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Full Length Research Paper

Fatigue Life extension in HMA Concretes through the inclusion of Candle Wax as modifier for heavy trafficked Pavement

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Highway flexible pavements, probably the largest infrastructural components in many developed nations today are a complex system having multiple layers made up of different materials. However, this very large infrastructural component during use suffer many drawbacks resulting from different adverse conditions such as irregular traffic loading, and varying environmental conditions like temperature, moisture and oxidation rates. Therefore, a realistic prediction of the long-term service life of flexible pavements is one of the most challenging tasks for pavement engineers in Highway Engineering. Generally, there are two main types of distresses that impede the performance of flexible pavement – fatigue cracking and rutting deformations. The former generally associated with stiffness and horizontal tensile strains at the bottom of the asphalt concrete layer was the focus of the present study since it is the most significant factor controlling pavement life. In this study hot mix asphalt concretes were prepared and modified at optimum asphalt content using non bituminous modifier – candle wax. The results obtained revealed that the candle wax modified asphalt concrete produced pavements with extended pavement life for all loading frequencies considered for the given traffic category. Overall the addition of candle wax produced pavement having average stiffness increase of 8%, average strain reduction of 27% and average fatigue extension of 171%.

Keywords: Fatigue Life, Extension, Candle Wax, HMA Concretes, Heavy Traffic

INTRODUCTION

Flexible pavements, one of the largest infrastructure components in some parts of the developed nations like the United States, is a complex system that involves multiple layers of different materials, various combinations of irregular traffic loading, and varying environmental conditions such as temperature, moisture and oxidation rates (Igwe et al., 2009). Therefore, a realistic prediction of the long-term service life of flexible pavements is one of the most challenging tasks for pavement engineers in Highway Engineering. It is general knowledge among pavement engineers that the performance of flexible pavement is closely related to the performance of hot mix asphalt (HMA) concrete. Thus, proper evaluation of the performance and behaviour of asphalt concrete is of great importance; therefore performance models of asphalt concrete provides the links among various processes involved in asphalt mix design, pavement structure design, construction, and rehabilitation. The physical properties and performance of HMA is governed by the properties of the aggregate (e.g., shape, surface texture, gradation, skeletal structure, modulus, etc.); properties of the asphalt binder (e.g., grade, complex modulus, relaxation characteristics, cohesion, etc.), and asphalt aggregate interaction (e.g., adhesion, absorption, physiochemical interactions, etc.). As a result, the properties of asphalt mixtures are very complicated and sometimes difficult to predict (You and Buttlar, 2004; Xiao et al., 2007). Therefore, if the microstructure of asphalt mix can be obtained, its properties can be evaluated from the properties of its constituents and microstructure (Wang et al., 2004; Xiao et al., 2006). Hence, development of a fundamentally sound performance model serves two important purposes. For pavement engineers, such a model can provide accurate information about the performance of asphalt concrete under realistic loading conditions, thus leading to a better assessment of the service life of a new pavement or the remaining life of an existing pavement. For materials engineers, the performance model founded on basic principles of mechanics provides relationships between material properties (chemical or mechanical) and model parameters, which can be used for the selection or design of better performing binders or mixtures.

Generally, **pavement response** synonymous with performance of asphalt concretes can be categorized into two major types of distress; **fatigue cracking** which is directly associated with **pavement stiffness** and **rutting deformation**. Both **Cracking and Rutting of asphalt concrete** can be caused by a number of factors such as mechanical loading from repetitive traffic and/or thermal loading from changes in temperature. When the asphalt concrete is subjected to repeated loading, whether it is mechanical or thermal, distributed micro-structural damage occurs primarily in the form of micro-cracks. These micro-cracks exist ahead of the macro-crack tip, forming a so-called ***damage zone*** **(**Kim et al 1997**)**. Propagation, coalescence, and re-bonding of these micro-cracks in the damage zone affect the macro-crack growth and healing and, thus, the fatigue behaviour of asphalt concrete. That is to say, the modelling of the fatigue behaviour of asphalt concrete requires an evaluation of the effects of both micro- and macro-cracks and their interaction on the global behaviour of the mixture. At high temperatures and/or slow loading rates, the asphalt binder becomes too soft to carry the load and, thus, the principal type of damage is permanent deformation due to volume change (i.e., densification) and rearrangement of aggregate particles caused by shear flow. The degree of aggregate interlocking and anisotropy in asphalt concrete caused by aggregate orientation under compaction become important factors in the accurate prediction of the permanent deformation behaviour of asphalt concrete.

Fatigue which is associated with repetitive traffic loading is considered to be one of the most significant distress modes in flexible pavements. Shakir (1997) in his study defines it as failure due to repeated stresses that are not large enough to cause immediate fracture. The fatigue life of an asphalt pavement is related to the various aspects of hot mix asphalt (HMA). 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. It is general knowledge in pavement engineering that two main factors directly control fatigue life of asphalt concrete pavements, namely, stiffness and tensile strains. Thus a major concern in highway engineering by pavement engineers is to develop techniques and methods that will reduce tensile strain levels at the bottom of the asphalt bound layer thereby enhancing fatigue life of the pavement. Previous studies have been conducted to understand how fatigue can occur and **fatigue life be extended under repetitive traffic loading** (SHRP 1994; Daniel and Kim 2001; Benedetto et al. 1996; Anderson et al. 2001). Very few fatigue studies of modified asphalt mixtures, including crumb rubber and reclaimed asphalt pavements, have been performed in recent years (Raad et al, 2001; Reese Ron 1997).

However, for the present study the methodology employed is the inclusion of a non bituminous modifier (i.e. materials from which bitumen or asphalt cannot be derived) into the HMA mixture at optimum binder content in order to re-arrange the material composition of the mix in terms of void reduction in the overall mix within acceptable limits. In turn the reduction in voids increases material stiffness and reduces tensile strains in the asphalt bound layer. Since, fatigue is controlled directly by these two main factors it is therefore expected that for the present study the fatigue life should be extended. It is pertinent to say that in highway engineering pavement fatigue life can be expressed as the number of load repetitions or applications that can be applied to a pavement before it fails under fatigue denoted by N_f. Finally, for the present study the non bituminous material used was candle wax and 3 loading frequencies were investigated (1Hz, 5Hz and 10Hz respectively).

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 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

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

MATERIALS AND METHODS

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.

Sample preparation

Samples were prepared using Marshal Design Procedures for asphalt concrete mixes as presented in Asphalt Institute (1956), 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 unmodified asphalt concrete samples, the aggregates were first heated for about 5 minutes before asphalt was

Table 4. Variation of Stiffness/Strain and Load Repetitions to failure with candle wax content @ Frequency of 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	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 5. Variation of Stiffness/Strain and Load Repetitions to failure with candle wax content @ Frequency of 5Hz

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 6. Variation of Stiffness/Strain and Load Repetitions to failure with candle wax content @ Frequency of 10Hz

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

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^{0}C and frequencies of 1, 5, and 10Hz respectively as specified by AASHTO Design Guide (2002). The results obtained were used to determine the optimum asphalt content of the unmodified asphalt concrete. Candle wax content were 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 stiffness and tensile strains. The varying values of air voids content obtained by inclusion of the candle wax into the asphalt concrete was inputted into our Asphalt Institute model equation to obtain varying E* values used for comparism. Finally, tensile strains at failure of concretes were measured and the results recorded for use in analysis of fatigue life.

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, 1956; National Asphalt Pavement Association, 1982) as follows:

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

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):

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

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

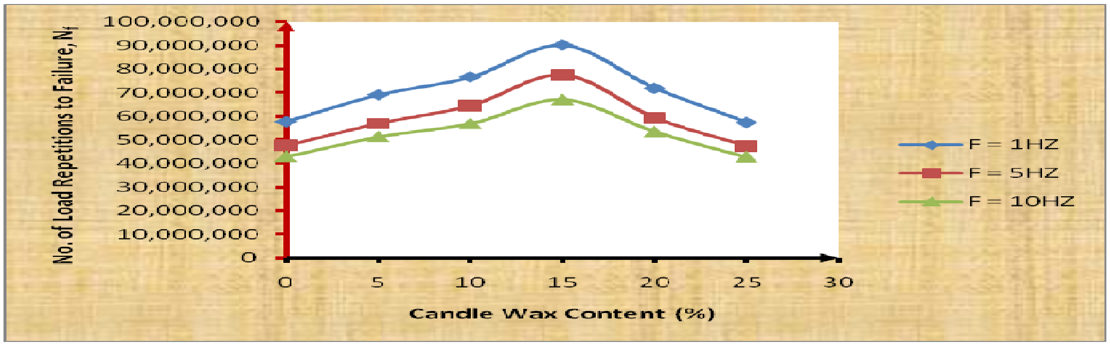

Figure 1. Variation of No. of Load Repetitions to Failure with Candle Wax Content

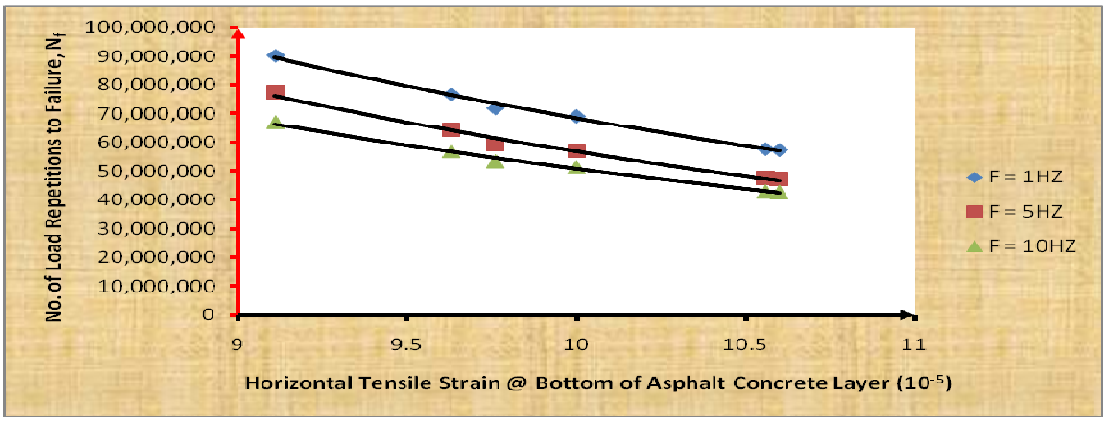

Figure 2. Variation of No. of Load Repetitions to Failure with Horizontal Tensile Strain

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

$$\beta_3 = 0.553833 + 0.028829 \left(P_{200} f^{-0.1703} \right) - 0.03476 V_a + 0.070377 \lambda + 0.931757 f^{-0.02774} \quad (5)$$

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

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

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 (1981) 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

RESULTS (see Tables 1-6 & Figures 1-2)

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

DISCUSSION OF RESULTS

From figure 1, it is evident that the fatigue life of the hot mix asphalt concrete synonymous with no. of load repetitions to failure increased with increasiing candle wax content up to 15% and having an avearge value of percent increment of 171% at this candle wax content for the 3 categories of traffic considered. However, further additions of the non bituminous modifier resulted in decrease of the fatigue life of the HMA concrete for same traffic categories.

Secondly, results from Tables 4 - 6 revealed that stiffness of the pavement increased with increasiing candle wax content up to 15% and having an avearge value of percent increment of 8% at this candle wax content for the 3 categories of traffic considered.

Thirdly, Tables 4 - 6 also revealed that tensile strains at same candle wax content of 15% reduced under increasing candle wax content due to increasing pavement stiffness resulting from voids reduction in the asphaltic mixture (Van Rooijen, 1938) for all categories of traffic considered. Figure 2 shows the relationship between tensile strains at bottom of asphalt concrete layer and fatigue life. In other words as tensile strains reduce in the bottom of the asphalt concrete layer fatigue life increases and vice versa. Therefore, at 15% candle wax content the average reduction at this candle wax content was observed as 27% for all traffic categories.

The overall conclusions from the study are that;

1. The addition of candle wax into asphaltic concrete mixture produces a pavement with extended fatigue life.
2. However, from the findings of the study limiting or critical candle wax content to produce best pavement performance with respect to fatigue life was 15%.
3. Results showed that average increase in stiffness in the hot mix asphalt concretes was 8% for all loading frequencies of the given traffic category (1, 5 and 10 Hz respectively).
4. Results also showed that average tensile strain reduction in the asphalt bound layer of the asphalt concrete mixtures was 27% for all loading frequencies in question for the given traffic category (1, 5 and 10 Hz respectively).
5. Lastly, the combined effect of increase in stiffness and reduction in tensile strain due to candle wax addition resulted in fatigue life extension of 171% for all loading frequencies in question for the given traffic category (1, 5 and 10 Hz respectively).

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