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THE PREDICTION OF FATIGUE LIFE OF ASPHALT MIXTURES USING FOUR-POINT BENDING TESTS

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ABSTRACT

Fatigue resistance is used in the analysis and design of pavements to predict their life cycle. The results of fatigue tests are expressed in terms of the number of cycles for the tensile strain level applied. Two constants (k_1 and k_2) take part in this relationship. To know these two constants, at least two fatigue tests are needed, performed at different strain levels to obtain those constants. However, based on laboratory results analysis, k_1 and k_2 can be correlated and, in this case, the relationship between the fatigue life and the strain level has only one constant, which can be evaluated using the results obtained by a fatigue test. This paper presents the evaluation of the k_1 and k_2 relationship for Portuguese mixtures based on the results obtained from more than 50 different asphalt mixtures and the prediction of only one of those constants with fatigue test results. The paper also presents an analysis of the fatigue life using fatigue laws with only one constant.

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 used 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 a 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 level, 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 prolong about one month.

The results of fatigue tests are expressed in terms of the number of cycles for the tensile strain level applied. Two constants, k_1 and k_2 (Equation 1), obtained from a statistical analysis, are involved in this relationship. In Equation 1, N represents the fatigue life and ε represents the tensile strain. These constants correspond to the interception and slope of the fatigue line in the log-log scale. Two fatigue tests, which are performed at different strain levels, are needed to obtain those constants. For each strain level a certain number of specimens were tested to ensure a correct characterization of fatigue.

$$N = k_1 \times \left(\frac{1}{\varepsilon} \right)^{k_2} \tag{1}$$

There are some studies where the coefficients of the fatigue law (k_1 and k_2) are correlated and, in this case, the relationship between the fatigue life and the strain level has only one constant which can be evaluated using the results of the fatigue test for one strain level.

This relationship, and consequently, a fatigue life law with only one parameter, if existing, can be used for preliminary studies and obtained with very short fatigue tests which last no more than a couple of hours.

However, this approach does not replace the normal procedure to characterize the fatigue life of an asphalt mixture, where at least two strain levels are tested.

This paper presents the evaluation of the k_1 and k_2 relationship for Portuguese mixtures based on the results of 53 different asphalt mixes composed by four different types of aggregate gradations. The 53 mixtures include 3 wearing course mixes, 9 mixes used in binder course layers, 16 mixtures used in base layers, 6 mixtures with high stiffness binder (10/20 penetration bitumen) and 19 asphalt rubber mixtures. The mixtures for binders and base layers use conventional bitumen, whereas the mixtures for wearing courses use both conventional and modified binders. The binder of asphalt rubber mixtures include some with a low content of crumb rubber and others with a high content of crumb rubber and various sources of crumb rubber and base bitumen. The binder content is identical in each group of mixtures.

FATIGUE APPROACHES

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 2:

$$N = k_1 \times \left(\frac{1}{\varepsilon_t ; \sigma_t} \right)^{k_2} \tag{2}$$

Where N is the number of repetitions to failure; ε_t; σ_t are tensile strain and stress applied; k_1 and k_2 are experimentally determined coefficients.

The coefficients k_1 and k_2 correspond to the intercept and slope of the fatigue line in the log-log scale. At least, two fatigue tests are needed to obtain them, mainly performed at different strain levels. For each strain level a certain number of specimens were tested to ensure a correct characterization of fatigue.

However, Monismith and Salam (1972) state that Pell suggested that there exists a relationship between k_1 and k_2 in the form:

$$k_2 = f\left(\log\left(k_1\right)\right) \tag{3}$$

Lytton et al. (1993) also stated that, based on fracture mechanics, parameter k_1 is a function of k_2, A (a parameter that defines the cracking propagation rate), and E (stiffness modulus).

More recently, Zhou et al. (2007) stated that k_1 and k_2 are correlated by Equation 4, where E represents the stiffness modulus of the asphalt mixture.

$$k_1 = 10^{\,6.97 - 3.20 \times k_2 - 0.837 \times \log(E)} \tag{4}$$

Mello (2008) found out, for 37 asphalt mixtures including asphalt rubber mixtures, that there exists a relationship between k_1-k_2 (Figure 1) and that it produces an excellent correlation between both parameters, allowing to use only one parameter in the fatigue characterization of asphalt mixtures.

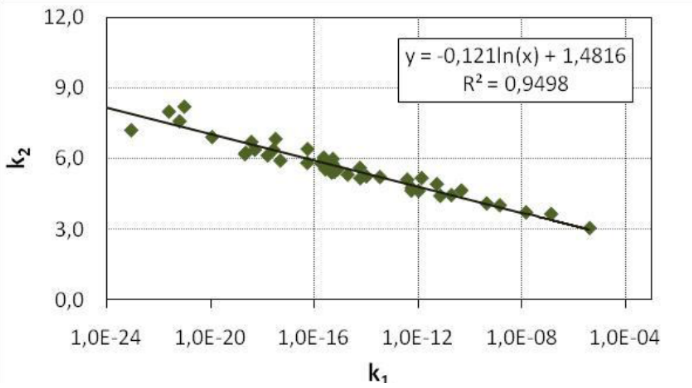

Figure 1: Relationship between k_1 e k_2 obtained by Mello (2008).

Identical conclusion was obtained by Pais et al. (2009) for 36 Portuguese asphalt mixtures from wearing course layers, binder layers, base layers and high stiffness asphalt mixtures, as expressed by Figure 2. The correlation coefficient (R^2) of 0.98 is an indication that only one parameter can be used to describe the fatigue life laws of asphalt mixtures.

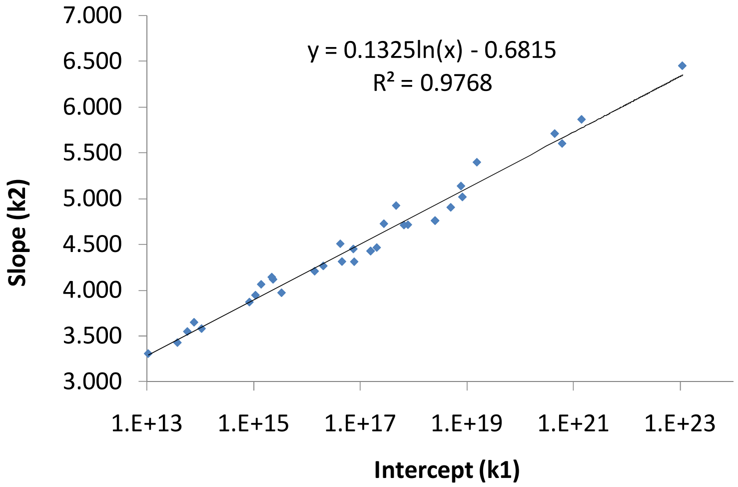

Figure 2: Relationship between k_1 e k_2 obtained by Pais et al (2009).

Way et al (2009) found an identical conclusion for 102 asphalt mixtures from Arizona (USA) where most of them are asphalt rubber hot mixtures produced with asphalt rubber binded with high crumb rubber content, as expressed by Figure 3. The correlation coefficient (R^2) of 0.96 is an indication that only one parameter can be used to describe the fatigue life laws of asphalt mixtures.

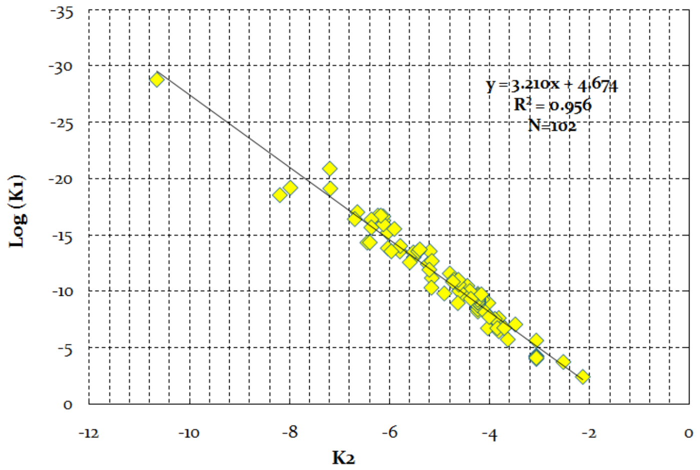

Figure 3: Relationship between k_1 e k_2 obtained by Way et al (2009).

ASPHALT MIXTURES

This study was carried out by analyzing 53 different asphalt mixtures tested through four-point bending tests at a temperature of 20ºC and a frequency of 10 Hz. The 53 mixtures included 3 wearing course mixtures, 9 mixtures used in binder course layers, 16 mixtures used in base layers, 6 mixtures with high stiffness binder (10/20 penetration bitumen) and 19 asphalt rubber mixtures with high and low contents of crumb rubber. The mixtures for binder and base layers use conventional bitumen, whereas the mixtures for wearing courses use both conventional and modified binders. The binder content is identical in each group of mixtures.

Each mixture was tested using the AASHTO T321-03 standard, which establishes testing at least 6 specimens in two or 4 tensile strain levels. Some mixtures were tested using 18 specimens at 3 strain levels, as recommended by the European standard - EN 12697-26.

The results obtained for the 53 mixtures were expressed in the terms represented in Equation 5, which relates fatigue life to the tensile strain applied:

$$\mathrm{N} = k_1 \times \left(\frac{1}{\varepsilon_t} \right)^{k_2} \tag{5}$$

where N is the number of repetitions to failure; εt; σt are tensile strain applied and stress applied; k_1 and k_2 are experimentally determined coefficients.

The k_1 and k_2 coefficients, as well as the correlation coefficient (R^2) and the N_{100}, the number of cycles at a strain level of 100E-6 and the ε_6, the strain level for a fatigue life of 1E6, are presented in Table 1.

The analysis of the results from Table 1 allows concluding that the correlation coefficients for all mixtures are extremely high, proving the best fit obtained for the fatigue models. It can be also observed that the mixtures for a specific layer present fatigue behaviors expressed by the different values of the N_{100} and ε_6. The only parameter that seems to have a relatively constancy is the slope of the fatigue model (k_2).

Table 1: Fatigue test results

Layer	Mixture	Intercept (k1)	Slope (k2)	Correlation coefficient (R^2)	N_{100}	ε_6
Wearing course	Mix 01	1.591E+17	4.430	0.984	2.2E+08	338
	Mix 02	2.576E+18	4.762	0.983	7.7E+08	404
	Mix 03	4.784E+17	4.927	0.994	6.7E+07	235
Binder course	Mix 04	8.371E+18	5.021	0.990	7.6E+08	375
	Mix 05	1.591E+17	4.430	0.984	2.2E+08	338
	Mix 06	2.076E+17	4.468	1.000	2.4E+08	341
	Mix 07	5.050E+18	4.907	0.972	7.8E+08	388
	Mix 08	7.837E+16	4.314	0.997	1.8E+08	335
	Mix 09	2.576E+18	4.762	0.983	7.7E+08	404
	Mix 10	6.213E+20	5.604	0.983	3.9E+09	437
	Mix 11	1.563E+19	5.399	0.995	2.5E+08	278
	Mix 12	1.410E+15	4.067	0.976	1.0E+07	178
Base course	Mix 13	7.977E+17	4.717	0.980	2.9E+08	333
	Mix 14	4.628E+16	4.316	0.960	1.1E+08	296
	Mix 15	1.419E+16	4.210	0.996	5.4E+07	258
	Mix 16	2.823E+17	4.728	0.979	9.9E+07	264
	Mix 17	1.074E+13	3.311	0.968	2.6E+06	133
	Mix 18	2.353E+15	4.121	0.977	1.3E+07	188
	Mix 19	4.297E+16	4.510	0.993	4.1E+07	228
	Mix 20	7.865E+18	5.140	0.995	4.1E+08	323
	Mix 21	2.060E+16	4.268	0.959	6.0E+07	261
	Mix 22	1.103E+15	3.948	0.954	1.4E+07	195
	Mix 23	5.833E+13	3.552	0.949	4.6E+06	154
	Mix 24	3.785E+13	3.431	0.990	5.2E+06	162
	Mix 25	1.078E+14	3.584	0.986	7.3E+06	174

	Mix 26	6.720E+17	4.714	0.968	2.5E+08	323
	Mix 27	2.228E+15	4.146	0.984	1.1E+07	180
	Mix 28	7.772E+13	3.652	0.992	3.9E+06	145
Base with high stiffness modulus	Mix 29	1.113E+23	6.452	0.995	1.4E+10	439
	Mix 30	8.474E+14	3.873	0.997	1.5E+07	202
	Mix 31	3.402E+15	3.975	0.995	3.8E+07	250
	Mix 32	4.511E+20	5.711	0.968	1.7E+09	368
	Mix 33	1.437E+21	5.866	0.993	2.7E+09	384
	Mix 34	7.538E+16	4.452	0.991	9.4E+07	277
Asphalt rubber mixtures	Mix 35	5.361E+15	4.250	0.971	1.7E+07	195
	Mix 36	1.857E+16	4.322	0.973	4.2E+07	237
	Mix 37	1.588E+14	3.592	0.951	1.0E+07	192
	Mix 38	5.305E+11	2.675	0.987	2.4E+06	138
	Mix 39	4.966E+13	3.315	0.977	1.2E+07	210
	Mix 40	4.470E+10	2.275	0.985	1.3E+06	111
	Mix 41	8.704E+13	3.582	0.946	6.0E+06	165
	Mix 42	3.614E+12	2.815	0.979	8.5E+06	214
	Mix 43	6.406E+14	3.567	0.991	4.7E+07	294
	Mix 44	9.747E+10	2.433	0.904	1.3E+06	112
	Mix 45	1.156E+17	4.602	0.988	7.2E+07	253
	Mix 46	3.147E+15	4.086	0.973	2.1E+07	211
	Mix 47	9.878E+14	3.783	0.953	2.7E+07	239
	Mix 48	1.882E+17	4.537	0.974	1.6E+08	305
	Mix 49	1.392E+17	4.564	0.990	1.0E+08	276
	Mix 50	1.330E+15	3.933	0.931	1.8E+07	209
	Mix 51	4.755E+17	4.644	0.984	2.5E+08	327
	Mix 52	2.355E+14	3.652	0.901	1.2E+07	196
	Mix 53	2.279E+16	4.285	0.982	6.1E+07	261

RELATIONSHIP BETWEEN K1 AND K2

Bearing in mind the form of the relationship between k1 and k2 proposed by Pell, Figures 4 presents the relationship between k1 and k2 for the studied mixtures. The analysis of this figure allows verifying an excellent relationship between k_1 and k_2 for all mixtures. However, discrepancies between some points and the trend line are evident, but this can constitute a first approach to define a relationship between k_1 and k_2.

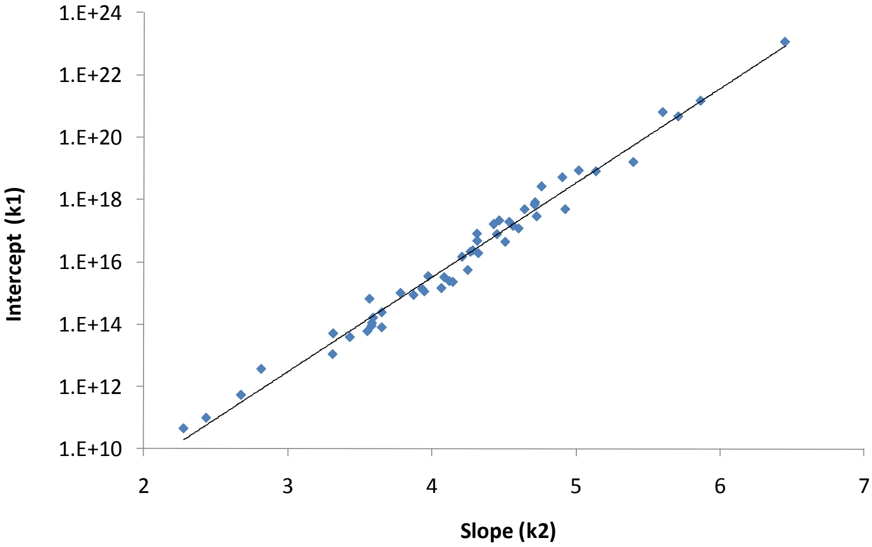

Figure 4: Relationship between k_1 and k_2 for all tested mixtures.

Based on the present work, a model is proposed for the relationship between k_1 and k_2 as expressed in Equation 6, with a $R^2=0.98$:

$$k_1 = 2503.836 \times e^{6.968 \times k_2} \tag{6}$$

In this case, Equation 5 can be written as:

$$N = 2503.836 \times e^{6.968 \times k_2} \times \left(\frac{1}{\varepsilon}\right)^{k_2} \tag{7}$$

The determination of the coefficient of Equation 7 only requires one pair of values (N, ε). This pair of values must correspond to a series of fatigue testing at a unique strain level, a high strain level is preferred, which takes short testing time.

In spite of the excellent correlation obtained between k_1 and k_2 for any type of mixtures and for all the tested mixtures, it is important to verify the fatigue life obtained by the application of those relationships and the influence in the pavement life calculation.

In spite of the excellent correlation between k_1 and k_2 for all mixtures, which indicates that only one parameter is necessary to characterize the fatigue of asphalt mixtures, the calculation of k_2 using the laboratory fatigue results for the highest strain level (800 microstrain) leads to a set of values that does not represent the fatigue parameters (k_1 and k_2) of the asphalt mixtures, as it can be observed in Figure 5.

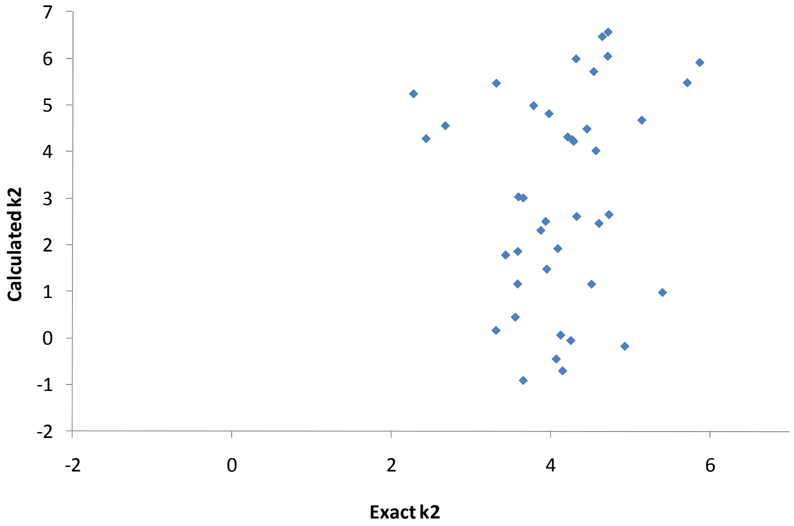

Figure 5: Relationship between real k_2 coefficient and the one calculated using the fatigue tests performed at 800 microstrain.

The precision of this method continues to be inaccurate even when the results of low strain levels are used, such as 100 microstrain, for which the k_2 calculated using the laboratory results does not represent the exact value, as demonstrated in Figure 6. In this case the difference between the exact value of k_2 and the calculated one continues to be very large which produce significant differences in terms of fatigue life when this value of k_2 is used.

Furthermore, the use of a strain level of 100 microstrain is not suitable to predict the fatigue life because the fatigue test performed at this strain level lasts longer. The best method to estimate the fatigue life of asphalt mixtures is to perform fatigue tests and to extrapolate the fatigue life for in service strain levels such as 100 microstrain.

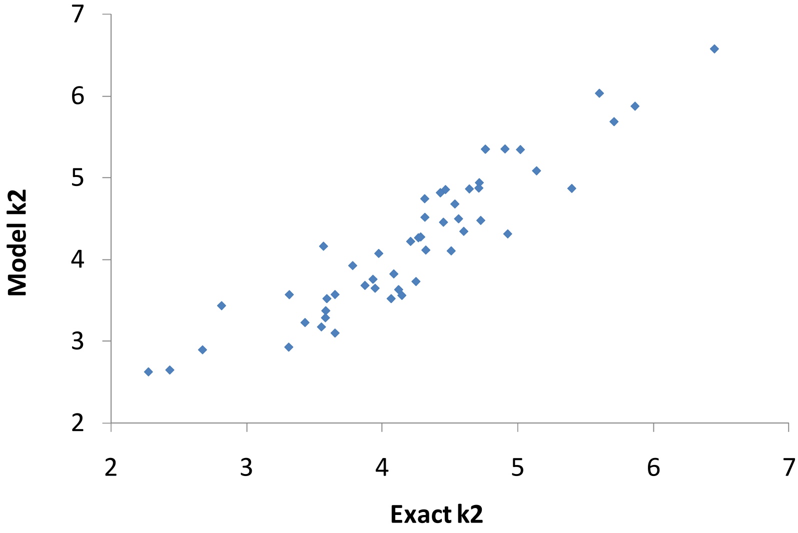

Figure 6: Relationship between real k_2 coefficient and the one calculated using the fatigue tests performed at 100 microstrain.

The analysis performed in terms of fatigue life produces similar results as the ones obtained in the k_2 comparison. The fatigue life obtained by the k_2 calculated using fatigue results (N, ε) for a high strain level, i.e, 800 microstrain, cannot be compared to the exact fatigue obtained using all fatigue tests results, as it can be observed in Figure 7. The predicted fatigue life for a 100 microstrain is much greater than the exact one.

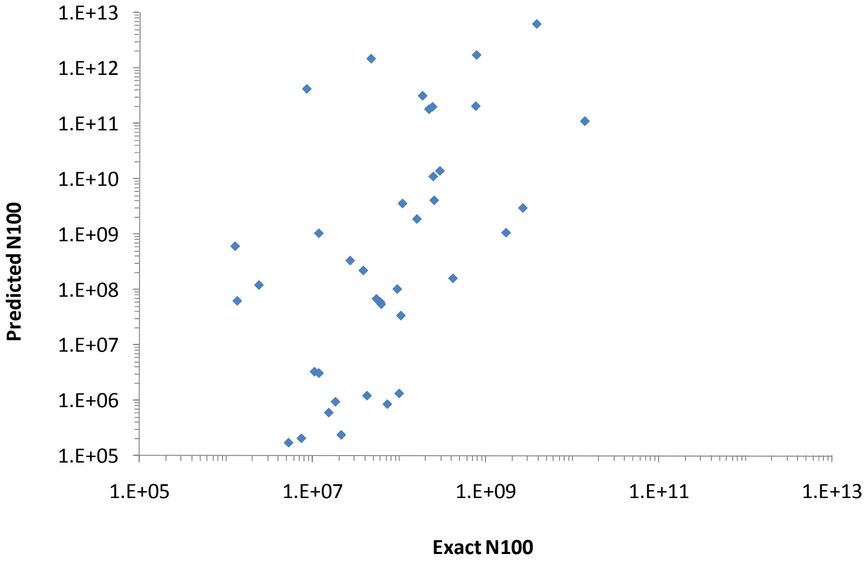

Figure 7: Fatigue life at 100 microstrain calculated using k_2 coefficient from fatigue tests at 800 microstrain.

An identical analysis using the k_2 coefficient obtained with fatigue tests performed at 400 microstrain is presented in Figure 8. In this case the fatigue life for a 100 microstrain strain level also presents a large difference for the exact fatigue life that does not allow using fatigue tests performed at 400 microstrain to predict the fatigue life at 100 microstrain. However, the use of 400 microstrain in comparison to the 800 microstrain reduces significantly the different between the predicted and the exact fatigue life.

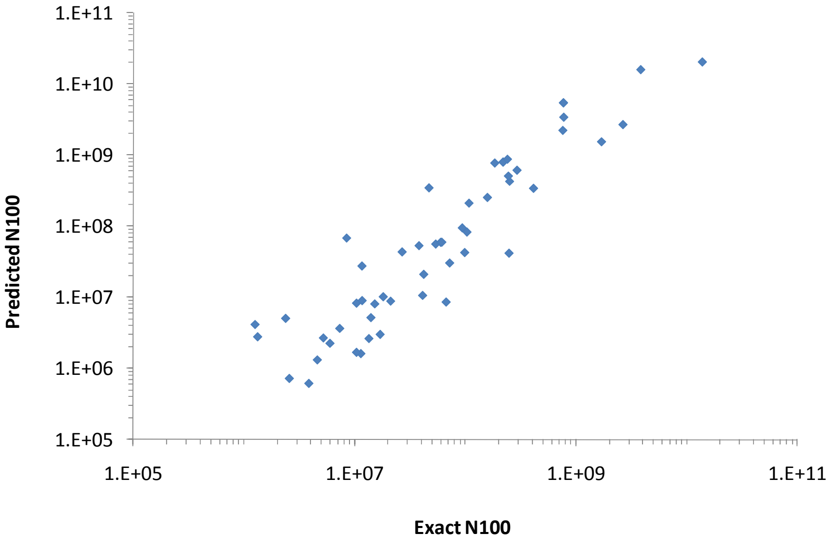

Figure 8: Fatigue life at 100 microstrain calculated using k_2 coefficient from fatigue tests at 400 microstrain.

The analysis of the fatigue life using the k_2 coefficient obtained from fatigue tests at 200 microstrain produces a fatigue life which is identical to that obtained in the fatigue tests, as it can be observed in Figure 9.

However, the use of low strain levels seems to be suitable to predict fatigue life. However, it is more time-consuming than to obtain a complete fatigue life law.

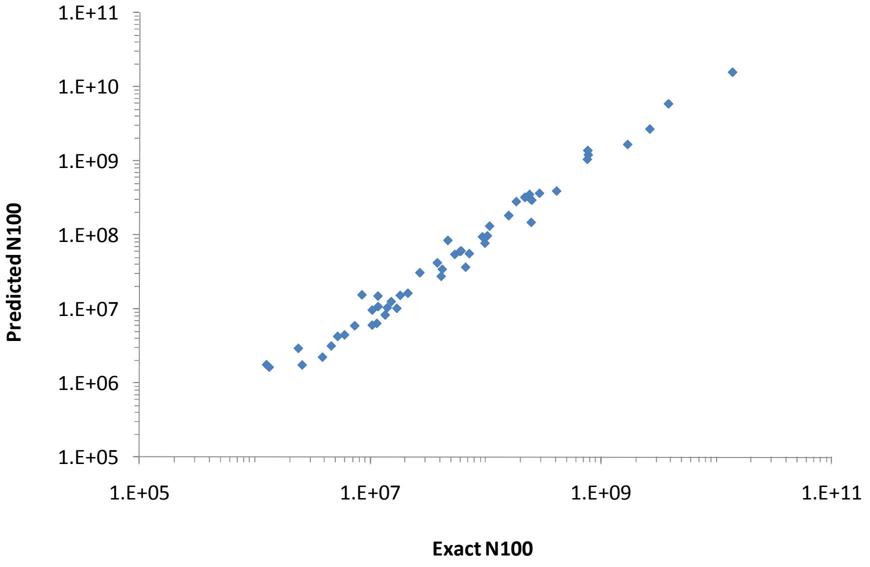

Figure 9: Fatigue life at 100 microstrain calculated using k_2 coefficient from fatigue tests at 200 microstrain.

This approach can be used to predict fatigue life for other strain levels such as 200 microstrain by using the fatigue results obtained at 400 microstrain (Figure 10). In this case, the approach produces fatigue results which follow those obtained by the exact values and the results for a low strain (200 microstrain) can be obtained from the fatigue medium strain level (400 microstrain).

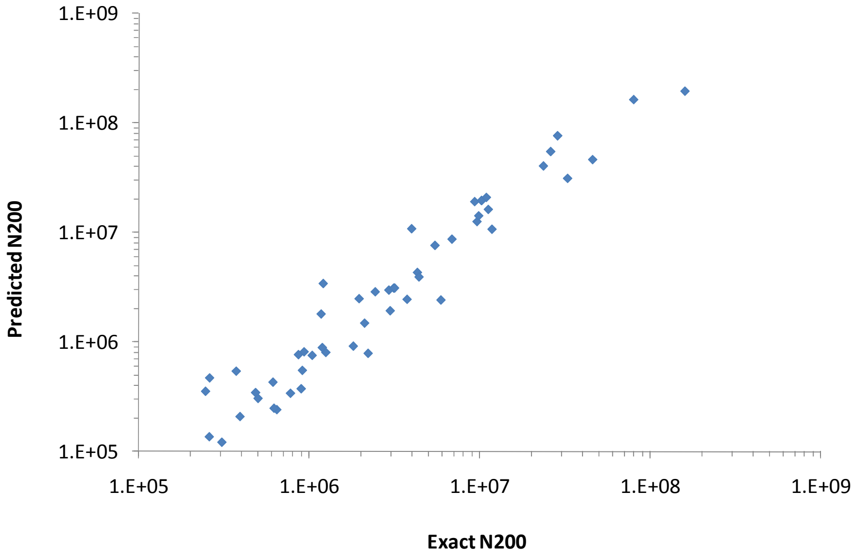

Figure 10: Fatigue life at 200 microstrain calculated using k_2 coefficient from fatigue tests at 400 microstrain.

The application of the k2 obtained from fatigue tests performed at high strain levels (800 microstrain) cannot be used to estimate the fatigue life at medium strain levels (400 microstrain), as it can be observed in Figure 11.

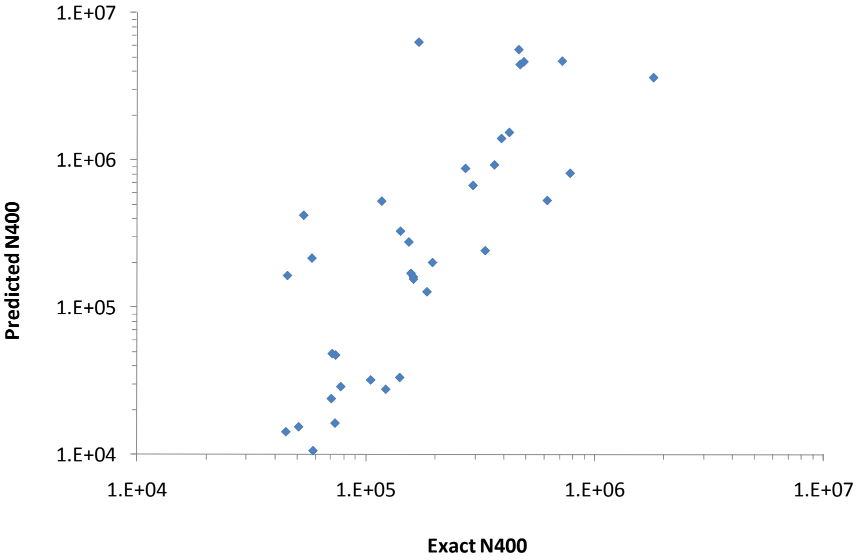

Figure 11: Fatigue life at 400 microstrain calculated using k_2 coefficient from fatigue tests at 800 microstrain.

However, this approach may be used to estimate the fatigue life at lower strain levels using higher strain levels, mainly to estimate the fatigue life for 100 and 200 microstrain using the k2 obtained for fatigue tests performed respectively at 200 and 400 microstrain.

CONCLUSIONS

This paper presented the evaluation of the k_1 and k_2 relationship for Portuguese mixtures based on the results obtained from more than 50 different asphalt mixtures composed by four different types of aggregate gradations and binder.

Relationship between k_1 and k_2 suggests that it can be used to predict the fatigue life of asphalt mixtures due to the good correlation between k_1 and k_2.

The model can be used to produce fatigue testing with only one strain level, once there is only one unknown parameter in the fatigue law (k_1).

Nevertheless, the use of the relationship between k_1 and k_2 for high strain levels does not produce exact values for the in-service fatigue life, such as 100 microstrain. The only valid application of that relationship appears when the k_2 coefficient is calculated for low strain levels around 200 microstrain that do not reduce considerably the testing time.

This approach seems to have potentialities to be used in the prediction of fatigue life based on fatigue test results obtained at higher strain levels to predict the fatigue life at lower strain levels, but it needs to be improved taking into account other factors that affect the k1-k2 relationship, such as the stiffness of the asphalt mixture.

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