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Investigating the Effect of Air Voids Content in Fatigue Life of Hot Mix Asphalt Mixtures: Case Study of Rubberized Asphalt Concrete

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Abstract

Highway flexible pavements, simulated in the laboratory by hot mix asphalt concrete are major infrastructural components in many parts of the world. Aside of Portland cement concrete hot mix asphalt concrete may be the second most used infrastructural component and therefore is of great concern to any nation’s physical infrastructural development. However the most important property of asphalt concrete pavement is the life of the pavement determined by its level of fatigue. Furthermore, fatigue life of pavements is strongly controlled by the level of tensile strains in the pavement layer together with the stiffness of the pavement. The present study sought to investigate the role of air voids content believed to be major determinants of strains and stiffness in the behaviour of fatigue life of asphalt concrete mixtures. The results revealed that as the air voids content increased the life of pavement with respect to fatigue decreased for all frequencies of test (1, 5 and 10Hz respectively). Secondly, the study revealed that the rate of loading or frequency of passage of destructive vehicles (≥80KN single axle) adversely affected the life of the pavement in terms of fatigue.

Key words: Fatigue Life, Air Voids, HMA Concretes, Rubberization

1.0 Introduction:

Hot mix asphalt concrete mixtures are used synonymously in the laboratory to represent or simulate asphalt concrete pavements in real life. Thus, the analysis of the behaviour of asphalt concrete mixtures is readily accepted as a framework that nearly simulates the true behaviour of flexible pavements during use. In highway engineering the performance of flexible pavements are directly related to pavement response. Generally, pavement response synonymous with performance of asphalt concretes can be categorized into two major types of distress; **fatigue cracking** and **sub-grade rutting**. Fatigue cracking however, is a phenomenon which determines fatigue life of asphalt concrete pavements. When failure of asphalt concrete pavement occurs due to cracking the number of load repetitions just before failure of the pavement represents fatigue life.

2.0 Background on Fatigue cracking

Fatigue is directly associated with pavement stiffness and strains which is caused by a number of factors such as mechanical loading from repetitive traffic and/or thermal loading from changes in temperature or moisture. 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 (Kim et al 1997). These cracks many times are a direct result of the volume of air voids content in the pavement which increases strains and reduces pavement stiffness. Fatigue failure is generally defined as a failure resulting from the repetitive action of loads, and in pavements the loads result from traffic moving over the pavement (Romanoschi et al, 2006). Typically, failure becomes visible, only after a long number of load repetitions, and results initially in the formation of small cracks. These small cracks are initially located in the wheel path and appear as a network of fine cracks. Different phases have been described in the fatigue failure process: namely the initiation of minor hairline cracks, followed by the development of these micro cracks into wider macroscopic cracks, which coalesce and form a network of cracks. In the final stage these macroscopic cracks propagate through the thickness of the pavement and lead to catastrophic failure resulting in the loss of structural integrity of the pavement. An example of the final stage of fatigue failure is shown in figure 1 of appendix 1 (Kim et al, 1997) and figure 2 of appendix 1 (Eisenmann and Hilmer, 1987); where in this case, the cracked material has already induced the formation of a pothole.

Fatigue failure of the pavement is often believed to start when a fatigue crack initiates at the bottom of the bituminous layers of the pavement, due to local tensile strains, and propagates through the complete thickness of the pavement becoming apparent on the top surface (Robins, 2009). This is referred to as bottom-up fatigue cracking, the opposite, top down fatigue has also frequently been observed, and there are indications that this type of fatigue growth has been related to an oxidative aging of the top surface layer (Mallick and El-Korchi, 2013). They also posited that the primary cause of top down cracking is the failure of the surface mix as a result of excessive surface shear and tensile stresses from tires of trucks. Furthermore, that the excessive stresses can be due to load distribution, axle configuration, axle loadings, tire types and rigidity (stiffness) as well as tire pressures.

2.1 Review of Fatigue Models

The fatigue resistance of asphalt mixtures is predicted based on material properties and load responses (Adhikari and You, 2010). Several authors and organizations have proposed different models for predicting fatigue failures in asphalt concrete mixtures such as Shell 1978 as presented in Baburamani 2001; Asphalt Institute 1981; Tayebali et al 1994; Read and Collop 1997; Hossain et al 1999 and Birgisson et al 2005. However, the present study was limited to both the Asphalt Institute and Shell fatigue models respectively. The asphalt Institute Model (1981) and Shell Model (Baburamani 2001) are as presented in equations 1 and 2 respectively;

$$N_f = 0.0796(\varepsilon_t)^{-3.291}(E)^{-0.845} \qquad \mathbf{1}$$

3.0 Theory of Air Voids

The dynamic modulus or any other form of asphalt mixture stiffness is a significant parameter that determines the ability of material to resist compressive deformation as it is subjected to cyclic compressive loading and unloading (Rowe et al, 2008). This ability of the material to resist compressive deformation is a major contributor to pavement resistance to cracking due to cyclic or other types of loading and loading configurations. It is therefore a reasonable argument to think that air voids play significant roles in the behaviour of fatigue related cracking experienced by road pavements during useful or design life since air voids in the pavement determines stiffness (Igwe 2015).

The Asphalt Institute developed a method for design in which the dynamic modulus is determined from the following equations, as presented in Huang's Pavement Analysis and Design textbook (1993):

$$\mathbf{E^* = 100{,}000\ (10^{\beta}{}_{1})} \qquad (2)$$

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

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

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

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

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

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

4.0 Objectives

The objective of the present research was to investigate the effect of variation in air voids content and its impact on the fatigue life of flexible pavement synonymous with hot mix asphalt concrete mixtures. It is pertinent to mention that fatigue life usually expressed as failure due to cracking is represented by number of load cycles greater than or equal to 80KN single axle that will pass on the pavement within the design life (i.e. 20years) before pavement failure occurs.

5.0 Materials and Methods

5.1. Sample collection

The materials used for this study were rubber latex, bitumen, coarse and fine aggregates. The rubber latex used was obtained from Ikot Essien in Ibiono Ibom Local Government Area of Akwa Ibom State in Nigeria while the bitumen used was collected from the Federal Ministry of Works in Rivers State, Nigeria. Commercial aggregates were, however, used. After sampling of the materials, laboratory tests - specific gravity, grading of bitumen and sieve analysis of the aggregates used for mix-proportioning by straight line method - were carried out.

5.2. Sample preparation

Samples were prepared using Marshal Design Procedures for asphalt concrete mixes as presented in National Asphalt Pavement Association (1982), Roberts *et al* (1996) and Asphalt Institute (1997). 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 35 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 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 pure asphalt concrete. Rubber latex was then added at varying amounts (0.5 – 3.0 percent) to the samples at optimum asphalt content and then redesigned using the same Marshal Design Procedures already stated above to produce rubberized concretes having varying mix design properties particularly **air voids content which greatly affects dynamic modulus which in turn is a measure of the pavement fatigue life**. The varying values of air voids content obtained by rubber latex introduction into the asphalt concrete was inputted into our Asphalt Institute model equation to obtain varying E* values. The values of E* together with horizontal tensile strains were used to determine fatigue life represented symbolically as N_f.

6.0 Results (see Tables 1-5 & Figure 1)

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

Table 1: Laboratory test results of stated materials

Material	Rubber	asphalt	Sand	Gravel
Specific gravity	0.90	1.36	2.66	2.90
Grade of binder material	-	40/50	-	-
Mix proportion (%)	-	-	42	58
Viscosity of binder (poise)	-	$0.45*(10^{-6})$	-	-
Softening point	-	48ºC	-	-
Penetration value	-	44mm	-	-

Table 2: Mix design properties for unmodified asphalt concrete

Asphalt Content (%)	Stability (N)	Flow (0.25mm)	Density (kg/m^3)	Air voids (%)	VMA (%)
6.0	722	17.4	2410	3.6	19.0
5.5	909	21.6	2420	4.0	18.0
5.0	936	21.2	2440	4.0	17.0
4.5	1979	17.8	2460	4.0	16.0
4.0	1952	17.04	2430	5.8	16.5
3.5	1284	16.4	2380	7.0	17.8
3.0	936	13.4	2330	8.3	19.0

Table 3: Mix design properties for rubberized bituminous concrete at 4.5% optimum asphalt content

Rubber Content (%)	Stability (N)	Flow (0.25mm)	Density (kg/m^3)	Air voids (%)	VMA (%)
0.0	1520	17.6	2450	3.6	16.4
0.5	2326	15.0	2510	2.7	13.8
1.0	2941	13.6	2520	3.1	13.4
1.5	3290	13.4	2530	3.4	13.0
2.0	1551	13.0	2500	4.0	14.0
2.5	1451	12.6	2470	4.3	15.0
3.0	321	10.4	2440	5.4	16.0

Table 4: Schedule of Aggregates used for mix proportion

Sieve size (mm)	**Specification limit**	**Aggregate A (Sand)**	**Aggregate B (Gravel)**	**Mix proportion (0.42A+0.58B)**
19.0	100	100	100	100
12.5	86-100	100	97	98
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 5: Variation of Fatigue Life with Air Voids Contents due to Rubber Latex addition at varying frequencies

Rubber Latex (R.L) Air Voids (A.V)							
	R.L - 0% A.V - 5.4%	R.L - 0.5% A.V - 4.3%	R.L - 1% A.V - 4.0%	R.L - 1.5% A.V - 3.4%	R.L - 2% A.V – 3.1%	R.L - 2.5% A.V - 2.7%	R.L - 3% A.V - 3.6%
F (HZ)	**Fatigue Life N_f at varying frequencies @ varying Rubber latex content and Air Voids content**						
1	39,137	49,552	69,411	123,565	210,493	430,026	666,914
5	27,810	38,060	40,265	72,502	140,011	270,182	447,160
10	19,739	27,388	29,936	53,850	87,542	155,475	214,940

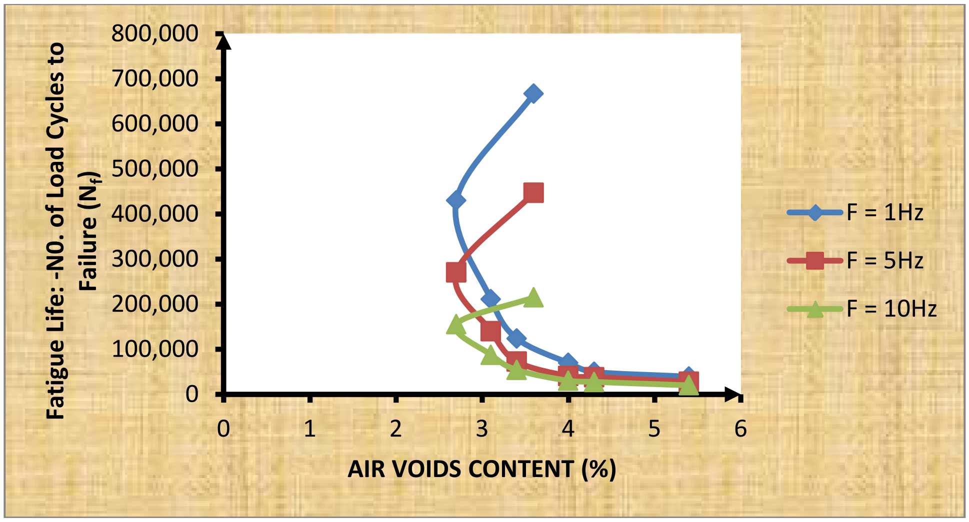

Figure 1: Variation of Fatigue Life with Air Voids Content

7.0 Discussions

The effect of air voids variation on fatigue life for rubber latex modified asphalt concrete at varying loading frequencies are as shown in Table 5 and Figure 1. Figure 1 presents the variation of fatigue life represented as number of load cycles to failure (N_f) with changing air voids content at loading frequency of 1Hz which was the initial loading frequency. The result showed that as the percent of air voids increased the number of load cycles to failure representing fatigue life decreased. Thus fatigue decreases with increasing air voids. The same holds true for fatigue life at all other frequencies of 5 and 10Hz respectively.

It was also observed that the frequency of loading inversely affected the fatigue life of the asphalt concrete mixture. In other words as the rate of loading was increased the life of the pavement was decreased in terms number of cycles that destructive vehicular load (≥ 80KN single axle load) will make before failure of pavement.

8.0 Conclusions

From the laboratory test results obtained including analysis made it is evident that the fatigue life of asphalt concrete mixtures simulating flexible pavements in reality is influenced by changing air voids content for a rubber latex modified pavement. However, results revealed that effect of air voids is adverse to the performance of the pavement in terms of fatigue life. In addition, the rate of loading or frequency of passage of destructive vehicular loads negatively affects pavement performance in terms of fatigue life.

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Appendix 1

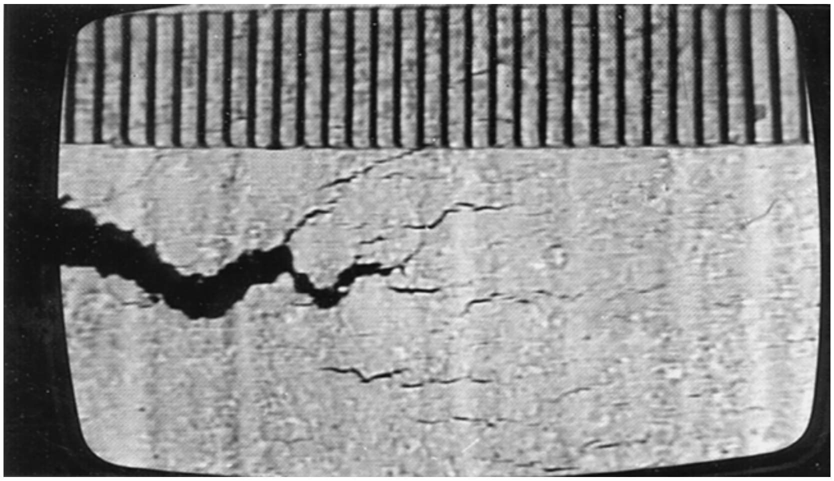

Figure 1: Microscopic surface image of cracking area in asphalt concrete. (Kim et al. 1997, with permission from International Society for Asphalt Pavements.)

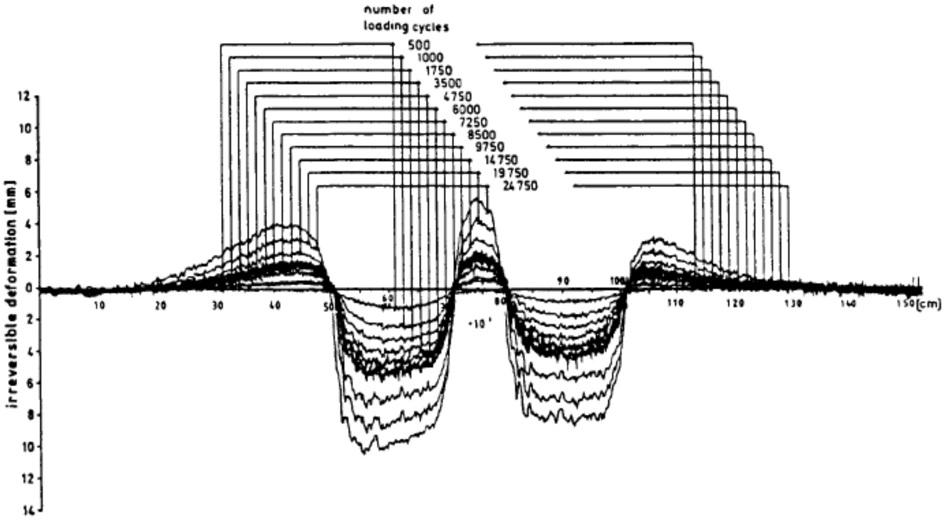

Figure 2: Effect of Number of Cycles on Transverse Surface Profile (After Eisenmann and Hilmer, (1987)