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Impact of Loading Frequency on Fatigue Life of Flexible Pavements: Case Study of Candle Wax Modified Asphalt Concrete Mixtures for Heavy Traffic

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ABSTRACT

One of the major types of distress modes in asphalt concrete pavements is fatigue cracking. This mode of pavement failure begins when fatigue cracks at the bottom of the asphaltic layers of the pavement propagate through the bottom to the topmost layer of the pavement surface; thus becoming visible on the outer pavement surface. Local tensile strains at the bottom of the pavement (i.e. the interface between the asphalt concrete and the sub-grade layer) are responsible for fatigue failure. However, this research paper sought to the fact that the frequency at which destructive axle loads make passes on a pavement can be a major factor generating these local tensile strains that impede the performance of the pavement with respect to its fatigue life. Thus the focus of this study was to correlate the impact of loading frequency on fatigue life of flexible road pavement. Results obtained revealed that the fatigue life of both the unmodified and candle wax-modified asphalt concrete mixtures decreased as the loading frequency increased from 0.1 – 25 Hz respectively. Furthermore, the optimum fatigue life was obtained at 15% candle wax content for all frequencies. In all pavement life was reduced as loading frequency increased.

Key words: Fatigue Life, Loading Frequency, Asphalt Concrete, Candle Wax and Flexible Pavement

1. INTRODUCTION

Generally, pavement response which is synonymous with the performance of asphalt concrete mixtures can be categorized into two modes of distress namely fatigue cracking and rutting deformation. The former can be defined as **the number of load applications or repetitions that the pavement will undergo before failure**. Shakir (1997) in his study defines it as failure due to repeated stresses that are not large enough to cause immediate fracture. Fatigue in general is associated with repetitive traffic loading, and is considered to be one of the most significant distress modes in flexible pavements. Previous studies have been conducted to understand how fatigue can occur and fatigue life extended under repetitive traffic loading – (SHRP 1994; Benedetto et al. 1996; Anderson et al. 2001and Daniel and Kim 2001). When an asphalt mixture is subjected to a cyclic load or stress, the material response in tension and compression consists of three major strain components: elastic, visco - elastic and plastic (horizontal tensile strain). The horizontal tensile strain or plastic deformation, in general, is responsible for the fatigue damage and consequently results in fatigue failure of the pavement. According to Khattak and Baladi 2001, a perfectly elastic material will never fail in fatigue regardless of the number of load applications. However, due to the visco - elastic nature of asphalt concrete pavements, fatigue failure resulting from stresses that generate local tensile strains become possible. Examples include temperature related stress, moisture, type of loading (i.e. combinations of irregular traffic loading) axle configuration and rate of loading (i.e. loading frequency) and in special cases it also comprise of admixtures and modifiers (Igwe et al., 2009). The present study seeks to establish the impact of loading frequency or the rate of destructive axle loading on the fatigue life of a candle wax modified flexible road pavement. However, in highway engineering it is common knowledge that the performance of flexible pavements is closely related to the performance of asphalt concrete mixtures. Thus, the study was based on the use of candle wax modified asphalt concrete mixtures. A previous related study by Ekwulo and Igwe (2011) revealed that the rate of loading or frequency of loading on rubberized asphalt concrete mixtures increased the stiffness modulus (in particular dynamic modulus) of the concrete for varying frequencies of loading. The study by Garcia and Thompson (2007) revealed that stiffness is also a major property of asphalt concrete mixtures that influence the structural response of a flexible pavement as do tensile strains. As a continuum the present study focused on the impact of varying frequencies of loading on a candle wax modified pavement having similar material mix properties as in the above study by Ekwulo and Igwe but with respect to fatigue life. Although, their study revealed increase in stiffness modulus due to increase in loading frequency; yet how this translates to fatigue response is the focus of the present study bearing in mind that frequency of loading is the number of periods, cycles or repeated occurrence that a destructive axle load generating local tensile strains will make on a pavement under a specified duration of time.

For the study five loading frequencies were used for analysis – 0.1, 1, 5, 10 and 25 Hz respectively. Also the stiffness modulus used was the dynamic modulus, E* which closely simulate true field conditions – Clyne et al (2003). Furthermore, the dynamic modulus values were obtained using the Asphalt Institute model equation as presented in Huang (1993). See Equations 2-7 below.

Similarly, the fatigue values were obtained using the Asphalt Institute model equation for fatigue – Asphalt Institute (1981). See Equation 8.

2. MATERIALS AND METHODS

2.1. Sample collection

The materials used for this study were waste candle wax, asphalt, coarse and fine aggregates. The candle wax used were obtained as wastes from domestic use of candles while the aggregates used were obtained from market dealers at Mile 3 Diobu, in Port Harcourt City Local Government Area of Rivers State, Nigeria. On the other hand the asphalt used was collected from a private asphalt plant company H & H situated at Mbiama, in Ahoada West Local Government Area of Rivers State, Nigeria. After sampling of the materials, laboratory tests - specific gravity, grading of asphalt and sieve analysis of the aggregates used for mix-proportioning by straight line method - were carried out.

2.2. Sample preparation

Samples were prepared using Marshal Design Procedures for asphalt concrete mixes as presented in Asphalt Institute (1981), National Asphalt Pavement Association (1982) and Roberts et al (1996). The procedures involved the preparation of a series of test specimens for a range of asphalt (bitumen) contents such that test data curves showed well defined optimum values. Tests were scheduled on the bases of 0.5 percent increments of asphalt content with at least 3-asphalt contents above and below the optimum asphalt content. In order to provide adequate data, three replicate test specimens were prepared for each set of asphalt content used. During the preparation of the pure or unmodified asphalt concrete samples, the aggregates were first heated for about 5 minutes before bitumen was added to allow for absorption into the aggregates. After which the mix was poured into a mould and compacted on both faces with 75 blows using a 6.5kg-rammer falling freely from a height of 450mm. Compacted specimens were subjected to bulk specific gravity test, stability and flow, density and voids analyses at a temperature of 60^0C and frequencies of 0.1, 1, 5, 10 and 25 Hz respectively as specified by AASHTO Design Guide (2002). The results obtained were used to determine the optimum asphalt content of the pure asphalt concrete. Candle wax was then added at varying amounts (5 – 25 percent by weight of the asphalt at optimum) to the samples at optimum asphalt content and then re-designed using the same Marshal Design

Procedures already stated above to produce candle wax modified concretes having varying mix design properties particularly air voids content which greatly affected tensile strains and dynamic modulus. The tensile strain (ε_t) were obtained by measurements at frequencies of loading as stated above at these candle wax contents at the point of failure of the asphalt concretes under loading from the stabilometer machine.

2.3. Theory

The optimum asphalt content (O.A.C.) for the unmodified concrete was obtained using equation 1, according to the Marshal Design Procedure cited in (Asphalt Institute, 1982; National Asphalt Pavement Association, 1982) as follows:

$$O.A.C. = \frac{1}{3}\left(A.C._{max.\ stability} + A.C._{max.\ density} + A.C._{median\ limits\ of\ air\ voids}\right) \quad (1)$$

The Asphalt Institute predictive model used for the study in which the dynamic modulus is determined is as presented in Huang's Pavement Analysis and Design textbook (1993):

$$\mathbf{E^* = 100{,}000\ (10^{\beta_1})} \quad (2)$$

$$\beta_1 = \beta_3 + 0.000005\ \beta_2 - 0.00189\ \beta_2 f^{-1.1} \quad (3)$$

$$\beta_2 = \beta_4^{0.5} T^{\beta_5} \quad (4)$$

$$\beta_3 = 0.553833 + 0.028829\left(P_{200} f^{-0.1703}\right) - 0.03476\ V_a + 0.07037\ \lambda + 0.931757\ f^{-0.02774} \quad (5)$$

$$\beta_4 = 0.483\ V_b \quad (6)$$

$$\beta_5 = 1.3 + 0.49825\ \log f \quad (7)$$

Where;
E* = dynamic modulus (psi)
F =loading frequency (Hz)
T = temperature (°F)
V_a = volume of air voids (%)
λ = asphalt viscosity at 77°F (10^6 poises)
P_{200} = percentage by weight of aggregates passing No. 200 (%)
V_b = volume of bitumen
$P_{77°F}$ = penetration at 77°F or 25°C

The Asphalt Institute predictive model used for the study in which fatigue life under varying loading frequencies were determined is as presented below;

$$N_f = 0.0796\ (\varepsilon_t)^{-3.291}\ (E)^{-0.845} \quad (8)$$

Where;
N_f = number of load repetitions to failure
E = stiffness modulus
ε_t = horizontal tensile strain at the bottom of the asphalt bound layer

3. RESULTS (TABLES 1-9 AND FIGURES 1 - 7)

Results obtained from preliminary laboratory tests and calibrations are tabulated in the following tables as follows;

Table 1: Laboratory test results of stated materials

Material	Candle Wax	Asphalt	Sand	Gravel
Specific gravity	0.80	1.05	2.52	2.86
Grade of binder material	-	40/50	-	-
Mix proportion (%)	-	-	41	59
Viscosity of binder (poise)	-	$1.45*(10^{-6})$	-	-
Softening point	-	50ºC	-	-
Penetration value	-	53mm	-	-

Table 1 above reveals the physical properties of the materials (asphalt, sand and gravel) that make up the asphalt concrete specimens and the properties of the modifiers (candle wax) used for carrying out the Marshal Mix Design for each concrete.

Table 2: Mix design properties for candle wax modified asphalt concrete at 4.6% optimum asphalt content

Candle Wax Content (%)	Stability (N)	Flow (0.25mm)	Density (kg/m^3)	Air voids (%)	VMA (%)
0.0	8,512	10.56	2,273	3.6	21.15
5	8,935	10.00	2,472	3.6	14.82
10	9,570	9.63	2,597	3.3	10.76
15	9,985	9.11	2,630	3.0	9.86
20	9,460	9.76	2,582	3.0	11.74
25	8,345	10.60	2,265	3.7	15.63

The above schedule (**Table 2)** shows the results of the mix design properties of the test specimens at varying asphalt content for each modified concrete at optimum asphalt content at various candle wax additions. The mix design properties include **Stability, Flow, Density, Air Voids and Volume in Mineral Aggregates (VMA).**

Table 3: Schedule of Aggregates used for Mix Proportion (ASTM: 1951)

Sieve size (mm)	Specification limit	Aggregate A (Gravel)	Aggregate B (Sand)	Mix proportion (0.59A+0.41B)
19.0	100	99.1	100	99.45
12.5	86-100	86.1	100	91.80
9.5	70-90	100	62	78
6.3	45-70	100	26	57
4.75	40-60	99	10	47
2.36	30-52	96	0	40
1.18	22-40	90	0	38
0.6	16-30	73	0	31
0.3	9-19	23	0	10
0.15	3-7	3	0	1.26
0.075	0	0	0	0

Table 3 above is the schedule used for proportioning the aggregates used for carrying out the Marshal Mix Design for each specimen before compaction of the specimens on both faces according to traffic category. Secondly, it reveals the percentage of each aggregate passing on each sieve size.

Table 4: Variation of Stiffness/Strain and Load Repetitions to failure with Candle Wax Content @ Frequency of 0.1 1Hz

Candle Wax (%)	Stiffness E* (lb/inch^2)	Maximum tensile strain, ε_t (10^{-5})	Number of Load Repetitions to failure, N_f Asphalt Institute	Log of Number of Cycles to failure (LOG N_f)
0	72,705.14	10.56	75,685,484	7.87901259
5	72,705.14	10	90,550,436	7.95689055
10	74,472.01	9.63	100,453,439	8.00196481
15	76,281.83	9.11	118,165,924	8.07249226
20	76,281.83	9.76	94,186,332	7.97398789
25	72,125.54	10.6	75,256,877	7.87654619

Table 5: Variation of Stiffness/Strain and Load Repetitions to failure with Candle Wax Content @ Frequency of 1 Hz

Candle Wax (%)	Stiffness E* (lb/inch^2)	Maximum tensile strain, ε_t (10^{-5})	Number of Load Repetitions to failure, N_f Asphalt Institute	Log of Number of Cycles to failure (LOG N_f)
0	100,150.34	10.56	57,740,935	7.76148381
5	100,150.34	10	69,081,501	7.83936177
10	102,584.18	9.63	76,636,564	7.88443603
15	105,077.18	9.11	90,149,534	7.95496348
20	105,077.18	9.76	71,855,351	7.85645911
25	99,351.95	10.6	57,413,948	7.75901741

Table 6: Variation of Stiffness/Strain and Load Repetitions to failure with Candle Wax Content @ Frequency of 5 Hz

Candle Wax (%)	Stiffness E* (lb/inch^2)	Maximum tensile strain, ε_t (10^{-5})	Number of Load Repetitions to failure, N_f Asphalt Institute	Log of Number of Cycles to failure (LOG N_f)
0	125,710.17	10.56	47,650,462	7.67806711
5	125,710.17	10	57,009,216	7.75594507
10	128,765.18	9.63	64,540,297	7.80983096
15	131,894.42	9.11	77,476,517	7.88917009
20	131,894.42	9.76	59,298,320	7.77304239
25	124,708.03	10.6	47,380,614	7.67560068

Table 7: Variation of Stiffness/Strain and Load Repetitions to failure with Candle Wax Content @ Frequency of 10 Hz

Candle Wax (%)	Stiffness E* (lb/inch^2)	Maximum tensile strain, ε_t (10^{-5})	Number of Load Repetitions to failure, N_f Asphalt Institute	Log of Number of Cycles to failure (LOG N_f)
0	142,171.07	10.56	42,944,705	7.63290962
5	142,171.07	10	51,379,228	7.71078758
10	145,632.25	9.63	56,996,255	7.75584632
15	149,171.40	9.11	67,046,141	7.82637379
20	149,171.40	9.76	53,440,365	7.72786941
25	141,043.66	10.6	42,699,983	7.6304277

Table 8: Variation of Stiffness/Strain and Load Repetitions to failure with Candle Wax Content @ Frequency of 25 Hz

Candle Wax (%)	Stiffness E* (lb/inch^2)	Maximum tensile strain, ε_t (10^{-5})	Number of Load Repetitions to failure, N_f Asphalt Institute	Log of Number of Cycles to failure (LOG N_f)
0	180,987.12	10.56	35,020,540	7.54432283
5	180,987.12	10	41,898,723	7.62220079
10	185,385.46	9.63	46,480,952	7.66727502
15	189,890.69	9.11	54,676,724	7.73780249
20	189,890.69	9.76	43,581,093	7.63929811
25	179,544.32	10.6	34,822,216	7.5418564

Tables 4 – 8 reveals the maximum tensile strain obtained for each compacted specimen at failure together with the calculated stiffness and load repetitions to failure at various candle wax content and varying frequencies of test.

Table 9: Results of Fatigue Life under varying Loading Frequency and Candle Wax Contents

	Candle Wax Content					
Loading Freq (Hz)	0	5	10	15	20	25
Fatigue Values Under Varying Frequency and Candle Wax Content						
0.10	75,685,484	90,550,436	100,453,439	118,165,924	94,186,332	75,256,877
1.00	57,740,935	69,081,501	76,636,564	90,149,534	71,855,351	57,413,948
5.00	47,650,462	57,009,216	64,540,297	77,476,517	59,298,320	47,380,614
10.00	42,944,705	51,379,228	56,996,255	67,046,141	53,440,365	42,699,983
25.00	35,020,540	41,898,723	46,480,952	54,676,724	43,581,093	34,822,216

Table 9 is the collation of Tables 4 – 8 for ease of coparism.

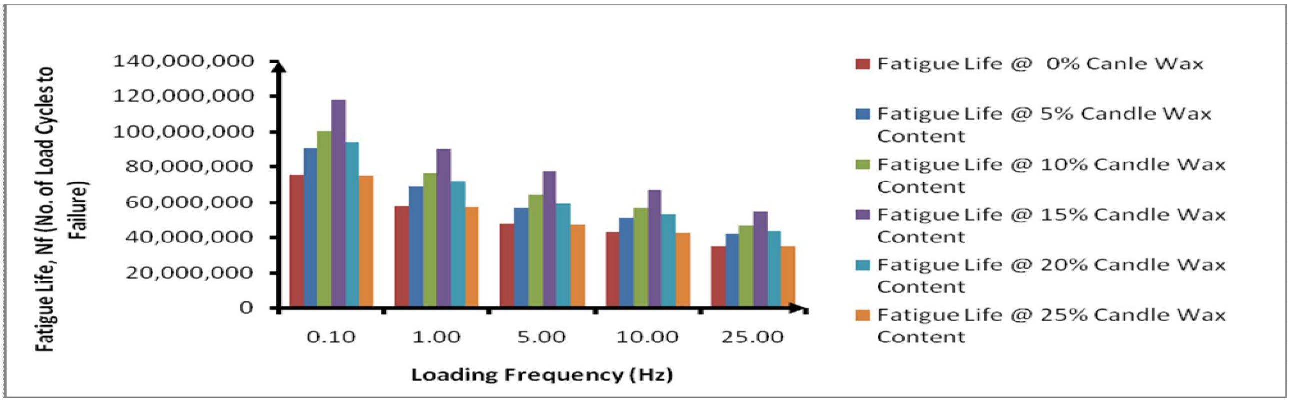

Figure 1: Variation of Fatigue Life with Loading Frequency @ varying Candle Wax Content

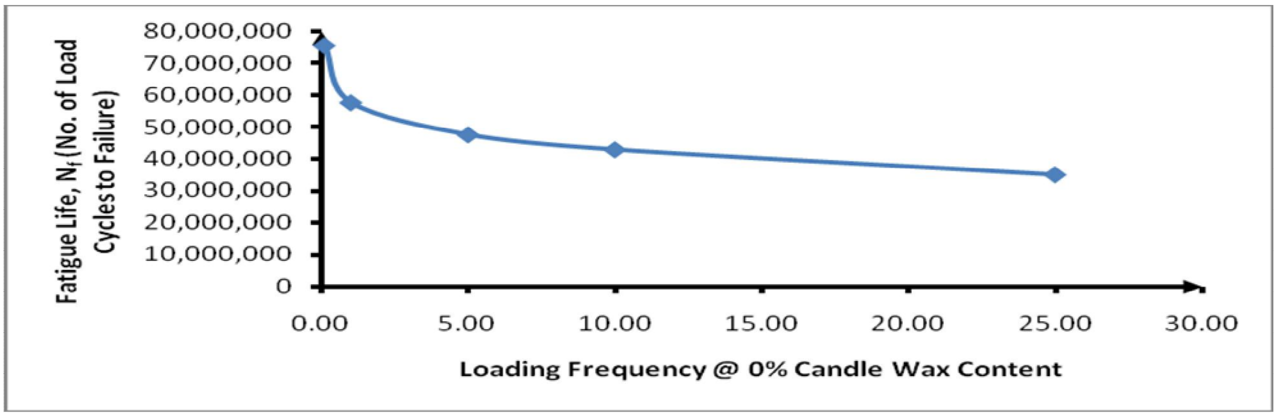

Figure 2: Variation of Fatigue Life with Loading Frequency @ 0% Candle Wax Content

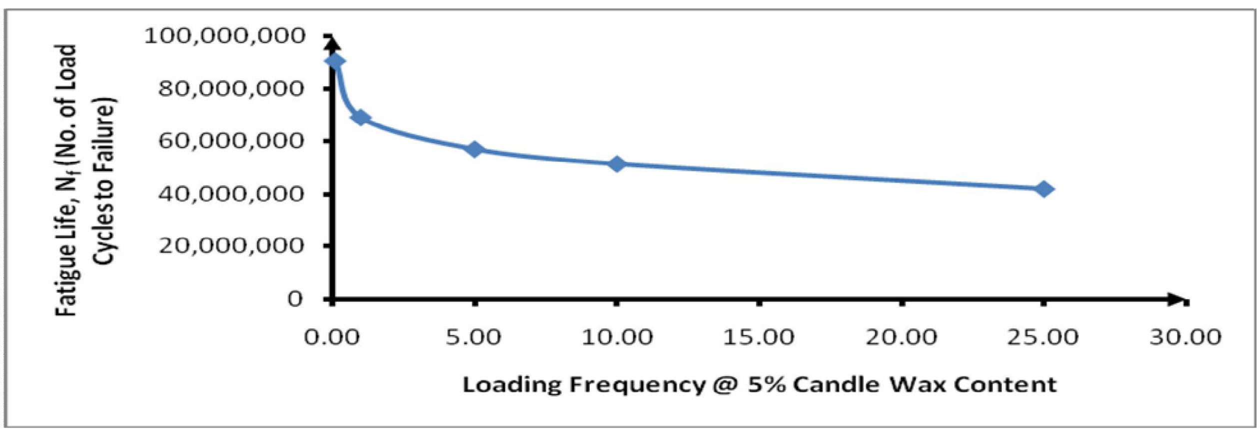

Figure 3: Variation of Fatigue Life with Loading Frequency @ 5% Candle Wax Content

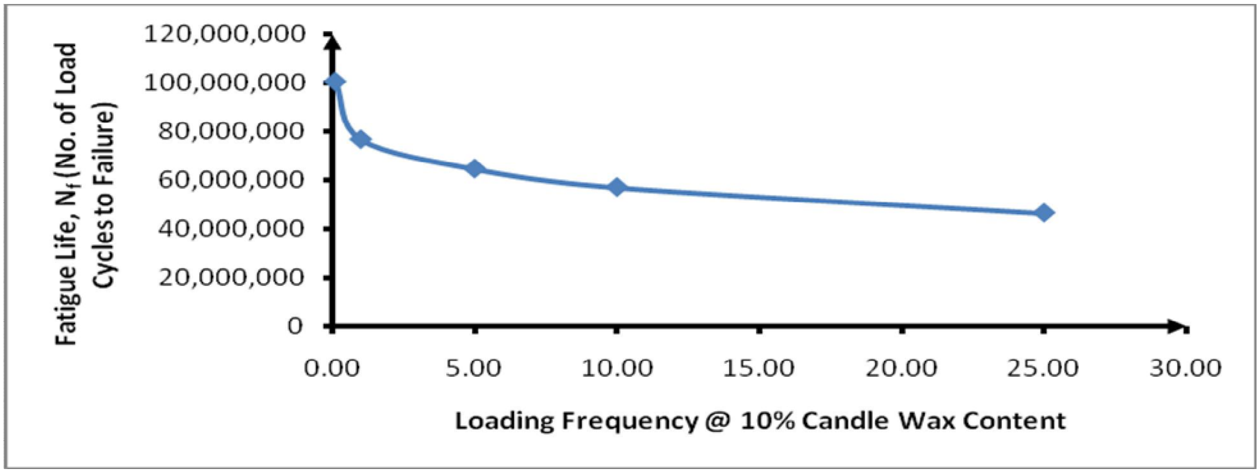

Figure 4: Variation of Fatigue Life with Loading Frequency @ 10% Candle Wax Content

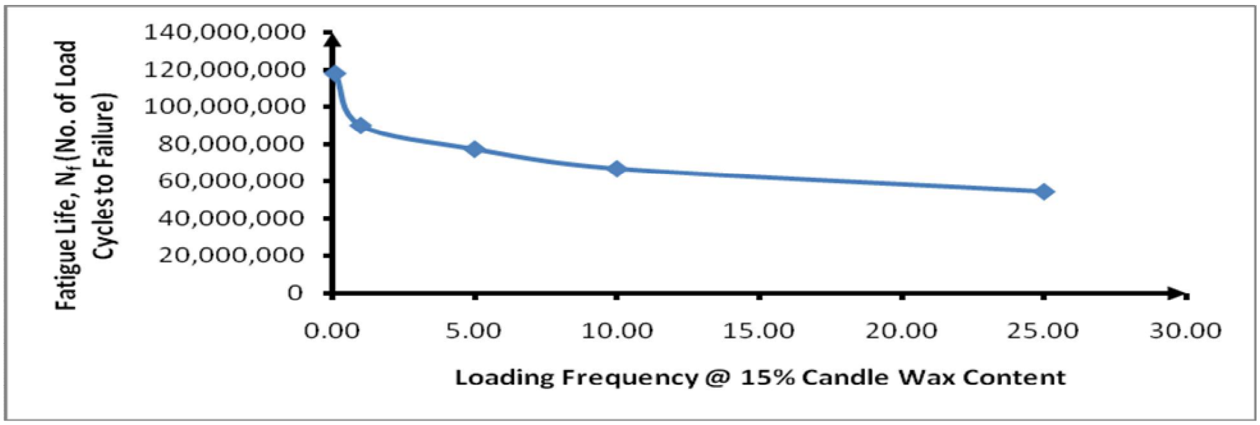

Figure 5: Variation of Fatigue Life with Loading Frequency @ 15% Candle Wax Content

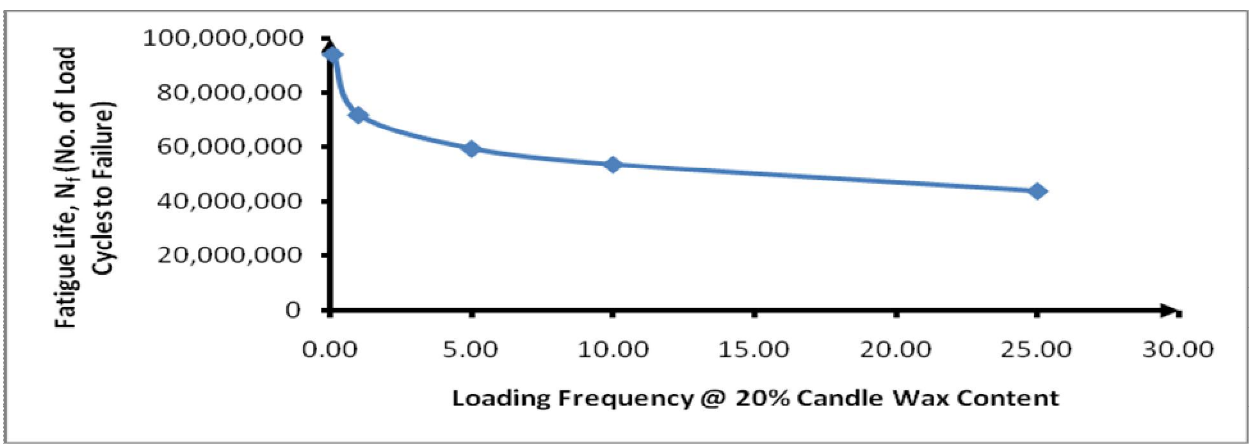

Figure 6: Variation of Fatigue Life with Loading Frequency @ 20% Candle Wax Content

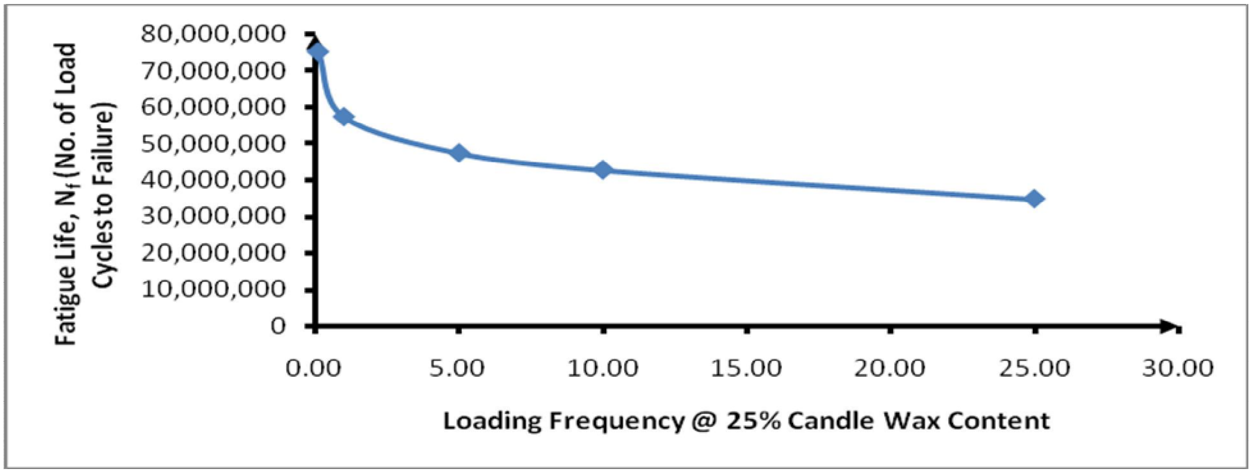

Figure 7: Variation of Fatigue Life with Loading Frequency @ 25% Candle Wax Content

4.DISCUSSION OF RESULTS

The result of the impact of loading frequency on the Fatigue Life of Candle Wax modified asphalt concrete is presented in Table 9 and Figures 1 - 7. From Figure 1, result showed that at a loading frequency of 0.1 Hz fatigue life increased from 75, 685, 484 at 0% candle wax content to a maximum of 118, 165, 924 at 15% candle wax content and then decreased to 75, 256, 877 at 25% candle wax content. The same trend was observed for frequencies of 1 Hz, 5 Hz, 10 Hz and 25 Hz respectively with optimum fatigue life values of 90, 149, 534; 77, 476, 517; 67, 046, 141 and 54, 676, 724 respectively at 15% candle wax content.

From Figure 2, result indicated that the fatigue life of the unmodified asphalt concrete (i.e. 0% candle wax content) decreased as the loading frequency increased; i.e. the fatigue life decreased from 75, 685, 484 at 0.1Hz to 35, 020, 540 at 25Hz.

Also, from Figures 3 – 7 for the candle wax modified asphalt concretes the fatigue life decreased from 90, 550, 436 → 41, 898, 723 at 5%; 100, 453, 439 → 46, 480, 952 at 10%; 118, 165, 924 → 54, 676, 72 at 15%; 94, 186, 332 → 43, 581, 093 at 20% and 75, 256, 877 → 34, 822, 216 at loading frequencies of 0.1 and 25 Hz respectively.

These results indicate that the candle wax-modified asphalt concrete showed similar behavior as the normal (unmodified) asphalt concrete. In general with respect to the focus of the study, fatigue life of the candle wax modified asphalt concrete decreased with increasing loading frequency.

5. CONCLUSION

From the result of both the unmodified and modified HMA concrete, it is evident that the fatigue life of both unmodified and candle wax-modified asphalt concrete decreased with increase in loading frequency.

From the above result, the following conclusions are made:

1. Fatigue life of candle wax-modified asphalt concrete decreased with increase in loading frequency.
2. The effect of loading frequency on fatigue life showed similar behavior both for unmodified and modified asphalt concrete
3. For the modified asphalt concrete optimum fatigue life was obtained at 15% candle wax content.
4. The study has proved that loading frequency is a vital factor to be considered during mechanistic design of asphalt road pavements with respect to pavement life.

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