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Full Length Research Paper

Increasing Axle Load Repetitions (N_f) Causing Fatigue Failure in Highway Flexible Pavements through Rubberization: Light Traffic Study

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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 especially because of its complex system having multiple layers made up of different materials. 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, this has resulted in the need for modifications that can enhance its durability during use. The present research used rubber latex to modify the material property of asphalt concrete in order to ascertain changes that can increase axle load repetition during use; since it is believed that these axle loads are major contributors to fatigue failure. The results obtained revealed that the rubber latex modified asphalt concrete produced pavements with increased axle load repetitions for all loading frequencies considered for the given traffic category. Overall the addition of rubber latex at 3% maximum produced pavement having increases of 16 times the original axle load repetition at frequency of 1hz, 15 times at frequency of 5hz and approximately 10 times at frequency of 10hz respectively. Furthermore, the results revealed that increase in axle load repetition responsible for fatigue failure was linear from 0-3% for all frequencies considered.

Key words: Axle Load Repetition, Fatigue Failure, Flexible Pavement and Rubberization

INTRODUCTION

In highway engineering it is generally believed that the performance of asphalt concrete pavements (i.e. highway flexible pavements) is closely related to the performance of asphalt concrete mixtures. Thus, it is the performance models of asphalt concrete mixtures that provide the links among various processes involved in asphalt mixture design, pavement design, construction, and rehabilitation (Kim, 1997). In some developed nations of the world like the United States, highway flexible pavements are considered to be the largest infrastructure components involving multiple layers of different materials and various combinations of traffic loading. In addition, it is also subjected to environmental conditions like temperature and weather that impedes its performance during use. Therefore, a realistic prediction of the long-term service life of asphalt pavements is one of the most challenging tasks for pavement engineers.

Fatigue, associated with repetitive traffic loading, is considered to be one of the most significant distress modes in flexible pavements. Since it is believed that axle loads are major contributors to flexible pavement damage by fatigue cracking/failure; it is pertinent to state here that fatigue cracking/failure is synonymous with the number of axle load repetitions (N_f) that will occur before failure of the pavement by fatigue. 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). 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. The tensile plastic (permanent) strain or deformation, in general, is responsible for the fatigue damage and consequently results in fatigue failure of the pavement. On the other hand a perfectly elastic material will never fail in fatigue regardless of the number of load applications (Khattak and Baladi 2001**)**.

Monismith et al (1985) proposed a general fatigue model relating the number of axle load repetitions to failure, (N_f) with respect to stiffness of the asphalt concrete pavement and horizontal tensile strains in the asphalt concrete layer assumed to be a maximum at the bottom (Robbins 2009). Upon this general model other studies have been carried out to modify the relationship which includes, Tayebali et al (1994); Shell model as presented by Baburamani (2001); Witczak (2002) and Respersion Road Engineering (2008). However, the study by the latter was based on an earlier research by Asphalt Institute (1981). It is thus pertinent to say that all of the studies mentioned above focuses on the number of axle load repetitions (N_f) that will occur before failure due to fatigue will occur. Therefore, it is desirable to ensure that this factor that determines pavement performance be sufficiently high enough to ensure a road pavement with high durability and extended life span. The implication of having an increased axle load repetition is that; as $N_f \rightarrow \infty$ the pavement life also $\rightarrow \infty$. In turn this will save rehabilitation costs in the near future, thus making an economic design. However, a major challenge facing highway engineers is the problem that some of the materials that make up the pavement present. For example asphalt/bitumen has a twin malady of temperature and oxidation that impedes its performance during service life; thus creating a challenge for durable pavement performance. In recent times there has been a great revolution in the method of design of highway flexible pavement both in material mix and structural design. However, the focus of the present research is on the former. In material mix design the use of admixtures and modifiers have gained ascendancy in this area of study. Various researchers have used admixtures and modifiers to alter physical, mix design and material properties of the constituents in order to provide asphalt concrete mixtures with improved performance. Flynn (1993) used recycled polyethylene from grocery bags; Collins and Ciesielski, (1993); Federal Highway Administration, (1993); Khan et al, (1999); Zoorob, (2000); Zoorob and Suparma, (2000)) all used recycled plastics composed predominantly of polypropylene and low density polyethylene to modify the properties of asphalt concrete. In addition, (Punith, 2001) used processed plastic bags and Mummah and Muktar (2001) used natural rubber to modify the physical properties of bitumen.

For the present study rubber latex was introduced as an admixture at the optimum design of asphalt content to alter the material properties (in particular dynamic modulus and tensile strains) that govern the behaviour of fatigue. This was done to ascertain whether or not rubber latex addition can help increase axle load repetition synonymous with pavement life before failure occurs due to axle load repetitions. For purpose of the study the Asphalt Institute fatigue model was adopted for analysis using 3 frequencies of test – 1Hz, 5Hz and 10Hz respectively.

MATERIALS AND METHODS

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.

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

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 asphalt concrete at 4.72% optimum asphalt content

Rubber Content (%)	Stability (N)	Flow (0.25mm)	Density (kg/m^3)	Air voids (%)	VMA (%)
0.0	1520	17.6	2450	4.0	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

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 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

Table 5. Variation of Stiffness/Strain and Load Repetitions to failure with rubber Latex content @ Frequency of 1Hz

Rubber Latex (%)	Stiffness E* (lb/inch^2)	Maximum tensile strain, ε_t (10^{-5})	Number of Repetitions to failure, N_f Asphalt Institute	Log of Number of Cycles to failure (LOG N_f)
0	98,371.65	9.74	39,137	4.59259043
0.5	105,719.22	8.90	49,552	4.69506047
1.0	102,388.21	8.10	69,411	4.84142766
1.5	99,959.01	6.84	123,565	5.09189389
2.0	95,272.15	5.89	210,493	5.32323739
2.5	93,011.78	4.77	430,026	5.63349451
3.0	85,173.00	4.27	666,914	5.82406979

Table 6. Variation of Stiffness/Strain and Load Repetitions to failure with Rubber Latex content @ Frequency of 5Hz

Rubber Latex (%)	Stiffness E* (lb/inch^2)	Maximum tensile strain, ε_t (10^{-5})	Number of Repetitions to failure, N_f Asphalt Institute	Log of Number of Cycles to failure (LOG N_f)
0	126,497.49	10.13	27,810	4.44419317
0.5	135,945.83	9.04	38,060	4.58046859
1.0	131,662.44	8.96	40,265	4.6049221
1.5	128,538.70	7.54	72,502	4.86035032
2.0	122,511.79	6.25	140,011	5.14616162
2.5	119,605.15	5.15	270,182	5.43165683
3.0	109,525.16	4.52	447,160	5.65046324

Table 7. Variation of Stiffness/Strain and Load Repetitions to failure with Rubber Latex content @ Frequency of 10Hz

Rubber Latex (%)	Stiffness E* (lb/inch^2)	Maximum tensile strain, ε_t (10^{-5})	Number of Repetitions to failure, N_f Asphalt Institute	Log of Number of Cycles to failure (LOG N_f)
0	144,215.28	10.87	19,739	4.29531711
0.5	154,987.01	9.66	27,388	4.43755382
1.0	150,103.66	9.48	29,936	4.4761862
1.5	146,542.40	7.98	53,850	4.73118256
2.0	139,671.34	6.97	87,542	4.94221833
2.5	136,357.58	5.89	155,475	5.19165964
3.0	124,865.74	5.46	214,940	5.3323175

design properties particularly air voids content which greatly affects dynamic modulus. The tensile strain (ε_t) were obtained by measurements at various frequencies of loading (F) at these varying rubber latex content at the point of failure of the asphalt concretes under loading from the stabilometer machine. On the other hand dynamic modulus (E*) were obtained by applying the asphalt institute model equation as presented in Huang's Pavement Analysis and Design textbook (1993). See equations 2-7.

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

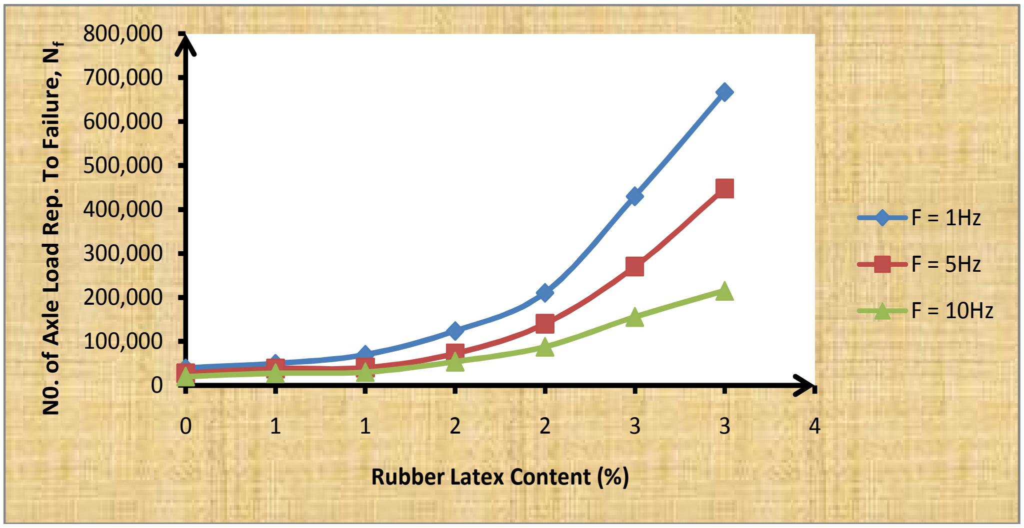

Figure 1. Variation of No. of Load Repetitions to Failure with Rubber Latex Content

in which the dynamic modulus is determined is as presented in Huang's Pavement Analysis and Design textbook (1993):

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

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

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

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

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

$$\beta_5 = 1.3 + 0.49825\ \log f$$ (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;

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

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

DISCUSSION OF RESULTS

From figure 1, it is evident that the fatigue life of the asphalt concrete pavement synonymous with number of load repetitions to failure under fatigue increased linearly with increasiing rubber latex content up to 3%.

Secondly, results from figure 1 also revealed that the fatigue life of the asphalt concrete pavement synonymous with number of load repetitions to failure under fatigue reduced with increasing loading frequency, F from 1-10Hz. This is true becasue as design axle loads (i.e. ≥ 80KN single axle) that cause failure repeatedly or frequently make cyclic passes on the pavement its life expectancy reduces.

Thirdly, tables 5-7 revealed that tensile strains which adversely affect fatigue life of asphalt concrete pavements synonymous with number of load repetitions to failure under fatigue reduced under increasing rubber latex content due to increasing pavement stiffness resulting from voids reduction in the asphaltic mixture (Van Rooijen, 1938).

CONCLUSIONS

The overall conclusions from the study are that;

1. The addition of rubber latex into asphaltic concrete mixture synonymous with flexible pavement

produces a pavement with extended number of axle load repetitions before failure under fatigue.

2. From the findings of the study maximum axle load repetition was obtained at 3% rubber latex addition

3. Lastly, the effect of reduction in tensile strain due to rubber latex addition resulted in the pavements having increase in axle load repetition of 16 times the original axle load repetition at frequency of 1hz, 15 times at frequency of 5hz and approximately 10 times at frequency of 10hz respectively.

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