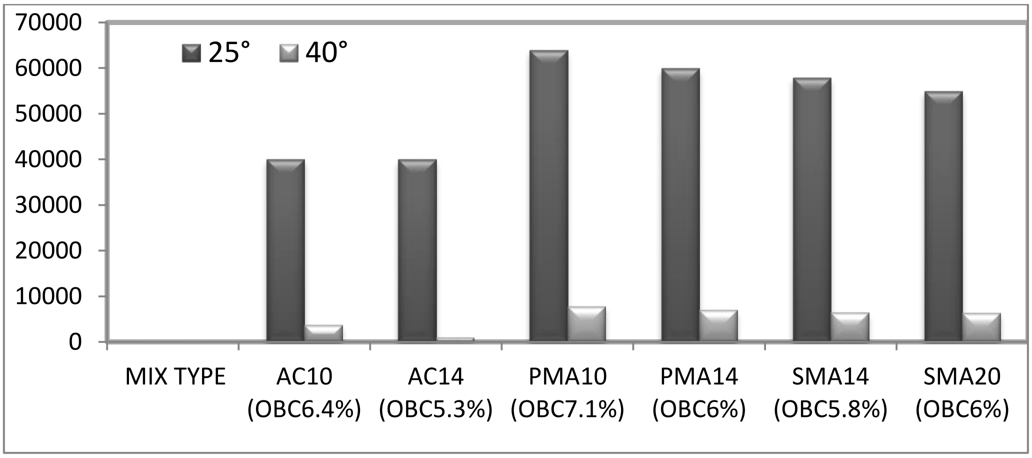

Figure 5: Indirect tensile fatigue test

3.2.4 *Effect of Asphalt Type and Asphalt Content on Fatigue Life*

Fatigue growth and the fatigue area are affected by the relationship between fatigue and the type of asphalt binder. If modified asphalt is used, fatigue will reduce. Asphalt researchers have discussed the perpetual pavements concept in HMA. They claim that it is a misconception that fatigue cracking is inevitable [9]. In order to evaluate the effect of asphalt types on fatigue life, the fatigue life of PMA10 and PMA14 (mixtures with modified asphalt) is greater than AC10 and AC14 (mixtures with normal asphalt 80/100 PEN) at the same temperature and the same aggregate gradation. Higher asphalt content is desired to improve the fatigue life and asphalt durability, but it tends to enhance rutting and shoving (permanent deformation) problems near the intersections [10-12].

The results for AC and PMA show that the mixtures with a greater amount of asphalt have higher fatigue lives. However, the results for SMA do not confirm this. Considering the effect of asphalt content on the fatigue life of SMA mixtures, SMA 20 with an asphalt content of 6% should have a fatigue life higher than SMA 14 with an asphalt content of 5.8%. But the results show the opposite. So it can be concluded from the result that the effect of the coarseness and fineness of the aggregate gradation on fatigue life is a lot greater than the effect of asphalt content [13].

3.2.5 Significant Statistical T-Test

T-Tests are tests for statistical significance that are used with interval and ratio level data. T-tests can be used in several different types of statistical tests. It can be used to test whether there are differences between two groups on the same variable, based on the mean (average) value of that variable for each group, or to test whether the same group has different mean (average) scores on different variables. The t-test is used to answer the question “is the result significant or not?” The t-test determines a p-value (probability value) that indicates how likely the results were obtained by chance. By convention, if there is less than a 5% probability of getting the observed differences by chance, the null hypothesis is rejected and it is assumed that there is a statistically significant difference between the two groups. The degrees of freedom (df) also need to be determined for the test in order to describe the number of values in the final calculation of a statistic that are free to vary. Table 5 shows the statistical significance of different mixture results; for example, the difference in the p-value for the resilient modulus test at 25 °C for AC10 and AC14 is 0.001, i.e. less than 0.05,which means that the null hypothesis is rejected. T-tests are also run to check the differences in statistical significance between groups, as shown in Table 6.

Table 5: T-Test between mixtures

Resilient Modulus						
Mixtures	25 °C			40 °C		
	T-value	P-value	DF	T-value	P-value	DF
AC10, AC14	-48.80	0.007	1	-6.38	0.049	1
PMA10, PMA14	-7.2	0.044	1	-4.24	0.026	2
SMA14, SMA20	-47.79	0.007	1	-11.37	0.028	1
Fatigue Life						
Mixtures	25 °C			40 °C		
	T-value	P-value	DF	T-value	P-value	DF
AC10, AC14	8.00	0.039	1	243.21	0.001	1
PMA10, PMA14	181.63	0.002	1	85.00	0.004	1
SMA14, SMA20	145.52	0.002	1	6.80	0.046	1

Table 6: T-Test between groups

Resilient Modulus						
Mixtures	25 ^{o}C			40 ^{o}C		
	T-value	P-value	DF	T-value	P-value	DF
AC, PMA	-10.90	0.001	3	-11.00	0.000	4
AC, SMA	-4.13	0.005	5	-2.99	0.020	4
PMA, SMA	3.48	0.020	3	3.30	0.023	3
Fatigue Life						
Mixtures	25 ^{o}C			40 ^{o}C		
	T-value	P-value	DF	T-value	P-value	DF
AC, PMA	-19.00	0.000	3	-6.00	0.005	3
AC, SMA	-18.97	0.000	3	-5.00	0.008	3
PMA, SMA	3.81	0.006	5	4.14	0.013	3

4.0 Conclusions

The research has evaluated the fatigue life of six different kinds of mixtures, and the following conclusions were drawn.

i) Increasing the temperature will decrease the resilient modulus and fatigue life of asphalt mixtures when compared between 25° C and 40° C. This result is independent of the gradation type, asphalt type, and other influencing factors in the fatigue behavior of asphalt mixtures.
ii) Dense graded PMA mixtures have a greater resilient modulus and fatigue performance than SMA mixtures (gap graded).
iii) Asphalt mixtures with a coarse aggregate gradation have a greater resilient modulus than those with a fine aggregate gradation.
iv) Asphalt mixtures with a finer aggregate gradation show a better fatigue life than those with a coarse aggregate gradation.
v) PMA mixtures have a greater fatigue life than AC mixtures, even if the same aggregate gradation is used.
vi) A greater asphalt content improves fatigue life and decreases the resilient modulus at the same temperature. This is true for PMA and AC mixtures.
vii) Mixtures using asphalt type PG76 (PMA, SMA) show a higher resilient modulus and fatigue life than mixtures using a normal asphalt type 80/100 penetration (AC).PMA mixtures have the longest fatigue life and greater stiffness modulus at any test temperature, followed by SMA mixtures and then ACW mixtures. PMA14 has a greater stiffness modulus, and PMA10 has the longest fatigue life.

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