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Fatigue Characteristics of Cold Recycled Bituminous Emulsion Mixtures Using the Nottingham Asphalt Tester in the ITFT Mode of Testing

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Abstract **- Knowledge of the fatigue characteristic of asphalt mixtures is essential for the design of flexible pavements since fatigue has been identified by researchers as one of the major failure mechanisms in flexible pavements. Information obtained from the laboratory fatigue characterization of such mixtures is normally used for predicting performance in service. While the literature is replete with information about the fatigue performance of hot asphalt mixtures (HMA), not much has been done to ascertain the responses of cold recycled asphalt mixtures which of late are increasingly becoming suitable and sustainable alternatives to HMA due to the energy, cost and environmental benefits they offer. This paper presents the results of laboratory fatigue characterization of cold recycled bituminous emulsion mixtures (CRBEMs) using the indirect tensile fatigue test (ITFT). The results showed among other things that cold recycled asphalt mixtures prepared at a mixing and compaction temperature of 32°C performed better in fatigue responses than their counterparts prepared at 20°C. The results of structural design and modelling of flexible pavement containing CRBEMs for fatigue life indicated that such materials would be applicable in low to medium volume traffic scenarios as road base materials.**

Keywords**-Cold asphalt, fatigue, RAP, bitumen emulsion**

I. Introduction

The present trend in road restoration practice in most developed countries of the world is recycling, and it is being driven chiefly by the resolve of the governments of these countries at enforcing the concept of sustainability in all human endeavours. This concept was introduced in Rio de Janeiro in 1992 during the United Nations Conference on Environment and Development [1]. Part of the recommendations made requires limiting wastes to landfills and also preserving the natural habitat as much as possible in all endeavours. Of course the road sector is not excluded from this, and as such one of the best ways of achieving this, is by the reuse and recycling of construction wastes [2]. Cold recycling of road pavements in particular assists in stretching road funds since old materials are reused and less energy is consumed in the process [3 and 4] and hence offers economic, safety and environmental benefits. It has been reported that total expenditure compared to conventional practices for road rehabilitation could be about 40-60% less when cold recycling of roads is adopted [5-7].

None-the-less, recycled road pavements must meet the structural and functional viability requirements just like the road pavement constructed with the conventional construction materials for it to gain wider acceptability. These are accomplished by proper mix and structural designs of such pavements. Fatigue has been identified by researchers as one of the major failure mechanisms in road pavements [2 and 8] and therefore most structural designs of road pavements require information about the fatigue responses of materials for the road pavement among other important parameters. Information obtained from the laboratory fatigue characterization of such mixtures is normally used for predicting performance in service. While the literature is replete with information about the fatigue performance of HMA, not much has been done to ascertain the responses of cold recycled asphalt mixtures.

This work therefore focused on fatigue characterization of CRBEMs. It is envisaged that a better knowledge of the fatigue responses of such materials would help in the total integration of cold asphalt mixtures (CAMs) as suitable and sustainable alternatives to HMA in the road construction industry.

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II. Experimental Programme

The experimental programme involved assessment of CRBEMs for fatigue response. Four types of materials in all were tested during the investigation. A full description of these materials is detailed in the succeeding section. The Indirect Tensile Fatigue Test (ITFT) mode in the Nottingham Asphalt Tester (NAT) is useful in this regard because it is easy and as well fast to conduct compared to other fatigue tests i.e. beam fatigue tests, and the relevant standard is DDABF-2003 ITFT [9]. The NAT is known to be widely used for tests on bituminous materials because of its versatility in aiding mixture design and specification in practical situations within the highway industry [10]. More importantly, this inexpensive facility provides a user friendly interface for conducting the tests even on a routine basis. It is suitable for testing cores (100mm or 150mm diameter) manufactured in the laboratory or those cored from road pavements. Such cylindrical specimens are also used for the Indirect Tensile Stiffness Modulus (ITSM) test (the relevant standard is DD 213:1993 ITSM [11]). As in the ITSM test, every other assumption for specimen and condition of testing holds for the ITFT as outlined by Read [12], except that load is applied repeatedly along the vertical diameter until the specimen fails i.e. when the loading strip vertically deforms by 9mm. This load induces an indirect tensile stress on the horizontal diameter. Rahman [13] reported that the magnitude of the stresses varies along the diameter but that they are at a maximum at the centre of the specimen. Thus prior to the ITFT test, an ITSM test in stress controlled mode is conducted on specimens at the required test stress level for the ITFT to determine the horizontal deformation and corresponding ITSM values. Once the test has been done, (2.1) and (2.2) are used to determine the maximum stress and maximum strain at the centre of the specimen.

$$\sigma_{hx} = \qquad 2.1$$

$$\varepsilon_{hx(max)} = \frac{\sigma_{hx(max)}}{S_m}(1 \qquad 2.2$$

Where:

D = specimen diameter
t = specimen thickness
P = applied compression or vertical load
σ_{hx} = maximum horizontal tensile stress at the centre of the specimen
ε_h= maximum horizontal tensile strain
= Poisson's ratio (assumed)
= Stiffness Modulus

The CRBEM specimens used were 50±2mm thick and 100±2mm in diameter. Tests were conducted at 20^{0}C and 30^{0}C. Trimming was not considered appropriate for such fragile mixtures in order not to compromise the integrity of the specimens. Also for very weak specimen conditions, especially for tests conducted at 30^{0}C, stress levels as low as 300kPa were chosen as the maximum. For the analysis of results, the initial maximum tensile strain at the centre of the specimen (ε_h) for each respective stress level as determined for each specimen using (2.2) was subsequently plotted against corresponding number of cycles to failure (N_f). Linear regression analysis using the least square method was then applied to the data. It is common for researchers to fit the curves using the relationship below in (2.3) suggested by Pell [14]:

$$N_f = c\,X\,(\frac{1}{\varepsilon_{hx(n}} \qquad (2.3)$$

Where:

= Number of load applications to failure
ε_h= maximum strain at the centre of specimen
c, m = factors depending on the composition and properties of the mixture; m is the slope of the fatigue line.

III. Materials and Procedure for Specimen Manufacture

The materials used for specimen manufacture for the investigations were:

- RAP with residual binder of 5dmm, 10dmm, and 20dmm
- Granite 5mm Dust
- Granite Filler
- Granite Aggregates of various sizes
- A proprietary bitumen emulsion with residual bitumen of 48dmm penetration
- Demineralised water

Four cold bituminous emulsion mixtures (CBEMs) were tested during this exercise as follows:

1. VACBEM - 100% virgin binder and aggregates
2. 5dmmCBEM - 65% RAP (recovered pen = 5dmm)
3. 10dmmCBEM - 65% RAP (recovered pen = 10dmm)
4. 20dmmCBEM - 65% RAP (recovered pen = 20dmm)

The CBEMs listed in 2 to 4 were constituted in the ratio 65:30:5 for RAP, fine aggregate (5mm) and filler respectively and the RAP was made in the laboratory [2] from aged 20mm Dense Bitumen Macadam (20mmDBM) with 4.25% binder content. The VACBEM was similarly constituted except that the RAP was replaced with virgin aggregate and the gradation used was 20mmDBM. Granite aggregates were used throughout. The choice of aggregate and RAP ageing was made to reflect conditions in Nigeria which was the subject of a wider study of which this work formed part. All the specimens produced had the same aggregate gradation (20mmDBM) and total fluid content (pre-wetting water and bitumen emulsion contents of 1.5% and 6.5% by aggregate mass respectively). These allowed for comparative analysis since one of the objectives of this research work is to identify the point at which the residual aged bitumen in the RAPs starts enhancing the engineering properties of the mix. Although some hot mixtures were brought into the picture later for a balanced comparison, VACBEM has been selected as the control mix mainly because practitioners in the field tend to favour the use of virgin materials in Nigeria. Performances of such mixtures compared with those containing RAPs will make it clear whether incorporating RAP CBEMs into the pavement structure is of any advantage or not.

The materials used for the manufacture of specimens were placed in the conditioning chamber at the desired temperature for about 8 hrs before mixing and the Sun and Planet mixer was used for the mixing operation. It had the advantage that mixing temperature could be controlled in it. As soon as the optimum total fluid content (OTFC) is known (by determining compaction characteristics of the cold bituminous mixture i.e. Optimum Moisture Content (OMC) and Maximum Dry Density (MDD) as detailed by Oke [2]), it is important to ensure that the appropriate mixing time for the mixture is ascertained. A 4-minute mixing time in which the first 2 minutes is used for the pre-wetting water addition/mixing, while the remaining 2 minutes is used for the bitumen emulsion addition/mixing was adopted. The Cooper Research Gyratory Compactor was used for the compaction of the CBEM materials. The 100 mm steel mould was used for the exercise in order to conserve materials. A pressure of 600 kPa, speed of 30 rev/min and an angle of gyration of 1.25^0 which have been widely used by researchers ([15] and [16] among others) were employed. A compactive effort of 200 gyrations was used. Since temperature could not be controlled in the compactor, each specimen (already in mould) was first placed in the conditioning chamber at the desired temperature for about 30mins before compaction. Curing was carried out at 60^{0}C over 96hrs in the forced draft oven under a relative humidity of approximately 40%.

The protocol followed was such that the specimens were left in the mould (in a sealed condition) immediately after compaction for up to 24hrs after which they were extruded. Specimens were subsequently placed in the forced draft oven at the required temperature for the specified time. Just before and immediately after curing, the specimens' masses were measured. The volumetric properties were measured after curing and thereafter placed in the cold store at 5^{0}C until they were ready for testing. However, prior to ITSM test and ITFT, specimens were removed from the cold store and placed in the conditioning cabinet at the desired test temperature (either 20^{0}C or 30^{0}C) for about 8hrs or preferably overnight.

IV. Fatigue Responses of CBEMS

For this test, CBEMs cured at 60^{0}C over 96 Hrs, mixed and compacted at 20^{0}C and 32^{0}C applying compactive effort of 200 gyrations were examined. VACBEM prepared at 20^{0}C was not included for being too fragile for the test. Table 4.1 details the fatigue responses of the CBEMs using the equations for strain and cycles to failure and the R-squared values. Equations for 20mmDBM and 28mmDBM 50 studied by Read [12] were included for comparison though tested at lower temperatures. Meanwhile the R-squared values in the table show a good fitness of the data for the relationship stated in (2.3) since all the values were above 0.90. For brevity, only figures in which VACBEM are represented have been plotted here since itis the control mixture.

TABLE 4.1. FATIGUE RESPONSES OF CBEMS AT FULLY CURED CONDITION

Mixture Type	Equation for Strain	Equation for Cycles to Failure	R^2
VA (Mixed & Compacted @ 32^{0}C) Tested@ 20^{0}C	$1906.1N_f^{-0.338}$	$1.67 \times 10^9 \varepsilon^{-2.776}$	0.94
VA(Mixed& Compacted @ 32^{0}C) Tested@ 30^{0}C	$69995N_f^{-0.916}$	$99856\varepsilon^{-0.989}$	0.91
5dmm (Mixed & Compacted @ 20^{0}C) Tested@ 20^{0}C	$5862.8N_f^{-0.45}$	$9.13x10^8\varepsilon^{-2.082}$	0.94
5dmm (Mixed & Compacted @ 32^{0}C) Tested@ 20^{0}C	$5243.2N_f^{-0.449}$	$1.13x10^8\varepsilon^{-2.141}$	0.96
5dmm (Mixed & Compacted @ 20^{0}C) Tested@ 30^{0}C	$6369.9N_f^{-0.453}$	$1.24x10^8\varepsilon^{-2.101}$	0.95
5dmm (Mixed & Compacted @ 32^{0}C) Tested@ 30^{0}C	$3217.1N_f^{-0.328}$	$1.7x10^{10}\varepsilon^{-2.878}$	0.94
10dmm (Mixed & Compacted @ 20^{0}C) Tested@ 20^{0}C	$9431.8N_f^{-0.559}$	$8.04x10^6\varepsilon^{-1.719}$	0.96
10dmm (Mixed & Compacted @ 32^{0}C) Tested@ 20^{0}C	$3296.3N_f^{-0.367}$	$1.77x10^9\varepsilon^{-2.585}$	0.95
10dmm (Mixed & Compacted @ 20^{0}C) Tested@ 30^{0}C	$9509.4N_f^{-0.51}$	$4.3x10^7\varepsilon^{-1.9}$	0.97
10dmm (Mixed & Compacted @ 32^{0}C) Tested@ 30^{0}C	$7434N_f^{-0.518}$	$1.27x10^7\varepsilon^{-1.799}$	0.93
20dmm (Mixed & Compacted @ 20^{0}C) Tested@ 20^{0}C	$2623.1N_f^{-0.377}$	$6.93x10^8\varepsilon^{-2.557}$	0.96
20dmm (Mixed & Compacted @ 32^{0}C) Tested@ 20^{0}C	$1942N_f^{-0.32}$	$3.79x10^9\varepsilon^{-2.803}$	0.90
20dmm (Mixed & Compacted @ 20^{0}C) Tested@ 30^{0}C	$7581.3N_f^{-0.451}$	$1.24x10^8\varepsilon^{-2.046}$	0.92
20dmm (Mixed & Compacted @ 32^{0}C) Tested@ 30^{0}C	$7182.5N_f^{-0.465}$	$1.16x10^8\varepsilon^{-2.068}$	0.96
20mmDBM (Read,1996)	$1562N_f^{-0.246}$	$9.6x10^{12}\varepsilon^{-4.065}$	
28mmDBM 50 (Read,1996)	$2595N_f^{-0.255}$	$2.45x10^{13}\varepsilon^{-3.922}$	

Figures 4.1 and 4.2 show the regressed fatigue lines for the tests conducted at 20^{0}C and 30^{0}C respectively. Figure 4.1 which is for tests conducted at 20^{0}C demonstrates that the 20dmmCBEM has the longest fatigue life of all the CBEMs studied, while the 5dmmCBEM indicated the shortest. This is against logic at face value as researchers have suggested that the material with the stiffest bitumen gives the longest fatigue life [17]. The explanation for this observation is that the residual bitumen from the emulsion played the prominent role in the fatigue response of the 5dmmCBEM. The activeness of aged residual bitumen was not significant enough to alter the property of the overall active binder in the mix.

Aside the VACBEM which ordinarily was expected to have displayed the least fatigue life response, the next in rank to the 5dmmCBEM is the 10dmmCBEM. It is likely that a relatively higher portion of the residual aged bitumen from the 10dmm RAP has possibly been rejuvenated compared to the 5dmmCBEM. Therefore, it is logical for the 20dmmCBEM to have demonstrated the longest fatigue life since it has the greatest possible potential for rejuvenation (if any rejuvenation is taking place) as a result of its containing the most active and stiffest bitumen at the temperature of 30^{0}C used for the preparation of the CBEMs.

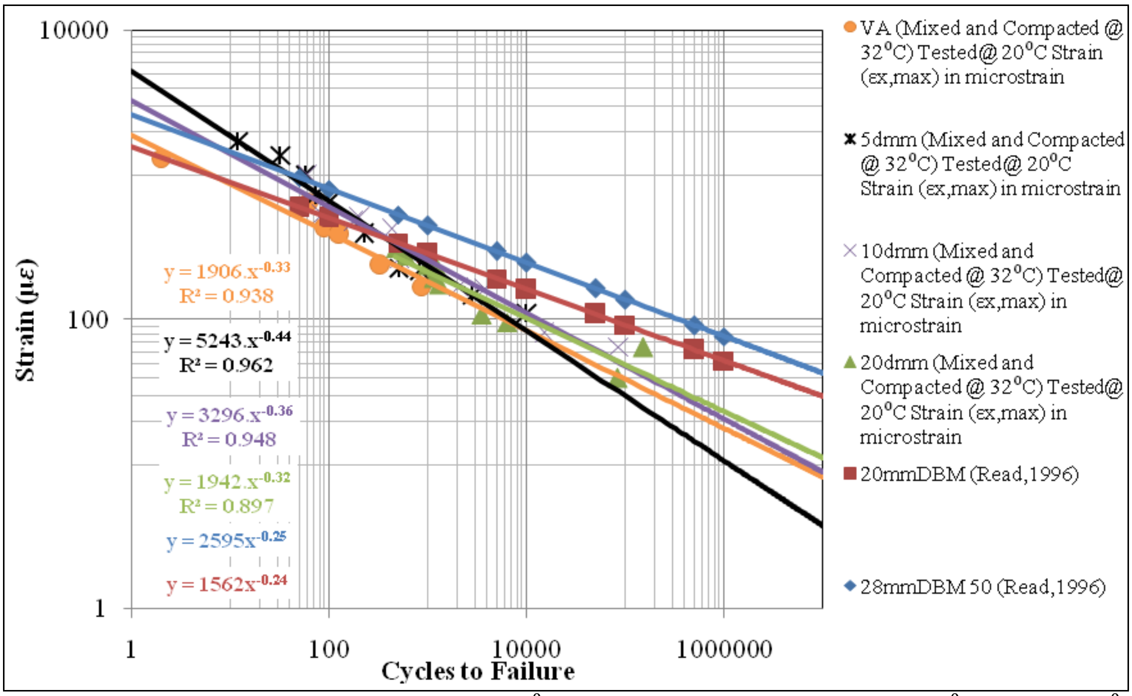

FIGURE 4.1 Fatigue Responses of CBEMs Cured at 60^{0}C over 96 Hrs, Mixed & Compacted @ 32^{0}C, Tested @ 20^{0}C

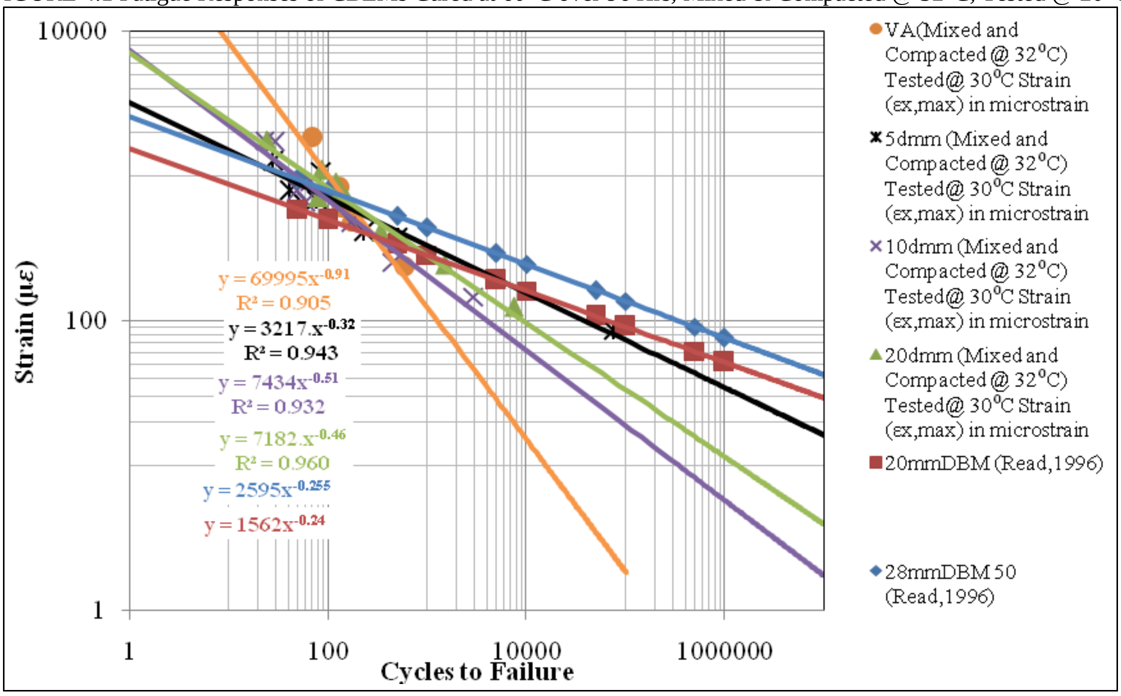

FIGURE 4.2 Fatigue Responses of CBEMs 60^{0}C over 96 Hrs, Mixed & Compacted @ 32^{0}C, Tested @ 30^{0}C

The preparation temperature was probably sufficient to excite a significant portion of the residual aged bitumen in the 20dmm RAP causing it to interact with the residual binder from the emulsion and in the process altering the overall behaviour of the active binder in the mix i.e. becoming stiffer. This order could have changed if the preparation temperature was sufficiently high to excite all the residual aged binders in the 5dmm and 10dmm RAPs.

Figure 4.2 for the tests conducted at 30^{0}C shows that the 5dmmCBEM displayed the longest fatigue life while the VACBEM indicated the shortest of all the CBEMs tested. This observation appears logical except for the order of the 10dmmCBEM and 20dmmCBEM at 20^{0}C and the earlier explanations given. At the test temperature of 30^{0}C, the residual aged bitumen in the 5dmmCBEM is probably now excited or active thus significantly enhancing its fatigue life. These CRBEMs were normally conditioned to test temperature before testing. Thus this CRBEM should have the overall stiffest active binding medium compared to the other CBEMs. The fatigue life of the VACBEM is short mainly because it has the softest and probably the lowest volume of active binding medium. The figure also indicated that the VACBEM was more stress sensitive compared to the other CBEMs at this test temperature. However, the fatigue lives of the CBEMs generally were lower than those for the hot mixtures as observed in the said figures. This confirms the general belief that HMA have superior mechanical properties than cold mixtures [18 and 19]. In order to have a fuller knowledge of what the equations presented earlier in Table 4.1 signify, the equations for cycles to failure were used to calculate fatigue lives consequent upon reaching strains of 30με, 50με, 100με and 200με, and similarly the equivalent strains using the equations for strain for 1.0E+03, 1.0E+04, 1.0E+05 and 1.0E+06 cycles respectively. Read [12] suggested that fatigue failure in bituminous mixtures normally occurs in the range 30-200 με. Table 4.2 details fatigue lives of CBEMs at the mentioned strains while Table 4.3 details the corresponding strains for the suggested fatigue lives.

TABLE 4.2 FATIGUE LIFE OF CBEMS AT VARIOUS MICROSTRAINS

CBEM Condition	Fatigue Life @ Various Microstrain			
	30(με)	50(με)	100(με)	200(με)
VA (Mixed & Compacted @ 32^{0}C) Tested@ 20^{0}C	132504	32090	4685	684
VA(Mixed & Compacted @ 32^{0}C) Tested@ 30^{0}C	3457	2086	1051	529
5dmm (Mixed & Compacted @ 20^{0}C) Tested@ 20^{0}C	76755	26498	6259	1478
5dmm (Mixed & Compacted @ 32^{0}C) Tested@ 20^{0}C	77725	26037	5903	1338
5dmm (Mixed & Compacted @ 20^{0}C) Tested@ 30^{0}C	97721	33411	7788	1815
5dmm (Mixed & Compacted @ 32^{0}C) Tested@ 30^{0}C	953441	219186	29816	4056
10dmm (Mixed & Compacted @ 20^{0}C) Tested@ 20^{0}C	23232	9654	2933	891
10dmm (Mixed & Compacted @ 32^{0}C) Tested@ 20^{0}C	268915	71802	11967	1994
10dmm (Mixed & Compacted @ 20^{0}C) Tested@ 30^{0}C	67133	25435	6815	1826
10dmm (Mixed & Compacted @ 32^{0}C) Tested@ 30^{0}C	27955	11152	3205	921
20dmm (Mixed & Compacted @ 20^{0}C) Tested@ 20^{0}C	115807	31367	5330	906
20dmm (Mixed & Compacted @ 32^{0}C) Tested@ 20^{0}C	274327	65528	9389	1345
20dmm (Mixed & Compacted @ 20^{0}C) Tested@ 30^{0}C	117823	41431	10033	2429
20dmm (Mixed & Compacted @ 32^{0}C) Tested@ 30^{0}C	102275	35562	8481	2023
20mmDBM [12]	9501088	1191127	71166	4252
28mmDBM 50 [12]	39302430	5297937	349274	23026

TABLE 4.3 MICROSTRAIN OF CBEMS AT VARIOUS FATIGUE LIVES

CBEM Condition	Microstrain @ Various Cycles to Failure (με)			
	1.0E+03	1.0E+04	1.0E+05	1.0E+06
VA (Mixed & Compacted @ 32^{0}C) Tested@ 20^{0}C	185	85	39	18
VA(Mixed & Compacted @ 32^{0}C) Tested@ 30^{0}C	125	15	2	0
5dmm (Mixed & Compacted @ 20^{0}C) Tested@ 20^{0}C	262	93	33	12
5dmm (Mixed & Compacted @ 32^{0}C) Tested @ 20^{0}C	236	84	30	11
5dmm (Mixed & Compacted @ 20^{0}C) Tested @ 30^{0}C	279	98	35	12
5dmm (Mixed & Compacted @ 32^{0}C) Tested @ 30^{0}C	334	157	74	35
10dmm (Mixed & Compacted @ 20^{0}C) Tested@ 20^{0}C	198	55	15	4
10dmm (Mixed & Compacted @ 32^{0}C) Tested @ 20^{0}C	261	112	48	21
10dmm (Mixed & Compacted @ 20^{0}C) Tested @ 30^{0}C	281	87	27	8
10dmm (Mixed & Compacted @ 32^{0}C) Tested @ 30^{0}C	208	63	19	6
20dmm (Mixed & Compacted @ 20^{0}C) Tested @ 20^{0}C	194	81	34	14
20dmm (Mixed & Compacted @ 32^{0}C) Tested @ 20^{0}C	213	102	49	23
20dmm (Mixed & Compacted @ 20^{0}C) Tested @ 30^{0}C	336	119	42	15
20dmm (Mixed & Compacted @ 32^{0}C) Tested @ 30^{0}C	289	99	34	12
20mmDBM [12]	286	162	92	52

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28mmDBM 50 [12]	446	248	138	77

The analysis is restricted to those comparable to the VACBEM (prepared at 32^{o}C), thus only similar colours in the tables are comparable. At 50με, 100με and 200με, the 10dmmCBEM recorded the longest fatigue life while the 5dmmCBEM had the least for 50με. The VACBEM returned the least performance for the 100με and the 200με. Overall, the result at this level indicates that the 10dmmCBEM has the best fatigue life.

For the tests conducted at 30^{o}C, the results in green in Table 4.2 are relevant for the cycles to failure. The 5dmmCBEM in all cases performed best followed by the 20dmmCBEM while the VACBEM had the least good performance. The earlier explanations given for the performances based on the regressed fatigue lines in Figures 4.1 and 4.2 are still relevant here. Therefore, there is an advantage for using RAPs in CBEMs when it comes to fatigue response over those made purely from virgin aggregates. As expected, the HMA in all cases performed better than the CBEMs though the 5dmmCBEM prepared at 32^{o}C and tested at 30^{o}C was close in performance to the 20mmDBM at 200με. In Table 4.3 and for tests conducted at 20^{o}C, the results for 1.0E + 03 cycles to failure indicated that the VACBEM had the least strain while the RAP CBEMs returned values generally greater than 200με. This trend was similarly observed for those tested at 30^{o}C.

V. The Effect of Mixing and Compaction Temperatures on the Fatigue Responses and Temperature Susceptibility of CBEMS

Based on the results of the studies carried out on the fatigue responses of the CBEMs, it was considered appropriate to ascertain the effect of preparation temperature on the fatigue responses. The analysis here was restricted to cycles to failure and thus Figures 5.1 and 5.2 were plotted using the results in Table 4.2. Figure 5.1 represents CBEMs tested at 30^{o}C. The black dashed ellipse captures the performance of the VACBEM which was prepared at 32^{o}C. There is no information here about its counterpart prepared at 20^{o}C. The 5dmmCBEM prepared at 20^{o}C was inferior in performance to its counterpart prepared at 32^{o}C. While those prepared at the two temperatures for the 20dmmCBEM showed similar performances, the 10dmmCBEM prepared at 20^{o}C was better than its counterpart prepared at 32^{o}C for all the strains considered.

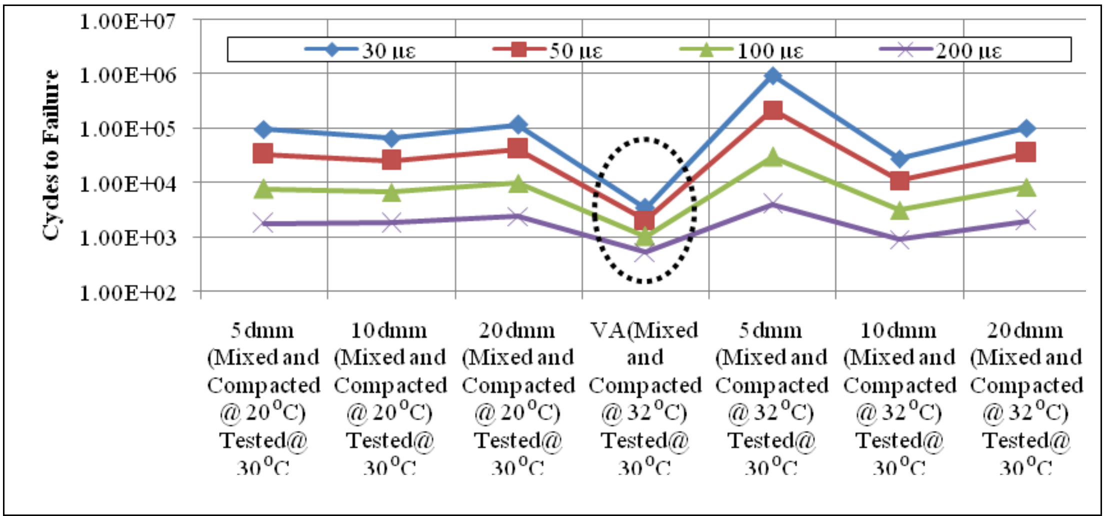

FIGURE 5.1 The Effect of Mixing and Compaction Temperature on Cycles to Failure of CBEMs Tested at 30^{o}C

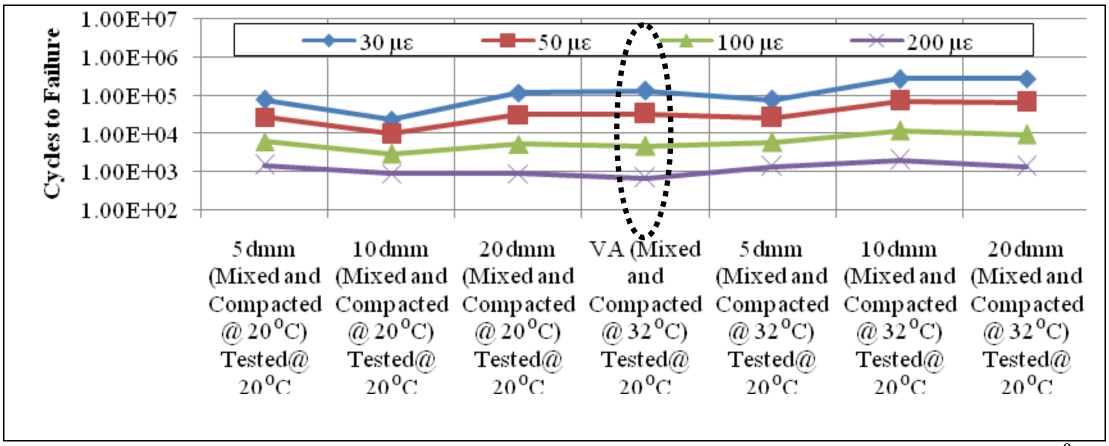

FIGURE 5.2 The Effect of Mixing and Compaction Temperature on Cycles to Failure of CBEMs Tested at 20^{0}C

The plots in Figure 5.2 are for the tests conducted at 20^{0}C. The black dashed line ellipse encloses the results for the VACBEM prepared at 32^{0}C. The performance here was average compared to the other CBEMs. At this test level, the effect of the preparation temperature was obvious in the performance of the 10dmmCBEM and 20dmmCBEM as those prepared at 32^{0}C performed better than those at 20^{0}C. No difference was however noticed for the 5dmmCBEM. The two graphs indicate that the VACBEM and 5dmmCBEM prepared at 32^{0}C were significantly sensitive to the test temperature. Overall, the RAP CBEMs prepared at a mixing and compaction temperature of 32^{0}C performed better than those prepared at 20^{0}C in fatigue response.

The temperature susceptibility of the CBEMs under fatigue response was studied. For brevity, the discussion here is limited to CBEMs mixed and compacted at 32^{0}C and the analysis was based on cycles required to reach the earlier stated target strains. The two test temperatures considered were 20^{0}C and 30^{0}C. The results indicate that increase in test temperature significantly enhanced the performance of the 5dmmCBEM, while it caused a significant reduction in performance for the VACBEM. These were followed by the 10dmmCBEM and 20dmmCBEM both having a reduction in response due to increase in temperature. The reasons for these observations have been discussed in the preceding sections. Thus for this study, the two most sensitive CBEMs to temperature changes were the VACBEM and 5dmmCBEM, though their responses were different.

Also, considering the behaviour of both the VACBEM and 5dmmCBEM, it seems that fatigue responses of CBEMs were not affected by air void contents although it was earlier established that air voids have a strong correlation with stiffness of CBEMs but depending on the level of curing attained. Generally, these two CBEMs have relatively higher air void contents compared to the other CBEMs. Also they were both inferior in stiffness compared to the other CBEMs. In HMA, stiffness and air void content alike have been noted to significantly affect fatigue responses [20]. This was similarly noted for foamed asphalt mixtures [16]. From all indications in this limited study, this might not be completely true for CBEMs. Since this is a limited study on CBEMs prepared at 32^{0}C, 200 gyrations, there is a need to investigate other CBEMs treated differently. Also, other methods of fatigue testing such as the trapezoidal test could be explored.

VI. Design of CBEM Road Base for Fatigue Life

The results (only one figure i.e. Figure 6.1 is included here for brevity but full details are contained in Oke [2]) of the analyses done using KENLAYER (non-linear analytical tool for pavement) developed by Huang [21] showed that the maximum horizontal strains in the CBEM layers are somewhere close to the middle, and thus, such strains are deemed more appropriate theoretically for design purposes than those observed at the bottom of the CBEM (road base) layers recommended by Ebels [22]. The design presented here considered these set of strains i.e. maximum and at the bottom, to ascertain their suitability or not. Where applicable, only laboratory test results i.e. fatigue line equations reported in Figure 4.2 conducted at 30^{0}C were used since the focus of the work is hot tropical climate. A conventional HMA road base layer of 28mm DBM [12] though analysed using BISAR 3.0 (linear analytical tool for pavement) was included for comparisons. A stiffness value of 3000MPa was assumed for the layer (at 30^{0}C). The design was conducted for both critical condition (point at which pavement crack initiation occurs) and failure.

The shift factors of 77 and 440 were used for the respective points as suggested by Brunton [23]. It is worth noting however that such shift factors might not be appropriate for the CBEMs (cold mixtures) since they were developed for HMA. At present, no such universally accepted values are available for cold mixtures. Thus, the results presented here are just estimates and can only be used with caution. For the analyses, the surfacing layer thicknesses used were 30mm, 50mm, 75mm and 100mm while the road base layer thicknesses used were 150mm, 200mm, 250mm and 300mm. The representative strains required for considering CBEM layers in structural design of pavements can be ascertained through full scale pavement tests and this will be an interesting area for further research work.

From the analysis done here, the 28mm DBM and 5dmmCBEM indicated the best fatigue lives followed by 20dmmCBEM and 10dmmCBEM. VACBEM indicated the worst performance. Fatigue lives of the 50mm HMA surfacing for critical condition which is between 2.8 and 10.5 million ESALs suggest longer lives to failure although it is difficult to make predictions. Liebenberg and Visser [24] recorded 30 million ESALs to failure for similar pavements. 28mm DBM gave very good support to 30/14 HRA surfacing layer compared to the CBEMs. A surfacing layer on HMA road base is highly sensitive to changes in thickness of the road base compared to CBEM road base. Such changes in HMA road bases resulted in significant increase in ESALs. The analysis showed that pavements containing HMA materials as surfacing and road base are better in performance compared to those made with CBEMs and thus confirms the findings/views of experts in the field. However, with all things being equal, pavements containing 5dmmCBEM/ 20dmmCBEM and probably 10dmmCBEM as road base should conveniently accommodate about 5million ESALs before reaching the end of their service lives and thus would be applicable in low to medium volume traffic scenarios as road base materials.

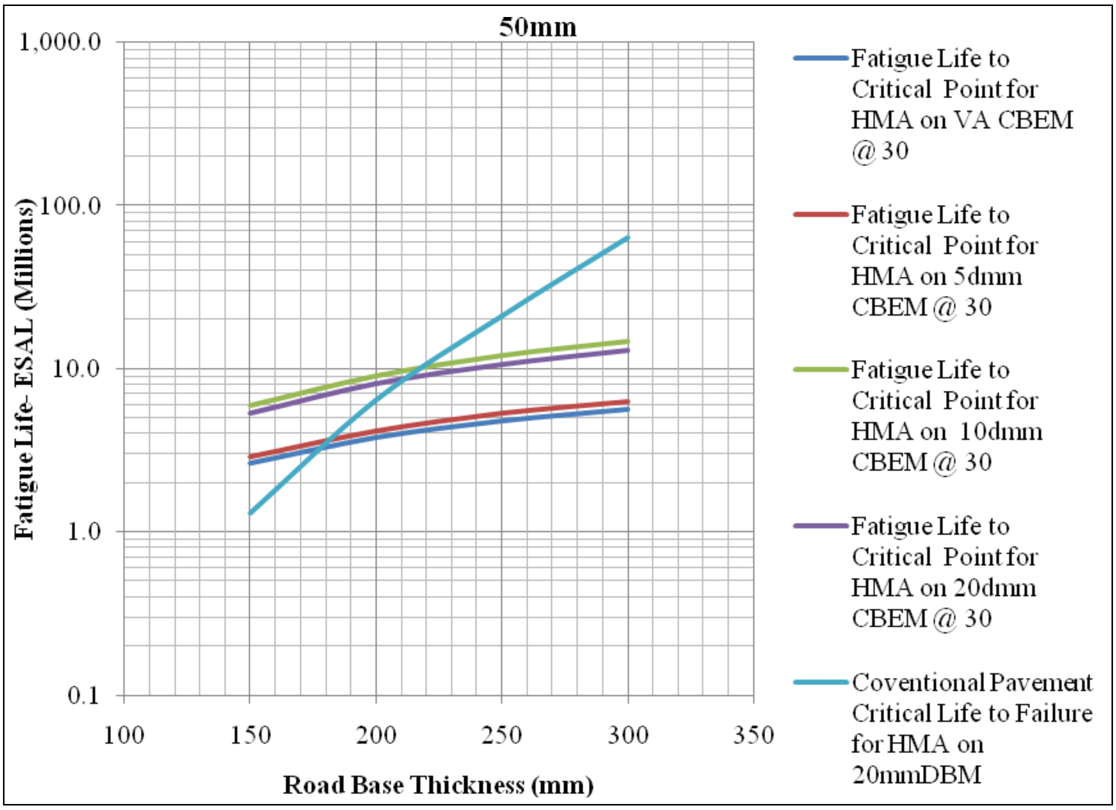

Figure 6.1 Effect of Road Base Layer Thickness and Material Type on Fatigue Lives to Critical Condition for Surfacing Thickness of 50mm HMA

VII. Conclusion

It was observed in this limited study that fatigue lives of the CBEMs generally were lower than those for HMA. For the tests conducted at 30^{0}C, the result for the 5dmmCBEM in all cases was the best followed by the 20dmmCBEM while the VACBEM had the least performance. For tests conducted at 20^{0}C, the results for 1.0E + 03 cycles to failure indicated that the VACBEM had the least strain while the RAP CBEMs returned values generally greater than 200με. This trend was similarly observed for tests at 30^{0}C. The results imply that the VACBEM has the best resistance at high stresses compared to all the other mixtures. The 5dmmCBEM on the other hand returned the least strain for CBEMs prepared at 32^{0}C and tested at 30^{0}C. Overall, the RAP CBEMs prepared at a mixing and compaction temperature of 32^{0}C performed better in fatigue than their counterparts prepared at 20^{0}C. In pavement analyses conducted, except for ranking CBEMs, the use of maximum horizontal strains anywhere within the CBEM layers for design purposes is not sensitive to changes in thicknesses of the surfacing and CBEM layers. It is thus better to focus on checking the fatigue lives of surfacing and the rutting lives of subgrade for pavements containing CBEM layers. The results presented here are generally for critical conditions, which imply failure would actually happen at larger ESALs values than presented in the design charts produced. The RAP CBEMs overall performed better than the VA CBEM in terms of ESALs applications that they offer. These RAP CBEMs would be applicable in low to medium volume traffic scenarios as road base materials. However, in a bid to validate the observations made in this work which were mainly laboratory based, other methods of fatigue testing such as the trapezoidal test could be explored. Representative strains required for considering CBEM layers in structural design of pavements can also be ascertained through full scale pavement tests and this will be an interesting area for further research work.

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[Overall, the RAP CBEMs prepared at a mixing and compaction temperature of 32^{o}C performed better in fatigue than their counterparts prepared at 20^{o}C.]