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Application of 4PB

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Analysis of the variation in the fatigue life through four-point bending tests

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ABSTRACT: The fatigue resistance of asphalt mixtures is calculated through laboratory tests which require some time depending on the strain level applied to the specimen. For very low strain levels, identical to the one installed in the pavement of this study, one test may last more than one week depending on the testing frequency. The time needed for the development of the fatigue law may last longer. The number of specimens used to calculate the fatigue resistance of an asphalt mixture plays an important role in the precision of pavement design. Thus, this paper presents a study to evaluate the number of tests to assess the fatigue resistance of asphalt mixtures through the four-point bending technique. The results obtained from the analysis of three different asphalt mixtures tested by applying 3 strain levels and 6 specimens for each strain level were used to evaluate the fatigue resistance dispersion to identify the number of tests to define a fatigue law.

1 INTRODUCTION

The design of a road pavement requires the knowledge of the material properties which, for the case of asphalt materials, are characterized by the stiffness modulus and the fatigue resistance. The fatigue resistance relates the number of load cycles to failure with the strain level applied to the mixture.

The most frequent standards used to evaluate the fatigue resistance of asphalt mixtures include the AASHTO T321-03 (AASHTO, 2003) and the European Standard (EN 12697-24, 2004). When evaluating fatigue resistance through four point bending beam tests, both standards define the specimen failure when the stiffness of the material is reduced by 50% of the initial stiffness.

To define the fatigue life law for an asphalt mixture, the European standard specifies the use of 18 specimens to be tested at 3 different strain levels with 6 specimens per strain level. For low strain levels, what in the standard is defined when the fatigue is about 1 million loading cycles, the test lasts more than one day. For the other strain levels, the tests may last longer. The entire testing time to evaluate a fatigue law may last two weeks and, in certain cases, it can be prolonged for about one month.

During the SHRP programme, where an extensive research on fatigue response was undertaken, Tayebali et al. (1994) defined a "24-Hour Procedure for Characterizing the Fatigue Response of an Asphalt-Aggregate Mix" based on a short fatigue test procedure that allows completing all the fatigue tests within 24 hours. This procedure involves testing four specimens, each at a different strain level, in the controlled-strain mode of loading at 10 Hz frequency. In this procedure, fatigue tests are performed over a range of strain levels (so that fatigue life varies between approximately 5000 cycles and 500,000 cycles). The specific testing procedure is as follows:

1. Conduct a test at a fairly high strain level so that the life of the specimen is between 5000 and 10,000 cycles. As a starting point, a strain level between 800 and 1000 micro in./in. should be used. If the fatigue life at this strain level is more than 10,000

cycles, then the strain is increased in the second fatigue test; otherwise, the strain level is decreased. Two tests at these strains are expected to take approximately 2 hours.
2. If the first two tests are conducted at different strain levels, then a crude estimate of the slope of the strain-versus-cycles relationship can be determined. By using this relationship, the strain level corresponding to a fatigue life of approximately 100,000 cycles can be determined. This test is expected to take approximately 4 hours.
3. With the result obtained from step 2, the strain-versus-cycles relationship can be better established and the strain level required for a life of approximately 350,000 to 500,000 cycles is thus estimated. This test is expected to take approximately from 13 to 15 hours and should be undertaken at the end of the work day, so that the specimen will have reached its fatigue life by the next morning.

Also in the SHRP programme, Tayebali et al. (1994) state that for Level 1 analysis, the fatigue resistance is estimated from a calibrated regression model, as function of the flexural strain, initial flexural loss stiffness at the 50th loading cycle and voids filled with bitumen. For Level 2, described in Table 1, analysis, fatigue resistance should be measured in the laboratory by subjecting beam specimens to repeated flexure (20ºC at 10 Hz frequency) with a minimum testing programme, which can usually be completed within 24 hours, involving four specimens subjected to strain levels expected to induce failure at approximately 10,000; 35,000; 100,000 and 350,000 load cycles (or 20 minutes, 1 hour, 3 hours and 10 hours, respectively). If the required accuracy cannot be achieved by testing four specimens, additional specimens must be tested.

Table 1. Distinguishing characteristics of the fatigue analysis system (Tayebali et al., 1994)

Variables		Level 1	Level 2	Level 3
		Abbreviated analysis with surrogate testing	Abbreviated analysis with limited fatigue testing	Comprehensive analysis with full fatigue testing
Testing	Type	Dynamic properties from shear frequency sweeps	Flexural beam fatigue	Flexural beam fatigue
	Temperature	20°C (68°F)	20°C (68°F)	Multiple
In Situ Conditions	Traffic	Equivalent ESALs at 20°C (68°F)	Equivalent ESALs at 20°C (68°F)	Equivalent ESALs at 20°C (68°F)
	Structure	Tensile strain under standard load at 20°C (68°F)	Tensile strain under standard load at 20°C (68°F)	Frequency distribution at bottom of surface layer
	Temperature	Frequency distribution at bottom of surface layer	Frequency distribution at bottom of surface layer	Frequency distribution at bottom of surface layer
Analysis	Mechanistic	Multilayer elastic	Multilayer elastic	Multilayer elastic
	Damage	Preanalysis (TEFs for design ESALs)	Preanalysis (TEFs for design ESALs)	Development of unique TEFs for design ESALs

Due to the nature of asphalt mixtures, heterogeneous mixes composed by aggregates and particles of various dimensions and shapes, it is necessary to take some specimens to represent appropriately the behavior of the material.

Thus, this paper presents a study to evaluate the number of tests necessary to assess the fatigue life of asphalt mixtures through the four-point bending device. The results obtained from three different asphalt mixtures are used to evaluate the fatigue life dispersion to define the number of tests.

2 FATIGUE

The fatigue resistance of an asphalt mixture refers to its ability to withstand repeated bending without fracture. Fatigue, a common form of distress in asphalt pavements, manifests itself in the form of cracking from repeated traffic loading. It is important to have a measurement of the fatigue characteristics of specific mixtures over a range of traffic and environmental conditions, so that fatigue considerations can be incorporated into the process of designing asphalt pavements. The fatigue characteristics of asphalt mixes are usually expressed as relationships between the initial stress or strain and the number of load repetitions to failure, determined by using repeated flexure, direct tension, or diametral tests performed at several stress or strain levels (Tayebali et al., 1994).

Fatigue tests are carried out in two modes, controlled strain and controlled stress. In controlled strain mode, the strain is kept constant by decreasing the stress during the test, whereas in controlled stress the stress is maintained constant which increases the strain during the test. In general, controlled stress testing has been related to relatively thick pavement construction where high stiffness is the fundamental parameter that underpins fatigue life. Controlled strain testing, on the other hand, has been associated with thin conventional flexible pavements where the elastic recovery properties of the material have a fundamental effect on its fatigue life (Artamendi et al., 2004).

The fatigue behaviour of a specific mixture can be characterized by the slope and relative level of the stress or strain versus the number of load repetitions to failure (N) and can be defined by a relationship of the following form proposed by Monismith et al. (1971), in Equation 1:

$$N = a\left(\frac{1}{\varepsilon_t;\sigma_t}\right)^b \tag{1}$$

Where N is the number of repetitions to failure; εt; σt are tensile strain and stress applied; a, b are experimentally determined coefficients.

The stiffness at any number of load repetitions is computed from the tensile stress and strain at that specific value. The fatigue life to failure (N) is dependent on the mode of loading condition. For controlled stress tests, failure is well defined since specimens are cracked through at the end of the test. In controlled strain testing, failure is not readily apparent; accordingly, the specimen is considered to have failed when its initial stiffness is reduced by 50% (Tayebali et al., 1994).

One of the most common methods used to evaluate fatigue life in laboratory is the flexural bending beam test. Flexural fatigue four bending tests were conducted according to the AASHTO TP 8-94 (Standard Test Method for Determining the Fatigue Life of Compacted Hot Mix Asphalt (HMA) Subjected to Repeated Flexural Bending). They are intended to simulate pavement distress due to traffic loads during its expected design life. They also determine fatigue life, dynamic modulus and the phase angle of the beams.

3 ASPHALT MIXTURES

The development of this study was based on the fatigue life results from 3 different asphalt mixtures tested in laboratory using a four point bending beam device. The mixtures are used in Portugal in base or binder layers with 25 mm as maximum aggregate size. The binder content for each mixture is indicated in Table 1. Both mixtures were produced with a 35/50 pen bitumen.

Table 1. Mixtures description

Mixture	Binder content (%)
1	4.4
2	4.3
3	4.5

The fatigue testing results of the mixtures used in this study are presented in Table 2, expressed in terms of strain level and fatigue life. Both mixtures were tested using 18 specimens

(3 strain levels and 6 specimens in each strain level). The greater strain level was chosen to have a fatigue life around $1x10^4$ cycles. For mixtures 1 and 2 it corresponds to a strain level of about 150E-6 to 200E-6, while for mixture 3 it corresponds to a strain level of about 300E-6. The lower strain level was chosen to have a fatigue life around $1x10^6$ cycles and it corresponds to a strain level of about 500E-6 to 700E-6, depending on the mixture characteristics. The mid strain level was defined to have a fatigue life of about $1x10^5$ cycles and it corresponds to a strain level of about 300E-6 to 500E-6.

Table 2. Fatigue test results

Mixture 1		Mixture 2		Mixture 3	
Strain	Fatigue life	Strain	Fatigue life	Strain	Fatigue life
183	6.08E+05	160	7.28E+05	307	2.21E+06
183	7.28E+05	161	1.53E+06	310	1.45E+06
185	4.08E+05	161	8.49E+05	310	1.03E+06
186	3.97E+05	161	1.01E+06	312	8.37E+05
188	4.27E+05	161	9.21E+05	312	9.79E+05
198	2.27E+05	164	1.18E+06	318	1.30E+06
307	1.32E+05	311	1.14E+05	522	7.24E+04
307	1.17E+05	313	1.26E+05	523	1.11E+05
308	1.05E+05	313	9.48E+04	526	1.15E+05
310	5.34E+04	316	9.87E+04	528	5.73E+04
315	1.63E+05	320	8.58E+04	529	7.69E+04
321	9.06E+04	321	9.53E+04	569	9.36E+04
488	1.25E+04	613	7.74E+03	625	4.38E+04
500	1.43E+04	618	9.18E+03	680	3.29E+04
503	1.50E+04	623	9.17E+03	687	3.97E+04
507	1.63E+04	630	1.01E+04	721	1.55E+04
509	1.27E+04	631	9.59E+03	738	2.09E+04
516	8.67E+03	644	1.20E+04	743	2.75E+04

The fatigue results for each asphalt mixture are represented in Figure 1, in terms of fatigue life as function of the strain level where the results dispersion can be observed. Mixture 1 presents the greater dispersion mainly in mid and lower strain levels. Mixture 2 does not present any important dispersion, while mixture 3 presents a small dispersion in both strain levels tested.

In terms of the fatigue life, the R2 coefficient, which measures the dispersion of the results, is 0.949 for mixture 1, 0.990 for mixture 2 and 0.968 for mixture 3. There is an evident reduced dispersion of the results of mixture 2 and a significant dispersion of the results of mixture 1.

4 COMBINATORY ANALYSIS

To define the number of strain levels and test specimens for accurate fatigue life characterization, a combinatory analysis was made, in which the fatigue life was calculated for each mix considering all possible combinations of number of strain levels and number of tests. This combinatory analysis is the full factorial of fatigue characterization using all results for a mix, i.e. considering 2 and 3 strain levels and 1 to 6 specimens per strain level.

Table 3 shows the number of possible combinations using all the 18 test results from the fatigue life test, where it can be observed that it is possible to perform 8000 combinations of results for the case of 3 strain levels with 4 replications for each level. This means that, for each mixture, more than 15000 combinations of the fatigue results can be performed with the fatigue test results of 18 specimens (3 strain levels and 6 specimens per strain level). Each one of the possible combinations with the fatigue results from 18 specimens leads to a different fatigue law and thus a fatigue life for a specific strain level.

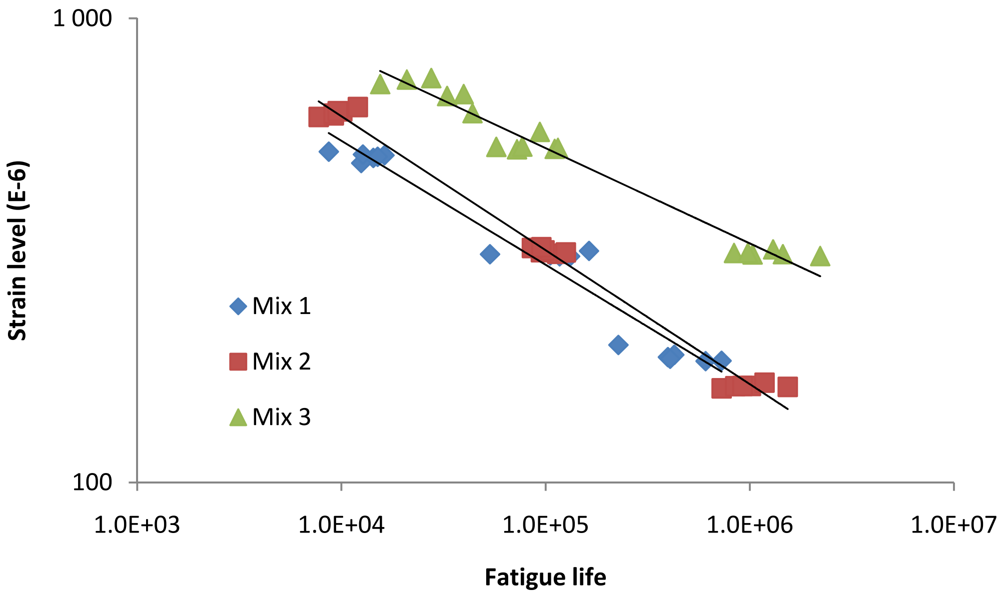

Figure 1. Fatigue line of tested mixtures

Table 3. Number of combinations using all fatigue results

	Number of combinations	
Tests for each strain level	2 strain levels	3 strain levels
1	1	1
2	36	216
3	225	3375
4	400	8000
5	225	3375
6	36	216

To define the number of strain levels and the number of replications needed to perform the four point fatigue test, fatigue life was calculated for 100E-6 strain level for each combination indicated in Table 3. The consideration of 2 strain level in the combinatory analysis was made in 3 different steps in which the following combinations of strain levels were considered: i) Firstly the low and mid strain levels; ii) Next, the low and high strain levels; iii) Finally, the mid and high strain levels. For those calculations a software, which calculates the fatigue life for each combination, producing a table (Table 4) with the number of concurrencies for each interval of fatigue life, was developed. The letters a, b, and c in Table 4 represent, respectively, the consideration of levels low and mid; low and high; mid and high. The software also calculates the maximum and minimum observed fatigue life as well as the average value and standard deviation.

The plot of the maximum and minimum value of the fatigue life for each mixture, as function of the number of specimens used in each combination, is represented in Figures 2, 3 and 4, respectively for mixture 1, 2 and 3. Identical representation is presented in Figures 5, 6 and 7 for the values of fatigue life corresponding to a probability of 68% (average - standard deviation; average + standard deviation). Using the maximum and minimum values of the fatigue life for all combinations, Figures 8, 9 and 10 present the maximum error that can be obtained in the fatigue life as function of the number of specimens used in each combination.

Table 4. Combination analysis for mixture 1

Fat. life	Comb 1	Comb 1a	Comb 1b	Comb 1c	Comb 2	Comb 2a	Comb 2b	Comb 2c	Comb 3	Comb 3a	Comb 3b	Comb 3c	Comb 4	Comb 4a	Comb 4b	Comb 4c	Comb 5	Comb 5a	Comb 5b	Comb 5c
2E+05	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3E+05	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4E+05	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5E+05	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6E+05	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7E+05	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8E+05	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9E+05	0	1	0	1	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1E+06	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2E+06	8	8	4	3	0	55	0	0	0	85	0	0	0	31	0	0	0	1	0	0
3E+06	30	9	4	1	282	70	42	4	111	167	37	0	0	125	4	0	0	27	0	0
4E+06	52	2	11	1	840	46	64	14	1984	102	148	0	602	60	98	0	16	8	13	0
5E+06	41	5	5	0	928	22	60	14	3176	34	143	7	1792	9	99	0	165	0	23	0
6E+06	24	2	4	0	738	17	37	12	2000	12	65	18	929	0	24	0	35	0	0	0
7E+06	20	3	2	0	381	3	15	8	672	0	7	25	52	0	0	4	0	0	0	0
8E+06	14	0	4	2	148	3	7	8	57	0	0	27	0	0	0	11	0	0	0	0
9E+06	14	0	1	0	50	1	0	6	0	0	0	26	0	0	0	13	0	0	0	1
1E+07	6	1	1	3	8	0	0	6	0	0	0	25	0	0	0	18	0	0	0	1
2E+07	7	1	0	9	0	0	0	67	0	0	0	143	0	0	0	123	0	0	0	29
3E+07	0	0	0	7	0	0	0	42	0	0	0	86	0	0	0	50	0	0	0	5
4E+07	0	0	0	2	0	0	0	21	0	0	0	35	0	0	0	6	0	0	0	0
5E+07	0	0	0	2	0	0	0	14	0	0	0	8	0	0	0	0	0	0	0	0
6E+07	0	0	0	1	0	0	0	6	0	0	0	0	0	0	0	0	0	0	0	0
7E+07	0	0	0	1	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0
8E+07	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
9E+07	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Min	1E+06	4E+05	2E+06	8E+05	2E+06	8E+05	2E+06	2E+06	3E+06	1E+06	3E+06	4E+06	3E+06	1E+06	3E+06	6E+06	4E+06	2E+06	3E+06	9E+06
Max	1E+07	1E+07	1E+07	2E+08	1E+07	8E+06	8E+06	8E+07	8E+06	6E+06	6E+06	4E+07	6E+06	4E+06	5E+06	3E+07	6E+06	4E+06	5E+06	3E+07
Ave-rage	5E+06	3E+06	4E+06	3E+07	5E+06	3E+06	4E+06	2E+07	5E+06	3E+06	4E+06	2E+07	5E+06	3E+06	4E+06	2E+07	5E+06	3E+06	4E+06	1E+07
Stand deviat	2E+06	3E+06	2E+06	3E+07	1E+06	1E+06	1E+06	1E+07	9E+05	9E+05	9E+05	9E+06	6E+05	6E+05	6E+05	7E+06	4E+05	4E+05	4E+05	4E+06

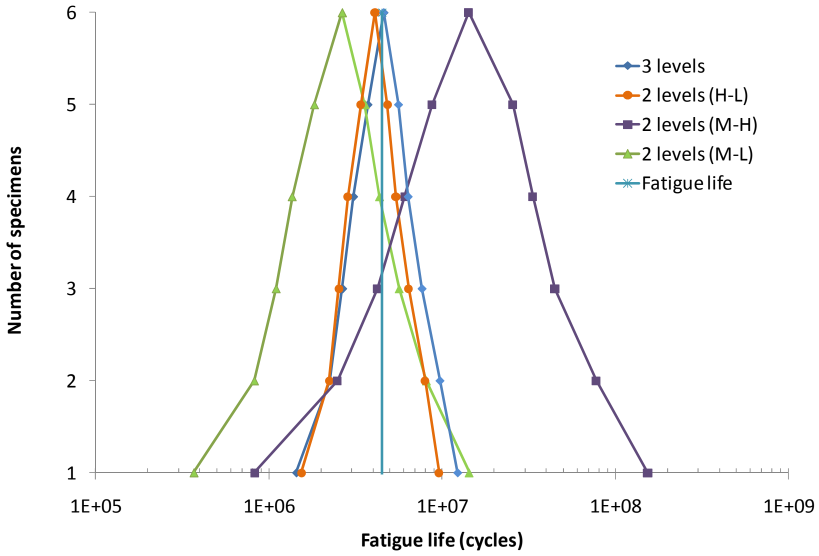

Figure 2. Maximum and minimum value of fatigue life for combinations of fatigue life of mixture 1

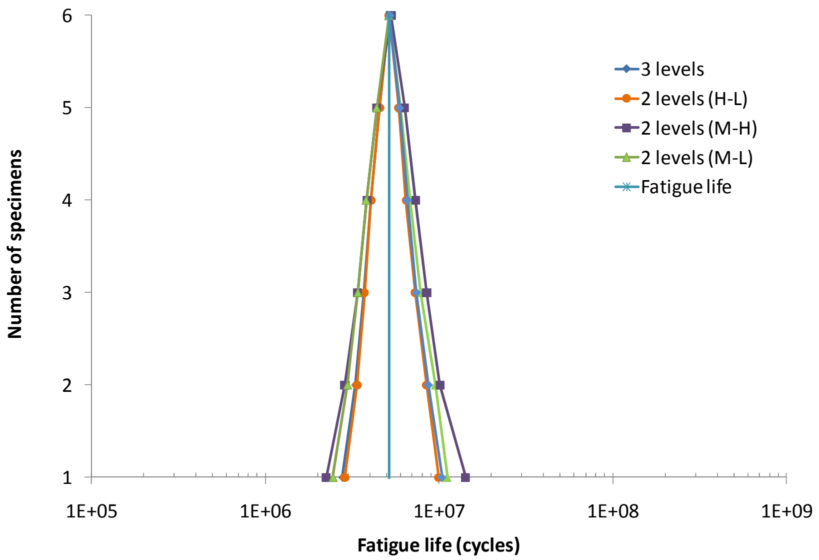

Figure 3. Maximum and minimum value of fatigue life for combinations of fatigue life of mixture 2

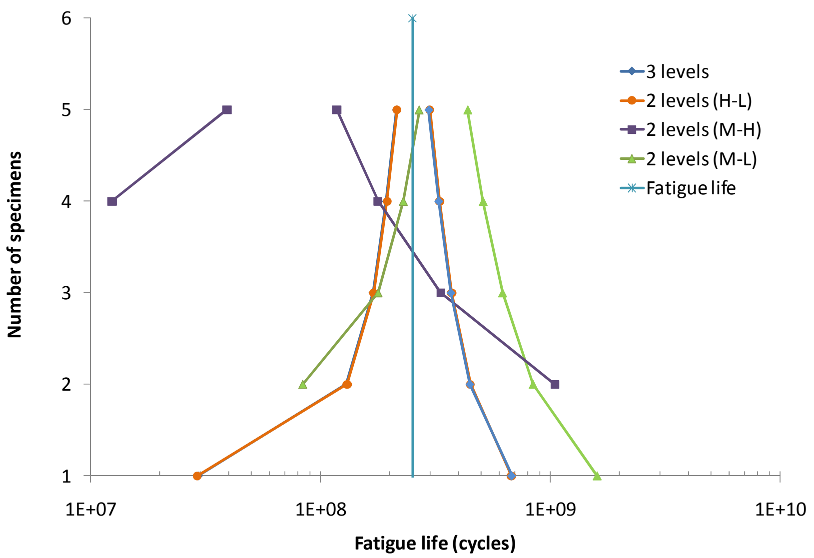

Figure 4. Maximum and minimum value of fatigue life for combinations of fatigue life of mixture 3

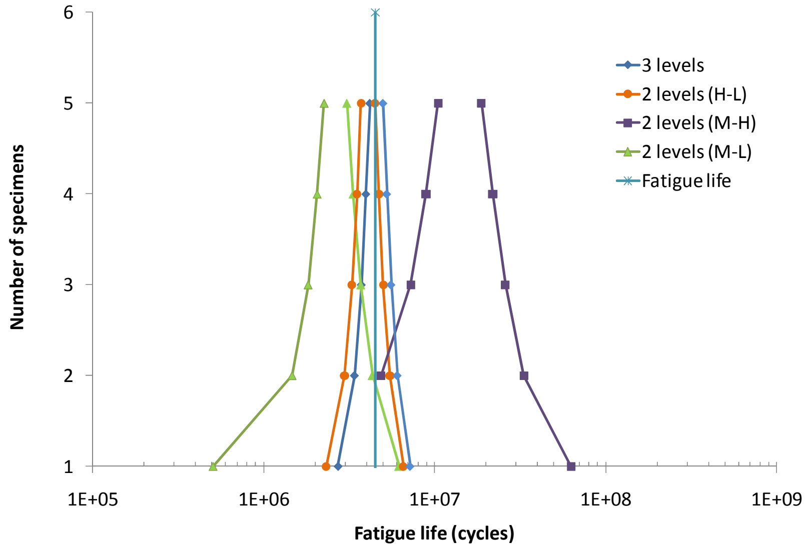

Figure 5. Fatigue life for a probability of 68% for mixture 1

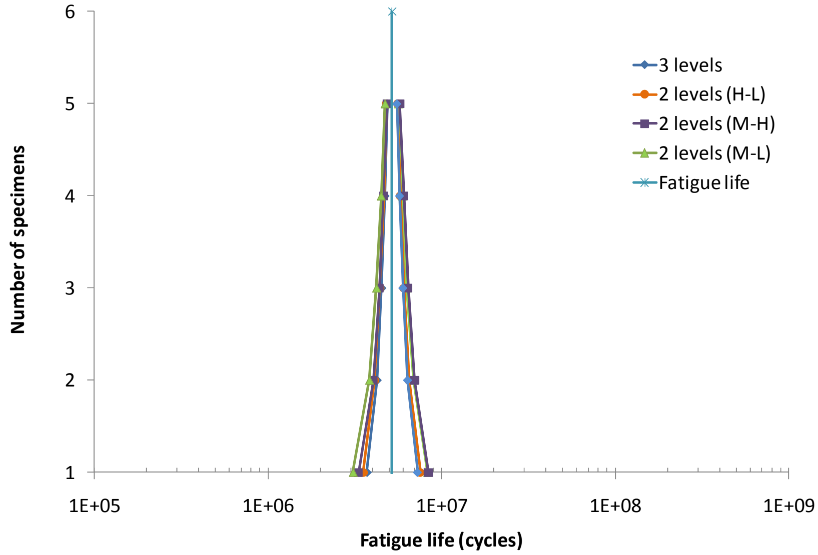

Figure 6. Fatigue life for a probability of 68% for mixture 2

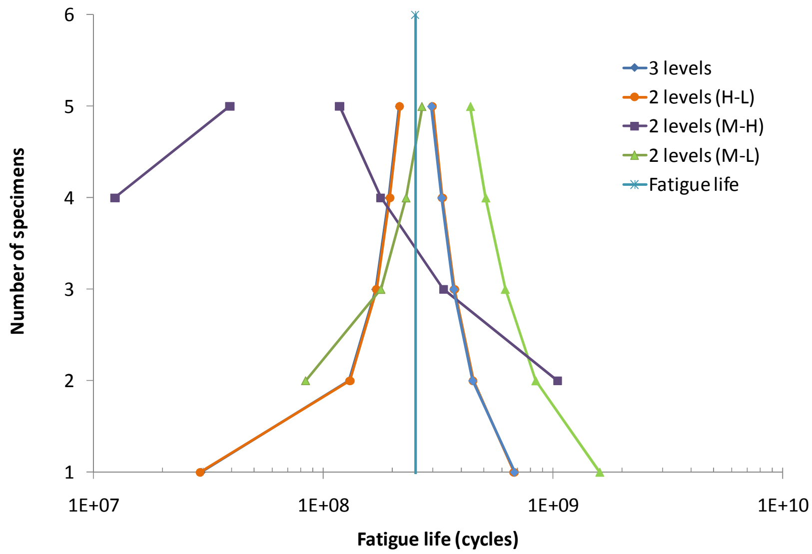

Figure 7. Fatigue life for a probability of 68% for mixture 3

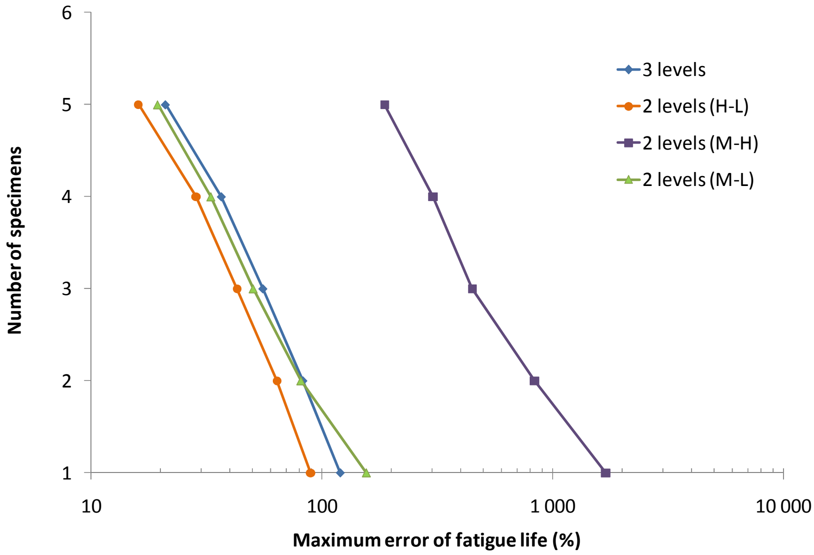

Figure 8. Maximum error in the fatigue life for the combination of the results from mixture 1

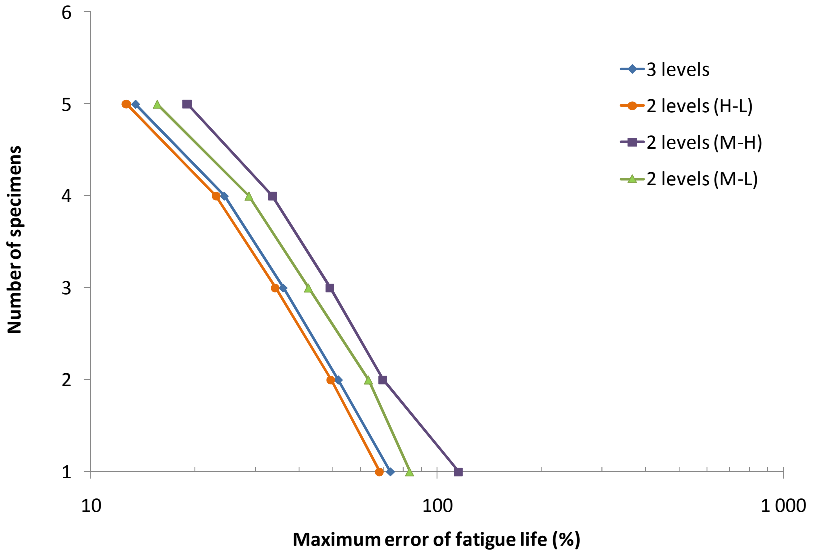

Figure 9. Maximum error in the fatigue life for the combination of the results from mixture 2

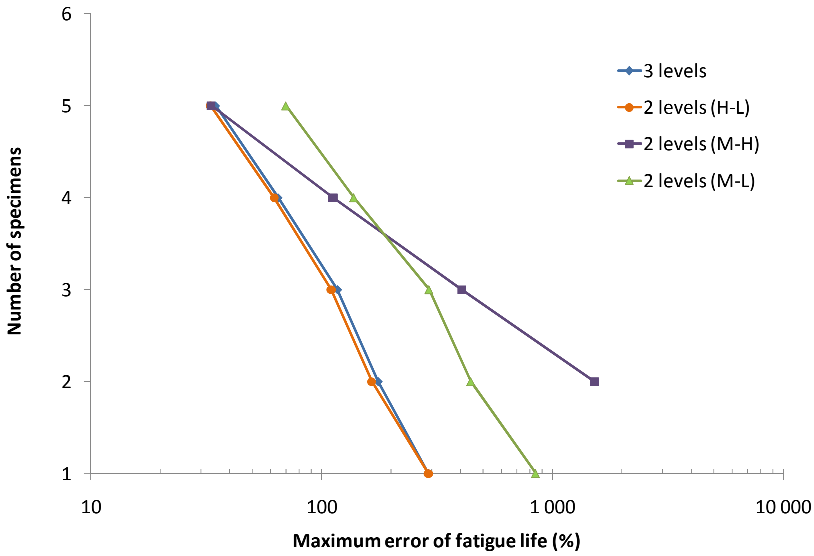

Figure 10. Maximum error in the fatigue life for the combination of the results from mixture 3

The analysis of the previous figures allows concluding that, when using 2 strain levels to predict the fatigue life, the use of the middle level reduces considerably the precision of the fatigue life, i.e., the cases "2 levels (M-H) and 2 levels (M-L)" should not be considered as levels to evaluate the fatigue life. The other two remaining studied cases (3 levels and 2 levels (H-L)) present the same precision in the evaluation of the fatigue life.

Thus, the fatigue life should be evaluated by using only two levels, a high and a low strain level, what was expectable as the fatigue law (a line in a log-log scale) can be defined by considering only two points.

For the definition of the number of specimens for each level there is no rule that may be applied. However, the use of 3 specimens seems to be sufficient to get a interesting precision in the fatigue life evaluation.

Bearing in mind that the fatigue tests must be performed using 2 strain levels (high and low) and 3 specimens per strain level, a combinatory analysis was performed considering a different number of specimens for each of the strain levels.

This second analysis was made considering the following combinations of 2 levels:

- 3 specimens in the high level and 2 specimens in the low level, referred as: 3H2L;
- 4 specimens in the high level and 2 specimens in the low level, referred as: 4H2L;
- 4 specimens in the high level and 3 specimens in the low level, referred as: 4H3L;
- 5 specimens in the high level and 3 specimens in the low level, referred as: 5H3L.

The study of these combinations intends to evaluate whether by using 2 strain levels and 2 specimens in the low level but more specimens in the high levels, an identical precision as that presented in the case of 3 specimens in both levels can be obtained. The other two cases have the same objective for the case of 3 specimens in the low level.

The use of these combinations does not increase the precision in the estimation of fatigue as it can be observed in Table 6, which depicts the results of the combinatory analysis by level and a different number of specimens per level, when compared to Table 5 which presents the results for 2 levels (high and low) for 2 and 3 specimens.

Table 5. Analysis of the combinatory analysis for 2 levels (high and low) for 2 and 3 specimens

Mixture	Combinations	Mininum	Maximum	Amplitude	Error (%)	Probability of 68%		Amplitude	Error (%)
1	2 specimens	2.2E+06	8.0E+06	5.7E+06	64	3.0E+06	5.5E+06	2.5E+06	28
	3 specimens	2.5E+06	6.4E+06	3.9E+06	43	3.3E+06	5.0E+06	1.7E+06	19
2	2 specimens	3.4E+06	8.5E+06	5.1E+06	49	4.1E+06	6.5E+06	2.4E+06	23
	3 specimens	3.7E+06	7.3E+06	3.5E+06	34	4.4E+06	6.1E+06	1.6E+06	16
3	2 specimens	8.6E+07	9.1E+08	8.3E+08	165	1.3E+08	4.5E+08	3.2E+08	63
	3 specimens	1.0E+08	6.5E+08	5.5E+08	110	1.7E+08	3.7E+08	2.0E+08	40

Table 6. Analysis of the combinatory analysis for levels with different number of specimens

Mixture	Combinations	Mininum	Maximum	Amplitude	Error (%)	Probability of 68%		Amplitude	Error (%)
1	3H2L	2.3E+06	7.6E+06	5.3E+06	59	3.0E+06	5.5E+06	2.5E+06	27
	4H2L	2.3E+06	7.3E+06	5.0E+06	55	3.0E+06	5.4E+06	2.4E+06	27
	4H3L	2.6E+06	6.2E+06	3.6E+06	40	3.3E+06	5.0E+06	1.7E+06	19
	5H3L	2.7E+06	6.0E+06	3.3E+06	37	3.3E+06	5.0E+06	1.7E+06	19
2	3H2L	3.4E+06	8.4E+06	4.9E+06	47	4.1E+06	6.5E+06	2.4E+06	23
	4H2L	3.5E+06	8.2E+06	4.7E+06	45	4.1E+06	6.5E+06	2.3E+06	22
	4H3L	3.8E+06	7.2E+06	3.4E+06	32	4.4E+06	6.1E+06	1.6E+06	16
	5H3L	3.8E+06	7.1E+06	3.2E+06	31	4.4E+06	6.0E+06	1.6E+06	16
3	3H2L	9.3E+07	7.8E+08	6.8E+08	136	1.4E+08	4.3E+08	2.9E+08	58
	4H2L	9.7E+07	7.1E+08	6.1E+08	121	1.4E+08	4.2E+08	2.8E+08	56
	4H3L	1.1E+08	6.0E+08	4.9E+08	98	1.7E+08	3.6E+08	1.9E+08	38
	5H3L	1.1E+08	5.4E+08	4.2E+08	84	1.8E+08	3.6E+08	1.8E+08	36

The proposal presented by Tayebali et al. (1994), which consisted of 2 tests at a high level, 1 test at a mid level and 1 test at a low level and referred in this work as 2H1M1L, was analyzed and the results are presented in Table 7. The comparison of this option, with only 4 specimens, to the combinations presented in Table 5 allows concluding that the use of these 3 levels produces less precision in the prediction of the fatigue life if compared to the use of 2 levels (H-L) with 2 and 3 specimens per level.

Table 7. Analysis of the combinatory analysis for the 2H1M1L

Mixture	Mininum	Maximum	Amplitude	Error (%)	Probability of 68%		Amplitude	Error (%)
1	1.5E+06	1.3E+07	1.2E+07	128	3.0E+06	7.5E+06	4.5E+06	50
2	2.9E+06	1.0E+07	7.0E+06	67	3.8E+06	7.1E+06	3.3E+06	32
3	5.9E+07	1.4E+09	1.4E+09	273	5.2E+07	5.9E+08	5.3E+08	106

5 CONCLUSIONS

This paper presents a study the objective of which was to evaluate the number of tests necessary to assess the fatigue resistance of asphalt mixtures through the four-point bending technique. The results obtained from the analysis of three different asphalt mixtures tested by applying 3 strain levels and 6 specimens for each strain level were used to calculate the fatigue resistance dispersion in order to determine the appropriate number of tests to define a fatigue law.

A combinatory analysis was made through the use of all the results for a mix, i.e. considering 2 and 3 strain levels and 1 to 6 specimens per strain level.

The study of the combinatory analysis allowed to conclude that the fatigue life should be evaluated by using only two levels, a high and a low strain level. In relation to the number of specimens per strain level, the use of 3 specimens seems to be sufficient to obtain an interesting precision in the fatigue life evaluation.

6 REFERENCES

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