Materiales de Construcción
Vol. 67, Issue 327, July–September 2017, e127
ISSN-L: 0465-2746
http://dx.doi.org/10.3989/mc.2017.04616

Analysis of stiffness and fatigue resistance of cold recycled asphalt mixtures manufactured with foamed bitumen for their application to airfield pavement design

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Received 15 April 2016
Accepted 10 November 2016
Available on line 17 July 2017

ABSTRACT: Cold recycled bound materials (CRBMs) provide an economic and environmental advantage for pavements since they decrease energy and raw material consumption. However, design methods for airfield pavements do not include key CRBM properties. In this paper an empirical-mechanistic method is used to study airfield pavement design with CRBM in order to develop design guidance. The aim of the paper is to obtain the inputs related to material properties needed for use in this method. For this purpose, CRBM containing reclaimed asphalt, with fly ash, cement and foamed bitumen as stabilising agents, was characterised. The methodology included indirect tensile stiffness modulus (ITSM) and indirect tensile fatigue tests (ITFT) in strain control mode. The inputs needed for a pavement design analysis with CRBM were then obtained. The results showed the importance of further study on CRBM fatigue to understand the behaviour of these mixes under cyclic loading.

KEYWORDS: Mechanical properties; Modulus of elasticity; Fatigue; Characterisation; Fly ash

Citation/Citar como: Lacalle-Jiménez, H.I.; Edwards, J.P.; Thom, N.H. (2017) Analysis of stiffness and fatigue resistance of cold recycled asphalt mixtures manufactured with foamed bitumen for their application to airfield pavement design. Mater. Construcc. 67 [327], e127 http://dx.doi.org/10.3989/mc.2017.04616

RESUMEN: *Análisis del módulo de rigidez y la resistencia a fatiga de mezclas asfálticas recicladas en frio fabricadas con betún espumado para su uso en el diseño de firmes para aeropuertos.* El uso de mezclas asfálticas recicladas en frío (MARF) proporciona ventajas tanto económicas como medioambientales al disminuir el consumo de energía y materias primas. Sin embargo, los métodos de diseño para firmes de aeropuertos no incluyen las propiedades de MARFs. En este artículo un método empírico-mecanístico se emplea para estudiar el diseño de firmes de aeropuertos con MARF. El objetivo es obtener los inputs relacionados con las propiedades de MARF necesarios para llevar a cabo el diseño del pavimento. Con este propósito, MARF con asfalto reciclado, ceniza volante, cemento y betún espumado ha sido caracterizado. La metodología incluye ensayo de tracción indirecta para la obtención del módulo de rigidez y ensayo de fatiga con tracción indirecta en modo de deformación controlada. Los inputs necesarios han sido obtenidos y los resultados muestran la importancia de un estudio adicional del comportamiento a fatiga de MARF para entender su comportamiento bajo cargas cíclicas.

PALABRAS CLAVE: Propiedades mecánicas; Módulo elástico; Fatiga; Caracterización; Ceniza volante

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1. INTRODUCTION

Material that is recovered from aged asphalt pavements is known as RAP (Reclaimed Asphalt Pavement) (1, 2). The requirement for using RAP in new asphalt is becoming increasingly urgent (3) because of the economic and environmental benefits (3), reducing demand on finite resources, generation of waste materials and embodied energy (4).

Cold recycling of asphalt is a proven technique that reduces energy consumption (5–7). This reduction is largely achieved by avoiding aggregate drying (8) and mixing the material at ambient temperature instead of 170°C-185°C, as required for hot mix asphalt (HMA) (9). The use of bituminous stabilising agents produces a flexible layer with superior fatigue performance to those with purely cementitious binders (10). This study looks at foamed asphalt with cement, material which is classified in the UK as a cold recycled bound material (CRBM) (8, 11).

Foamed bitumen is produced by injecting air and water droplets under high pressure (e.g. 5 bar) into hot (160–180°C) liquid bitumen, resulting in the formation of foam (12). The volume of bitumen increases while viscosity considerably reduces (13). Typically foam bitumen is added to the mixture at between 3% and 5% by weight of aggregate; however, when the bitumen content of the recycled material is high, this can be reduced to 2–3% (2, 13, 14).

Early life CRBM mechanical properties change over time (15). This phenomenon, during which the cohesion between the binder and the aggregates increases as the mixture loses water, is known as curing (16, 17). No standard curing procedure has been established for CRBM; however, from previous research, it has been demonstrated that curing specimens fully wrapped at 20°C for 28 days is an appropriately conservative practice (16, 18); therefore, this curing procedure was chosen for this study.

Despite the increasingly common use of CRBMs in roads (11, 19), the specifications for the use of these materials in airfields are underdeveloped (8) and there is no guidance to ensure that pavement design with these materials is trustworthy (20–22). Design guides for airfield pavements such as FAArfield (23), BAA (24) or Design and Maintenance Guide 27 (DMG27) (25) do not readily allow the introduction of new material properties (20), making it difficult for authorities and practitioners to use these materials on airfield pavements. A new design approach is therefore required (22). In Figure 1 a harmonised approach for analytical pavement design of pavements using CRBM is proposed (22).

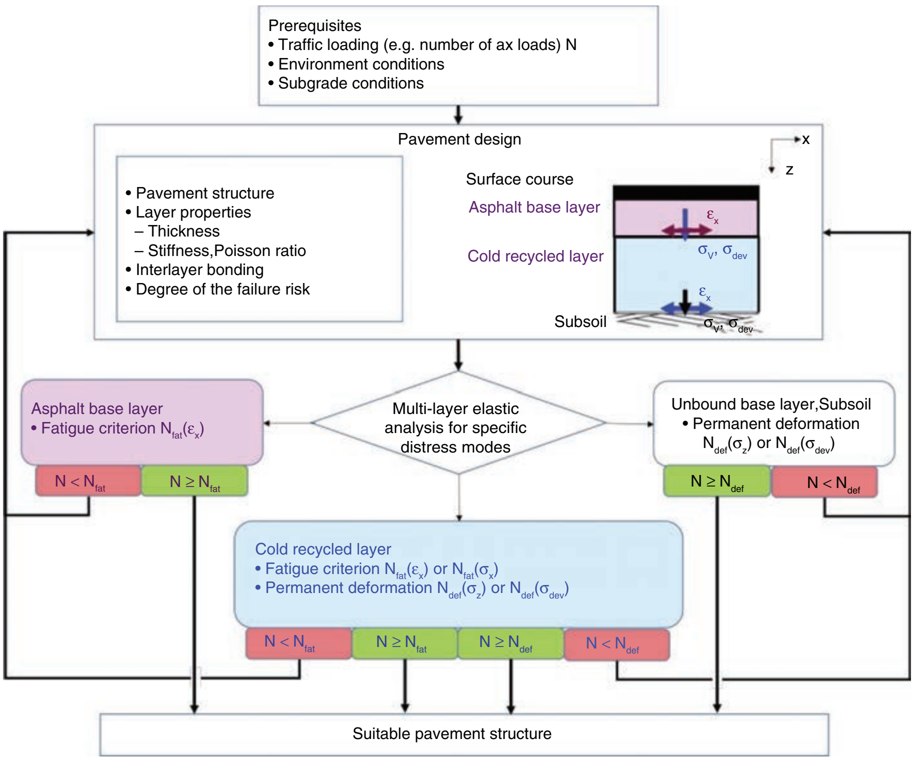

FIGURE 1. Analytical design principle for pavements with cold recycled layer (22).

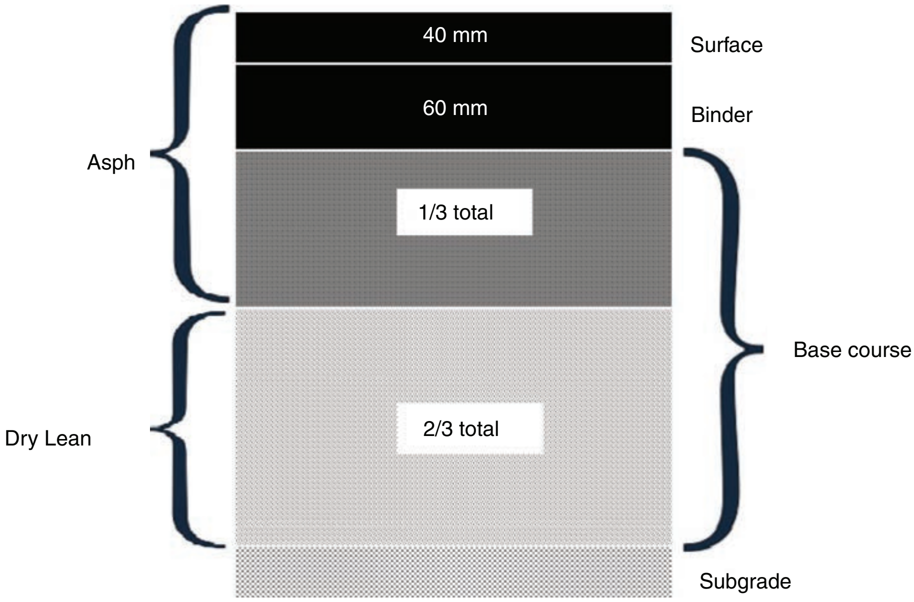

FIGURE 2. Airfield flexible pavement structure.

In this investigation Kenlayer, an empirical-mechanistic software package, was selected to undertake the multilayer-elastic analysis. This software allows analysis which can incorporate CRBM behaviour (26). It was decided to use a mechanistic design method because of the lack of the necessary performance data to undertake an empirical analysis (21; 22). Furthermore a mechanistic method provides a theoretically sound approach as it relates the stresses, strains and deflections within a pavement structure with the loads and material properties.

The structure of airfield pavements comprises surface, binder and base courses laid on a foundation as shown in Figure 2, for new build and full rehabilitation designs (24; 25). The surface and binder courses have typical thicknesses of 40 and 60 mm respectively; the base course thickness is designed as a function of traffic, subgrade conditions and desired design life (26).

According to the BAA approach the base thickness calculated is then divided into 1/3rd asphalt and 2/3rd dry lean concrete (24), while DMG27 requires a minimum of 120 mm of asphalt base to avoid reflective cracking for high traffic scenarios (25).

To carry out a pavement analysis with Kenlayer (or any other multi-layer linear elastic program), material mechanical properties need to be defined, such as stiffness, Poisson's ratio and failure criteria; these parameters therefore have to be determined for CRBM.

The material stiffness can be obtained from conventional indirect tensile stiffness modulus (ITSM) tests (27). Poisson's ratio has a relatively small effect on the pavement response (26); thus a typical value of 0.3 has been adopted here for CRBM (28). The failure criteria can be adjusted by modifying cracking and permanent deformation algorithms (26). Fatigue cracking is a common distress that affects pavement service life (29).

The failure criterion for permanent deformation is expressed by equation [1]:

$$N_d = f_1(\varepsilon_c)^{-f_2} \qquad [1]$$

where N_d is the allowable number of load repetitions to limit permanent deformation, ε_c is the compressive strain at the top of the subgrade, and f_1 and f_2 are coefficients determined from road tests or field performance (26). The compressive strain at the top of the subgrade is used as a failure criterion as the permanent deformation is considered to be caused by subgrade weakness rather than by the overlying layers (26). Taking this into account, for this research f_1 and f_2 were selected as $1.365\text{x}10^{-9}$ and 4.477 respectively, these values being taken from the Asphalt Institute analytical design procedure (26;30).

The failure criterion for fatigue cracking is expressed by equation [2]:.

$$N_f = f_3(\varepsilon_t)^{-f_4}(E_1)^{-f_5} \qquad [2]$$

where N_f is the allowable number of load repetitions to prevent fatigue cracking, ε_t is the tensile strain at the bottom of the asphalt layer, E_1 is the elastic modulus of the asphalt layer and f_3, f_4 and f_5 are coefficients determined from laboratory fatigue tests, with f_3 modified to correlate with field performance observations (26).

A key aim of this paper was to evaluate at a laboratory level the parameters needed to perform a pavement analysis with Kenlayer incorporating CRBM with foamed bitumen layers, namely stiffness and fatigue coefficients, f_3, f_4 and f_5.

2. MATERIALS AND METHODS

To obtain the inputs needed for Kenlayer mentioned in the introduction, a laboratory program was established. The materials used were specified fully in previous work (20) and are summarised in the next section.

2.1. Materials

For CRBM mixture manufacture, RAP, fly ash, cement and foamed bitumen were used with the mix design shown in Table 1. Fly ash was added as the RAP contained less fines than the specification demands. More information about the mix design optimization can be found in the authors' previous works (20; 31).

The binder contents in the RAP and in the final mixture were calculated in accordance with BS 598-102 (32). Binder was recovered in accordance with BS EN 12697-3 (33) for characterisation. The recovered bitumen and the bitumen used for foaming were characterised in terms of softening point in accordance with BS EN 1427-2007 (34) and penetration grade in accordance with BS EN 1426-2007 (35). The results are shown in Table 2.

Table 1. CRBM mix design

Ingredient	Proportion by mass (%)
0-10mm RAP	43.5
10-20 mm RAP	39.1
Fly ash	6.3
Cement	1.6
Foamed bitumen	3
Total water content	6.5

Table 2. Bitumen characterisation

Bitumen	Binder content (%)	Penetration (25°,1/10 mm)	Softening point (°C)
100/150	NA	107	44.2
RAP 0-10 mm	7.2	30	58.6
RAP 10-20 mm	4.4	32	55.0
Recovered from mixture	7.5	46	52.4

A Wirtgen WLB 10 mobile foaming plant, with the settings established in Table 3, and a gyratory compactor were used for specimen manufacture. Specimens were double wrapped in cling film and cured for 28 days at 20°C.

2.2. Methodology

The testing methodology comprised:

- Determination of indirect tensile stiffness modulus (ITSM) to BS EN 12697-26:2004 Annex C (36)
- Indirect Tensile Fatigue Tests (ITFT) in strain control mode to BS EN 12697-24:2012 Annex E (37)

2.2.1. ITSM

Asphalt material stiffness relates to its load spreading ability and temperature susceptibility, parameters used to assess pavement structural condition. In a structural asphalt layer, high stiffness indicates good load-spreading ability.

In determining ITSM the rise-time, which is the time taken for the applied load to increase from the initial contact load to its maximum value, was selected as 124 ms. 10 conditioning pulses were applied to set the load needed to obtain a peak horizontal deformation of 5μm. To calculate the stiffness modulus 5 pulses were applied across two perpendicular diameters (36).

As stated before, the stiffness value is a material property required to undertake analysis with Kenlayer and it was measured on 37 specimens at 10, 20 and 30°C.

2.2.2. ITFT in strain control mode

This test was developed at the University of Nottingham (38) and monitors the stiffness variation for a specified repeated strain value and the number of cycles until failure occurs. These parameters were needed to determine the fatigue coefficients in equation [2]. This is a relatively simple test and suitable for cylindrical specimens; therefore, the manufacture of test specimens was straight-forward, saving materials and using the same compaction

Table 3. Foaming conditions

Water Pressure	4 bar
Air pressure	5 bar
Bitumen type	100/150
Bitumen temperature	170°C
Water addition	1%

method as in the author's previous research, gyratory compaction. This also avoided the need to cut specimens from a slab, a process that can affect CRBM behaviour.

The strains selected for the ITFT were between 150 and 300 με (39) and the loading frequency was 2 Hz. The test was performed at 20°C on 14 specimens and the failure criterion used was the conventional target of 50% reduction of stiffness value (40).

3. ANALYSIS OF RESULTS AND DISCUSSION

3.1. Stiffness

The stiffness results presented in Figure 3 show low temperature susceptibility of CRBM mixes when compared to HMA (20). This is likely to be due to the action of cement within the mixture. Regarding the stiffness value used for design (at 20°C), 3500 MPa is comparable to the values of HMA assumed in airfield base layers, for example DBM50 for which stiffness values range between 2400 MPa and 5000 MPa (41). It would therefore appear that CRBM with foamed bitumen has appropriate stiffness modulus for airfield pavement design.

3.2. ITFT in strain control mode

Table 4 shows the results from the ITFT in strain control mode for CRBM.

To obtain the coefficients, the difference between the N_f obtained in the laboratory and the N_f calculated using equation [2] was minimised by optimising the values required for f_3, f_4 and f_5. The fatigue curves obtained from laboratory tests and from calculations are presented in Figure 4.

Maggiore's data (38), shown in Table 5, were also used for analysing the adequacy of this fatigue test method, and the values of f_3, f_4 and f_5 compared to those for HMA calculated by the Asphalt Institute and Shell (26; 30). HMA results and CRBM fatigue coefficients are presented in Table 6.

It is noted that the values calculated using Maggiore's HMA data and the values proposed by Shell are comparable. Thus it seems likely that the ITFT in strain control mode is a suitable test for fatigue coefficient calculation.

TABLE 4. Experimental data from strain control fatigue tests for CRBM

N_f	ε_t	E_1 (MPa)
184279	0.00015	3426
202363	0.00015	3081
165563	0.00018	2219
78554	0.00018	2330
123526	0.0002	2343
64123	0.0002	1660
88723	0.0002	2895
65933	0.00022	1996
90173	0.00025	1711
36413	0.00025	2179
82223	0.00027	1390
59043	0.00027	1343
15183	0.0003	1432
21673	0.0003	1646

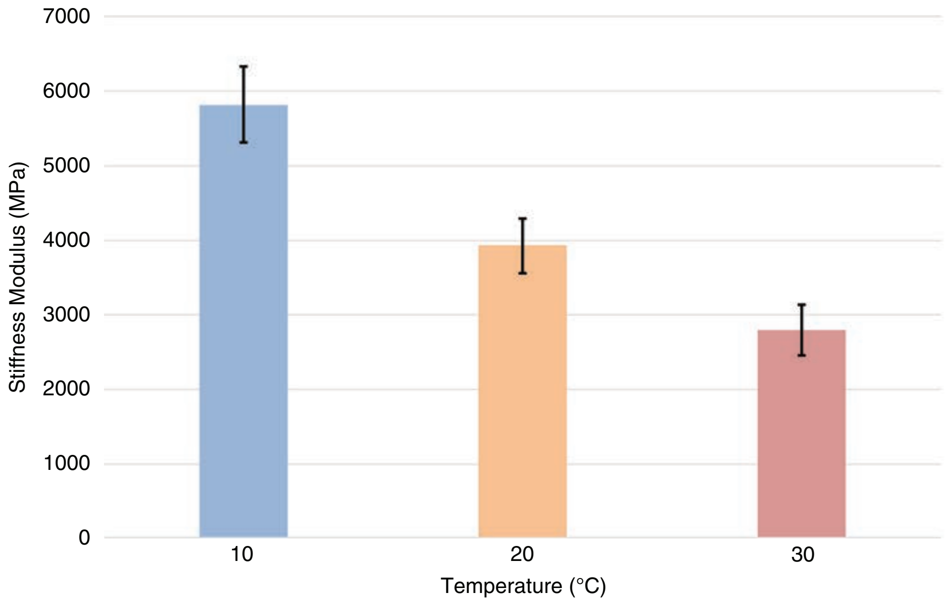

FIGURE 3. CRBM stiffness modulus.

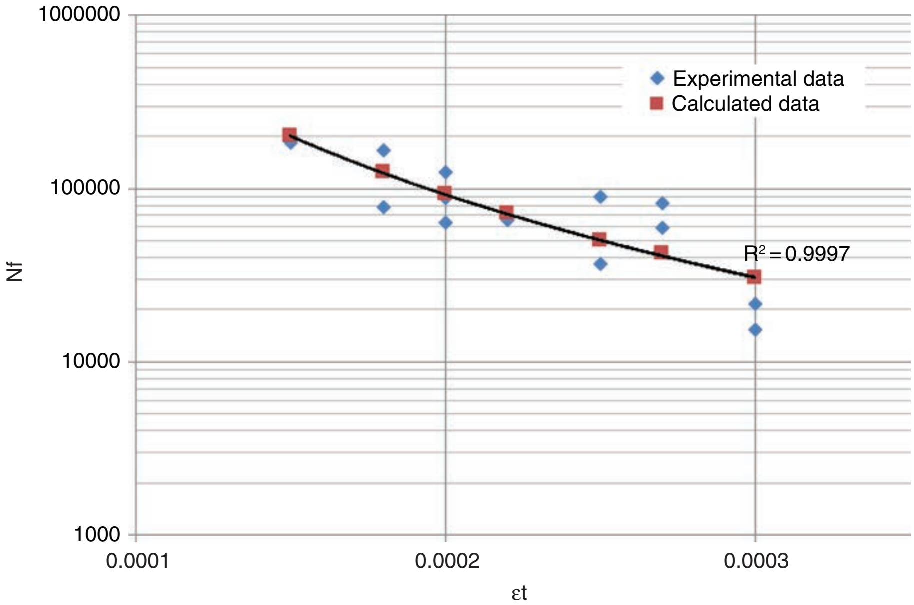

FIGURE 4. CRBM fatigue law calculation.

TABLE 5. Experimental data from strain control fatigue tests for HMA

N_f	ε_t	E_1 (MPa)
149243	0.000125	10900
126500	0.000135	10329
88923	0.000145	11081
42613	0.000155	10231
49383	0.000165	10220
22393	0.000175	10582
30963	0.000185	9828
18683	0.0002	9928
17773	0.00022	9245

TABLE 6. Fatigue coefficients

	f3	f4	f5
Calculated HMA	0,074	4.842	3.109
Shell factors	0.0685	5.671	2.363
The Asphalt institute factors	0.0796	3.291	0.854
Calculated CRMB	$7.61{\cdot}10^{-6}$	2.826	0.110

Previous researchers report various values for these coefficients, with the typical range of values for f_4 being between 3 and 6 (42); however, f_3 varies by several orders of magnitude, and these points relate to values obtained for HMA.

With the new coefficients obtained in Table 6, the fatigue law for CRBM can be expressed as in equation [3].

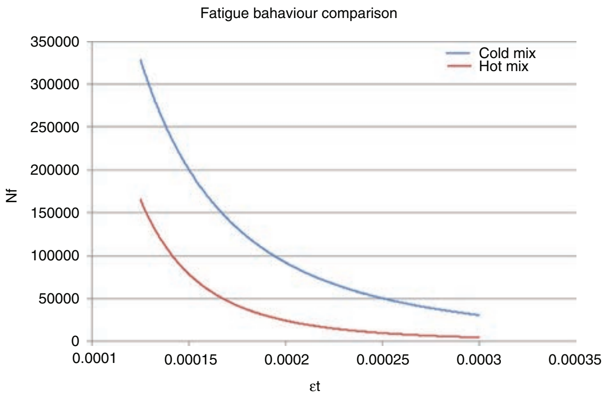

FIGURE 5. Fatigue laws comparison.

$$N_f = 7.61{\cdot}10^{-6}(\varepsilon_t)^{-2.826}(E_1)^{-0.11} \quad [3]$$

The fatigue curves from Maggiore's data and the CRBM mix are compared in Figure 5. This comparison highlights the difference in behaviour between HMA and CRBM. It should be noted that at the same strain, CRBM has a greater life. However, the fact that CRBM stiffness is lower than that of HMA has to be taken into account; thus, when HMA reaches 50% of its initial stiffness it is deemed to have failed but the stiffness is still greater than the initial stiffness of CRBM. This highlights the necessity for further study on failure criteria.

The fundamental material input variables for CRBM assessed with the Kenlayer model have been identified as stiffness and fatigue with permanent deformation being dependent on the subgrade. These variables are summarised in Table 7.

It is also interesting to study the material behaviour in terms of stress evolution during testing to analyse if the modes of failure of the two materials are comparable. In Figure 6 it can be appreciated that the stress evolution is different for HMA and CRBM mixes. HMA has a near-constant stress at the beginning and then it falls relatively rapidly. For CRBM the stress starts reducing from the beginning, but at a moderate slope. This highlights the importance of studying the mode of failure for CRBM, since it does not appear to be comparable with HMA.

Table 7. Kenlayer inputs

Input		Value
Poisson´s Ratio		0.3
Stiffness Modulus	20°C	3500 MPa
	f_3	$7.61{\cdot}10^{-6}$
Fatigue factors	f_4	2.826
	f_5	0.110

4. CONCLUSIONS

In this paper, the fundamental CRBM input variables for undertaking a pavement design analysis with Kenlayer have been identified as stiffness and fatigue life.

Laboratory determination of these inputs showed significant difference in the performance of CRBM versus HMA. In terms of stiffness, calculated values for CRBM are within specifications; therefore this material is identified as potentially appropriate for airfield pavement design. Fatigue coefficients have been established for CRBM; however, the failure criterion used in this research was the conventional target of 50% reduction of stiffness value, as generally used for HMA, and it remains to be investigated whether this failure criterion is also valid for CRBM.

Fatigue is a determining factor for understanding CRBM behaviour under cyclic loading. For this reason, further investigation is needed in order to develop fuller understanding of how CRBM performs, and how pavement design should best be progressed.

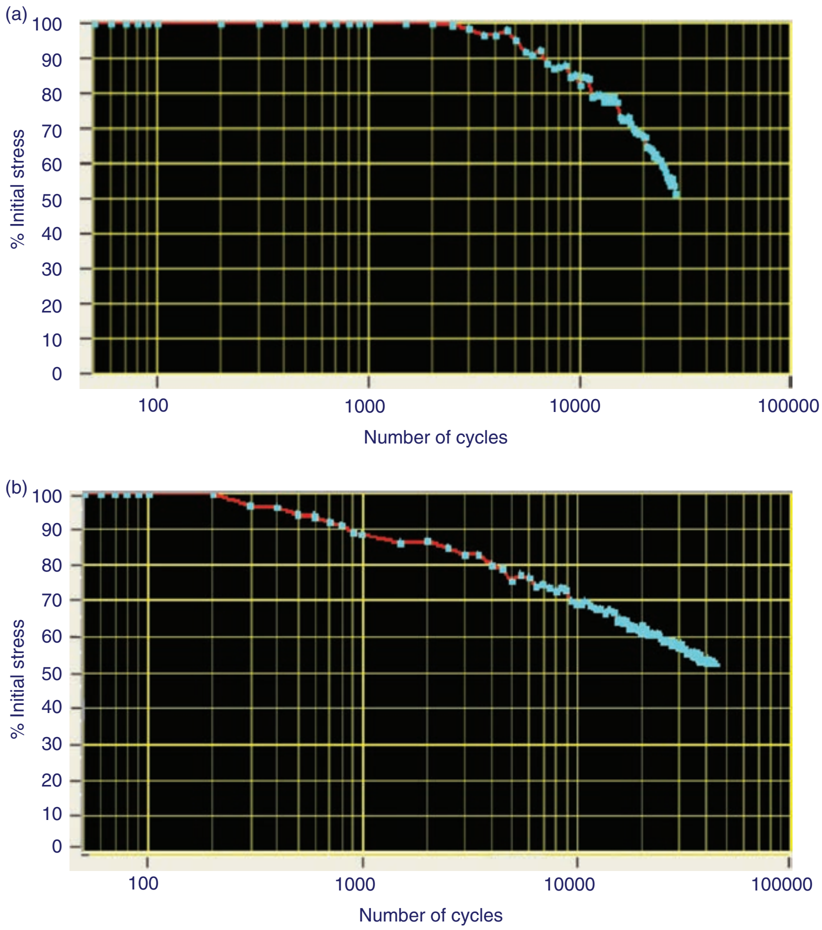

Figure 6. a) HMA fatigue behaviour (38) b) CRBM mix fatigue behaviour.

ACKNOWLEDGMENTS

The research presented in this paper was carried out as part of the Marie Curie Initial Training Network (ITN) action, FP7-PEOPLE-2013-ITN (http://www.superitn.eu). The funding for the research was provided by the European Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement number 607524.

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