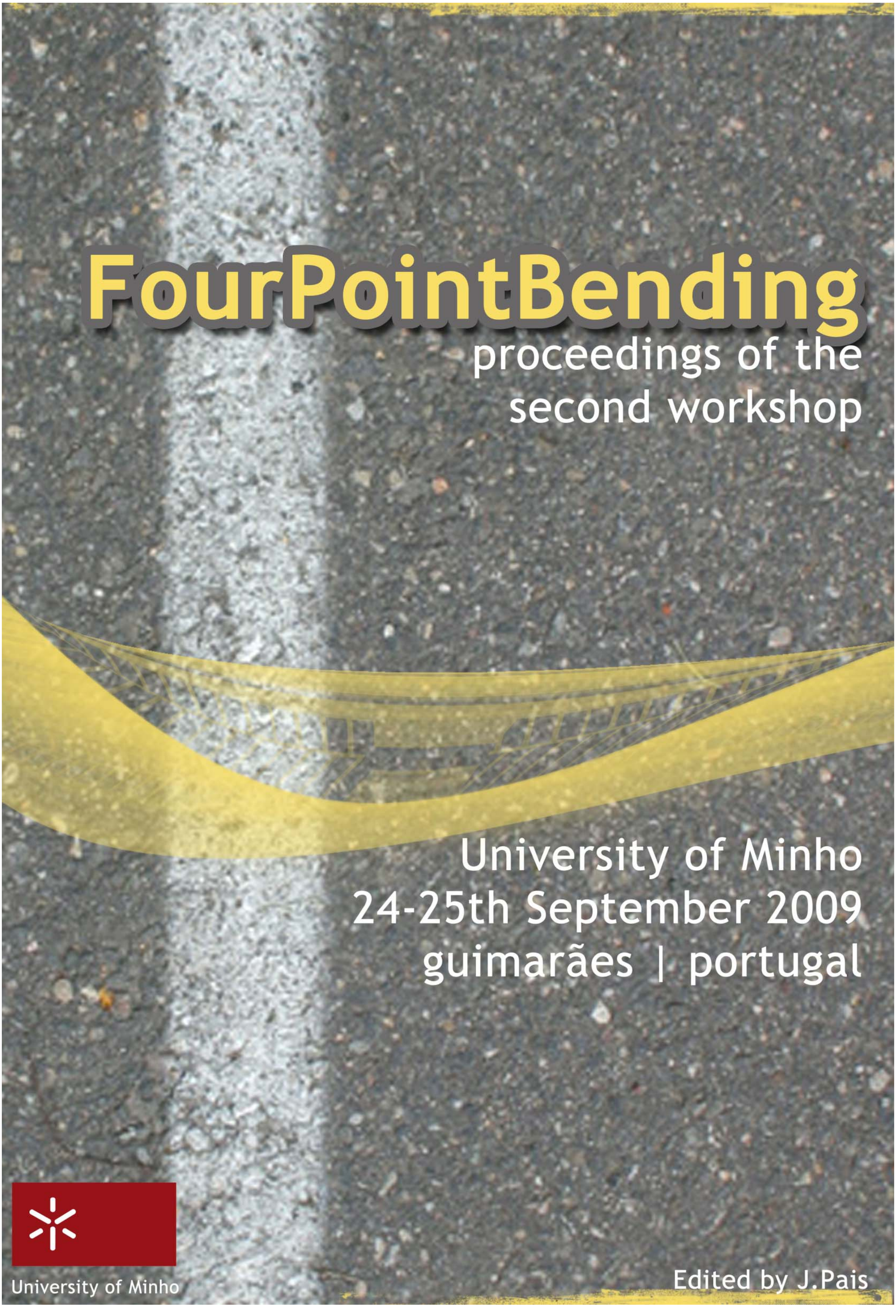

FourPointBending

proceedings of the second workshop

University of Minho
24-25th September 2009
guimarães | portugal

University of Minho

Edited by J.Pais

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2nd Workshop on Four Point Bending, Pais (ed.), © 2009. University of Minho. ISBN 978-972-8692-42-1

The effect of using rest periods in 4PB tests on the fatigue life of grouted macadams

J.R.M. Oliveira & J.C. Pais
University of Minho, Guimaraes, Portugal

N.H. Thom
University of Nottingham, Nottingham, UK

S.E. Zoorob
Senior Researcher, CSIR, Built Environment, South Africa

ABSTRACT: Four-point bending tests are commonly used to assess the fatigue resistance of bituminous bound materials that are used in road pavements. However, it is difficult to establish a reliable relationship between the laboratory test results and the field performance of the material. In order to predict the real life of the pavement, shift factors are normally used to convert the fatigue results obtained in the laboratory onto the actual fatigue life of the material in the field. Those shift factors depend on the type of test used, the testing conditions and the type of mixture used. In this study, an attempt was made to establish a shift factor for grouted macadams, based on four-point bending fatigue test results carried out with rest periods between the loading cycles. The result obtained was used to define a fatigue criterion for pavement design with grouted macadams.

1 CONSTITUTION OF GROUTED MACADAMS

Typical grouted macadams are normally used as a surface course and are composed of a combination of an asphalt mixture and a cementitious grout in the same layer. In essence, grouted macadams comprise an open-graded asphalt mixture (usually single sized), containing 25 to 35 percent air voids, which forms the skeleton into which a cementitious grout is poured (Figures 1 and 2). The final product combines part of the best qualities of concrete and asphalt pavements, namely the flexibility and freedom from joints that characterise asphalt and the high static bearing capacity and wear resistance of concrete. The impervious grouted macadam layer protects the underlying layers and its high strength effectively reduces the stress level in the base layer. The speed of construction of grouted macadam surfacing and the period of time required ahead of opening to traffic is a significant advance over conventional concrete (Setyawan, 2003). This type of surface layer is normally applied with a thickness of 30 to 60 mm (Densit, 2000), although some work has been done with thicknesses in the region of 80 mm (van de Ven and Molenaar, 2004) and some grout suppliers claim it is possible to use thicknesses of up to 200 mm (Contec, 2005).

The construction of a grouted macadam is a two stage procedure, since it is necessary to allow the asphalt layer to cool down before applying the grout into its voids. Thus, construction is normally carried out on two consecutive days. The porous asphalt layer is applied using a normal asphalt paver and is then lightly compacted using a steel roller without vibration to avoid the formation of cracks or tracks in the material. As soon as the porous asphalt mixture has cooled down, its voids can be filled with the selected high fluidity cementitious grout (Zoorob et al., 2002). The grout is spread on the surface, with the help of rubber scrapers (squeegees). Depending upon the powder type used to produce the grout and the producer's specification, a light steel roller may be used in the vibration mode to make sure that the voids of the asphalt are completely filled with the grout. After filling the voids, the surface may be treated to improve its properties, namely skid resistance, durability and aesthetics.

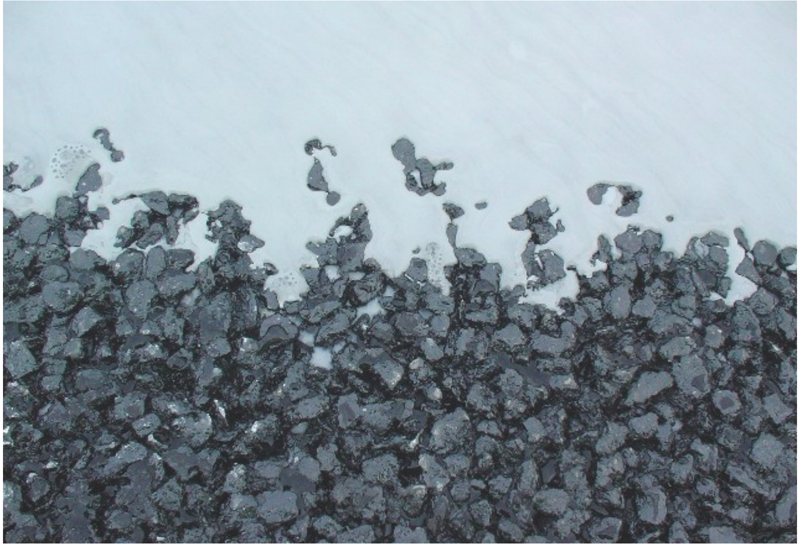

Figure 1. Cementitious grout during the process of penetrating the voids of a porous asphalt skeleton

Figure 2. Core extracted from a typical grouted macadam slab

2 RELATIONSHIP BETWEEN LABORATORY TESTS AND FIELD PERFORMANCE

A major difficulty with fatigue testing is developing a meaningful relationship between the results of laboratory tests and field performance. Laboratory tests usually use sinusoidal loading and fixed strain or stress during one test, while in practice, the mode of loading is randomly distributed, including rest periods and lateral distribution of loads. Temperature variations in the asphalt layer and healing effects, due to intermittent loading, also influence the field performance of asphalts. For these effects correction factors (known as shift factors) should be applied. However, determination of the correct shift factor is fairly complicated, since it depends on the type of test, mode of loading, testing temperature and type of mixture (Shell, 1978; Rao Tangella et al., 1990).

Shift factors of 2-10 (Shell, 1978) or 20 (Brown et al., 1985) have been suggested to take into account the influence of rest periods. Additional factors of 2.5 (Shell, 1978) or 1.1 (Brown et al., 1985) have also been used to simulate the lateral distribution of loads, while the fatigue life associated with the crack propagation phase has been considered by a shift factor of 20 (Brown et al., 1985) or by the use of controlled-strain bending tests, instead of controlled-stress tests, which have been found to correlate well with the failure stage in wheel tracking tests on asphalt slabs (Shell, 1978). Therefore, ultimate shift factors of 10-20 (Shell, 1978) or 440 (Brown et al., 1985) have been suggested. Rao Tangella et al. (1990) mentioned values of 100 and 20 for shift factors, considering high loading rate sinusoidal bending tests carried out, respectively, with and without rest periods. Khweir and Fordyce (2003) have obtained a shift factor of 77, which was the result of superposition of Indirect Tensile Fatigue Test (ITFT) data onto the fatigue line reported by TRRL LR1132 (Powell et al., 1984). Ekdahl and Nilsson (2005) have compared the fatigue criterion specified by the Swedish design code ATB Road with laboratory test results of different mixtures (using Indirect Tensile Fatigue Tests). According to these authors, a methodology based on ITFT tests developed by the Swedish National Road and Transport Research Institute, to study the fatigue properties of mixtures to apply in pavement design, gave results that correlated well to field performance when a shift factor close to 10 was used. However, Ekdahl and Nilsson (2005) have suggested that, according to their recent study, the shift factor of 10 is not large enough and that a shift factor of 42.4 would be more appropriate, highlighting for example the positive effects of using polymer modified binders in the fatigue life of bituminous mixtures.

3 LABORATORY FATIGUE RESULTS OBTAINED USING 4-POINT BENDING TESTS

Based on the diversity of shift factors mentioned above, and on the concerns relative to the application of a specific shift factor to results obtained under different testing conditions, an attempt was made to determine the shift factor appropriate to the testing conditions used in this investigation and for this particular type of material. This would allow the use, in pavement design, of the grouted macadam fatigue lines determined under the present project (Figure 3).

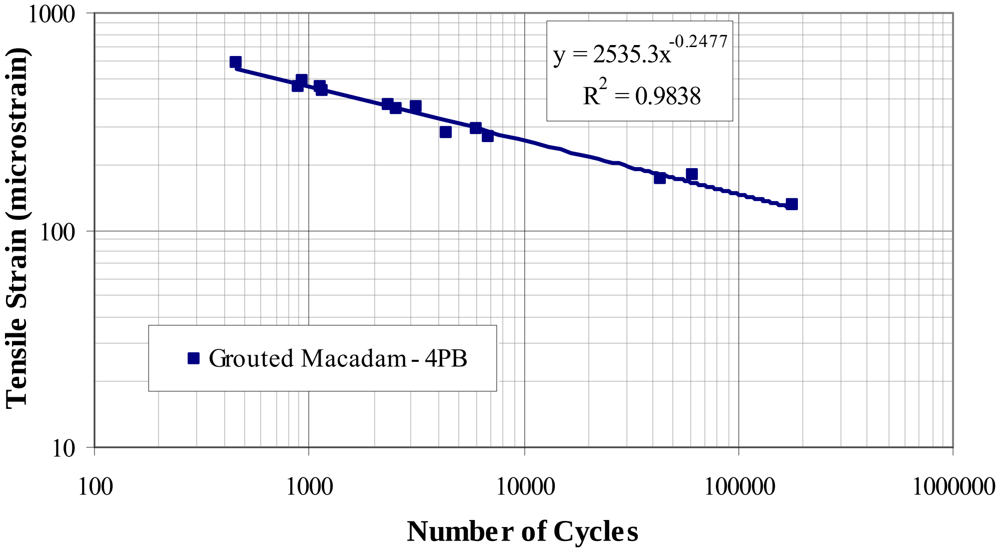

Figure 3. Fatigue line obtained for the studied grouted macadam mixture using 4-point bending tests

A laboratory testing programme was established, using four-point bending tests, where different loading patterns were used during each test, as illustrated in Figure 4. This study focussed mainly on the effect of rest periods on the fatigue life of the standard grouted macadam mixture. Thus, five different loading patterns were used: (i) a continuous sinusoidal load; (ii) two sinusoidal loading cycles followed by a rest period, with duration equivalent to one cycle; (iii) one loading cycle followed by a rest period of equivalent duration; (iv) one loading cycle followed by a rest period with duration equivalent to two cycles and; (v) 1000 loading cycles followed by an equivalent rest period.

Due to limitations of the equipment in controlling the actuator with an intermittent loading pattern (rest periods between loading cycles), the maximum frequency that could be used was 5 Hz. Therefore, all tests were carried out at this frequency. The results obtained according to the modes of loading shown in Figure 4 are presented in Figure 5, where the extended fatigue life obtained by the inclusion of rest periods in fatigue tests is clear, increasing with the duration of the rest periods. Tests were stopped after the stiffness modulus of the mixture had dropped below half of its initial value. This value (50% of initial stiffness) would be used as the failure criterion. The test becomes more time consuming when rest periods are included, especially when the duration of rest periods is longer than the loading time, and this was actually the reason why the longest rest period used was just two times the loading time.

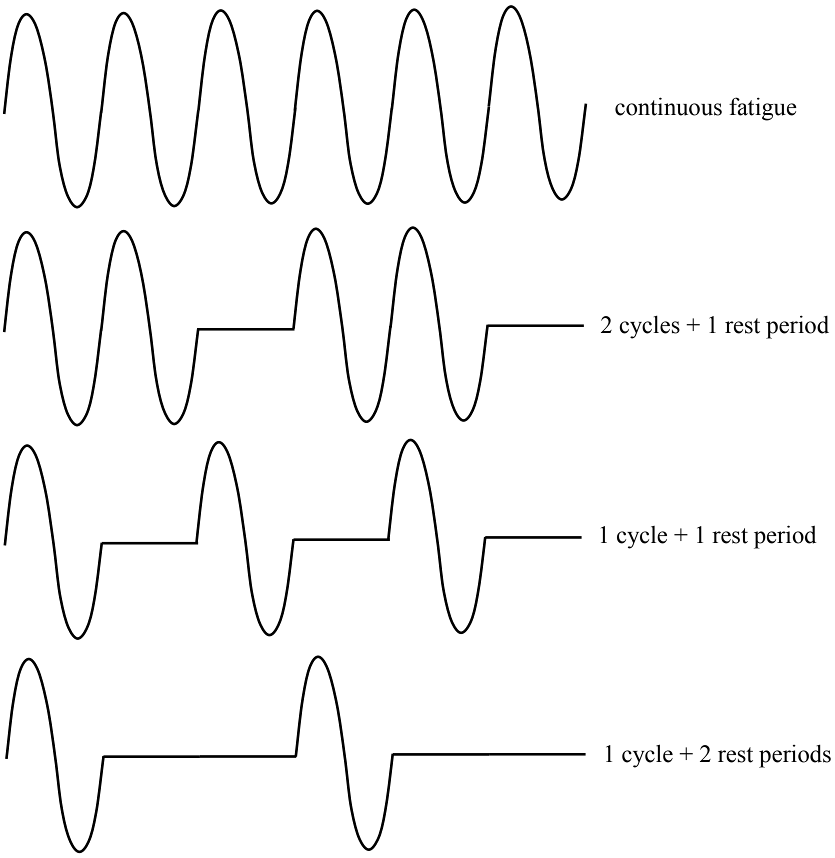

Figure 4. Modes of loading used to determine the influence of rest periods on the fatigue life of grouted macadams

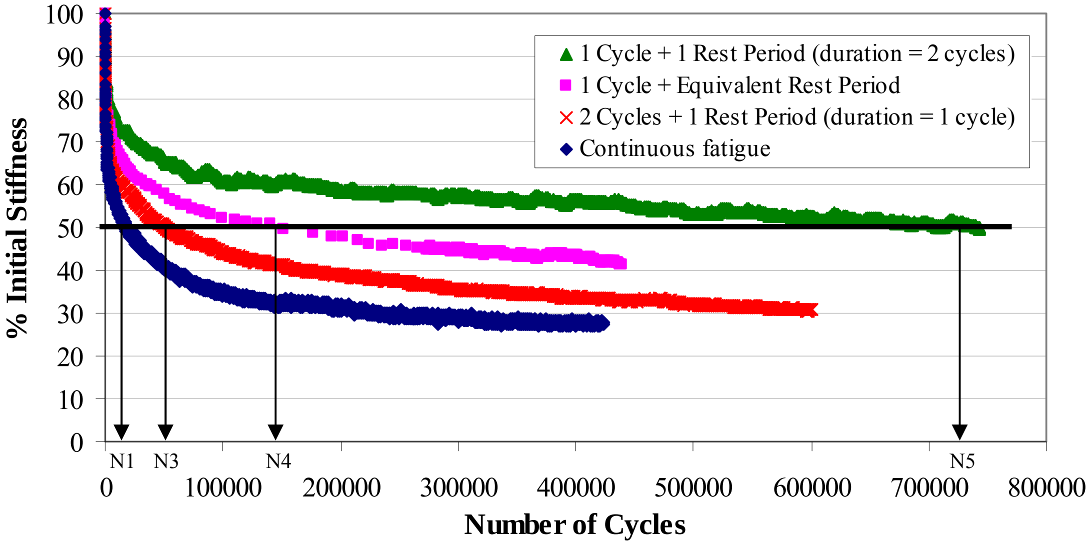

Figure 5. Influence of rest periods duration on grouted macadam fatigue life

A fifth result was obtained using a different loading pattern, not represented in Figure 5, which comprised 1000 consecutive loading cycles followed by an equivalent rest period. The results of this test are presented in Figure 6, where each data-point represents the stiffness of the mixture at the end of each series of 1000 loading cycles. The data shown in Figure 5 were re-plotted to highlight the initial 60000 cycles, as shown in Figure 6, in order to emphasize the influence of rest period duration on the fatigue life (which can be observed by the intersection of any horizontal line with the stiffness reduction lines).

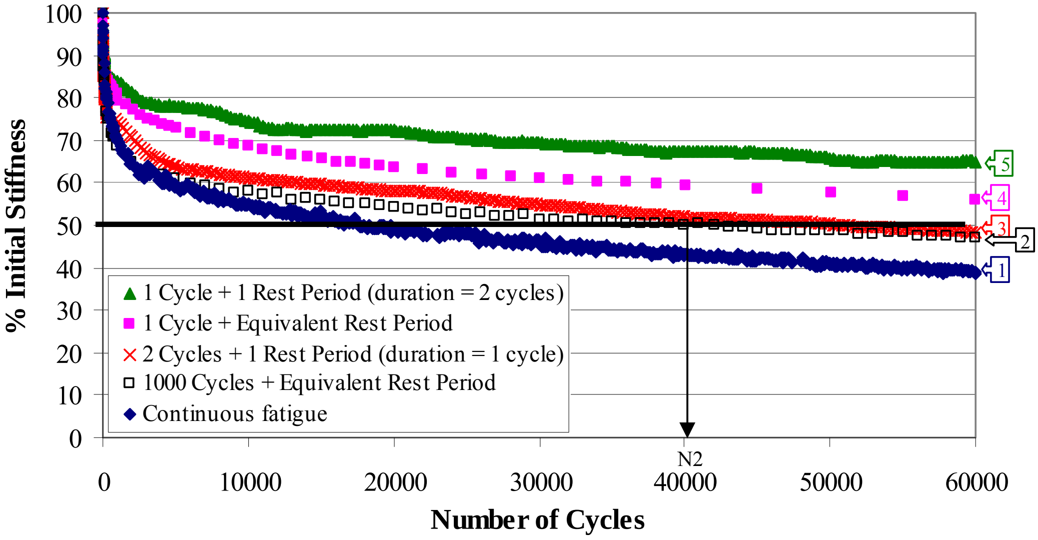

Figure 6. Influence of rest periods on the fatigue life of grouted macadams

Taking into account only the rest periods to define a shift factor (which is very conservative, according to the results of other researchers), and based on the results presented above, the shift factor corresponding to each of the studied loading conditions was obtained as the ratio between the fatigue life (number of cycles up to 50% stiffness reduction – N1, N2, N3, N4, N5) of each test and the fatigue life of the continuous fatigue test (N1). The results are summarised in Table 1.

Table 1. Shift factor obtained for each fatigue line

Mode of loading	No. of cycles	Shift factor
Continuous fatigue (1)	17739	1.0
1000 cycles + equiv. rest period (2)	40980	2.3
2 cycles + 1 rest period (3)	50823	2.9
1 cycle + 1 rest period (4)	140050	7.9
1 cycle + 2 rest periods (5)	734395	41.4

In order to analyse the results of these tests from a field performance perspective, some assumptions have to be made. Thus, a pavement design life of 20 years was used assuming the application of grouted macadams in a heavily trafficked highway (design traffic of 150 million standard 80kN axles), with 6000 commercial vehicles per day (assuming a wear factor of 3.5 standard axles per vehicle). If these commercial vehicles were distributed over a period of 12 hours, the frequency would be approximately 1 commercial vehicle every 7.2 seconds (or 1 axle every 2 sec., distributed over the time interval). On the other hand, the frequency used in the laboratory tests (5 Hz) would correspond to a 'loading' time of 0.7 sec (3.5 axles/5 Hz) per vehicle. Assuming an average vehicle length of 12.5 m, the vehicle speed would be 17.86 m/s (approximately 40 miles/h). A rest period of 6.5 sec would be expected after each 0.7 sec of commercial vehicle loading (7.2 sec in total, per vehicle). This corresponds to a rest period 9 times longer than the loading period.

In accordance with the calculations discussed above, the shift factor obtained from line 5 of Table 1 (41.4) would be a very conservative value, since the rest period used in the laboratory tests is 4.5 times shorter than the rest period between each commercial vehicle calculated above. However, each commercial vehicle actually represents the concentration of 3.5 axle loads. As can be observed from lines 2, 3 and 4, the application of consecutive loads before the rest period decreases the fatigue life of the mixture. Therefore, the extended life expected from the longer rest periods (9 times the loading period instead of 2 times, as for line 5) was ignored, taking the value of 41 as an adequate value for the shift factor (considering exclusively the effect of the rest periods). The ultimate value resulting from the present investigation was 45, which includes an extra factor of 1.1 for the lateral load distribution as suggested by Brown et al. (1985). The final value also concurs with that suggested by Ekdahl and Nilsson (2005). Nonetheless, the final shift factor (45) is still considered a conservative value, due to the particular behaviour of grouted macadams, in terms of crack propagation, as shown by Oliveira et al. (2008).

In the case of low volume roads or distribution centres/warehouses, a higher value should be used for the shift factor, as the duration of the rest periods is significantly higher. However, it is not sensible to suggest a different value based on the available results. A new set of tests should be carried out, using longer rest periods, but that was not possible during the current project.

In order to suggest a fatigue criterion for Grouted Macadam the equation of the fatigue line presented in Figure 3 was multiplied by the shift factor mentioned above (45), which resulted in Equation 1. For a comparison with the fatigue criterion traditionally used for asphalt in the UK, which was specified by Powell et al. (1984) and Nunn (2004) for the field performance of asphalt mixtures (Equation 2), both are presented in Figure 7.

$$N = 2.7 \times 10^{-9} \cdot \varepsilon_t^{-3.9718} \tag{1}$$

$$N = 4.169 \times 10^{-10} \cdot \varepsilon_t^{-4.16} \tag{2}$$

where:
N = Number of equivalent standard axle loads (ESALs);
ε_t = Tensile strain induced at either surface or underside of bound layers.

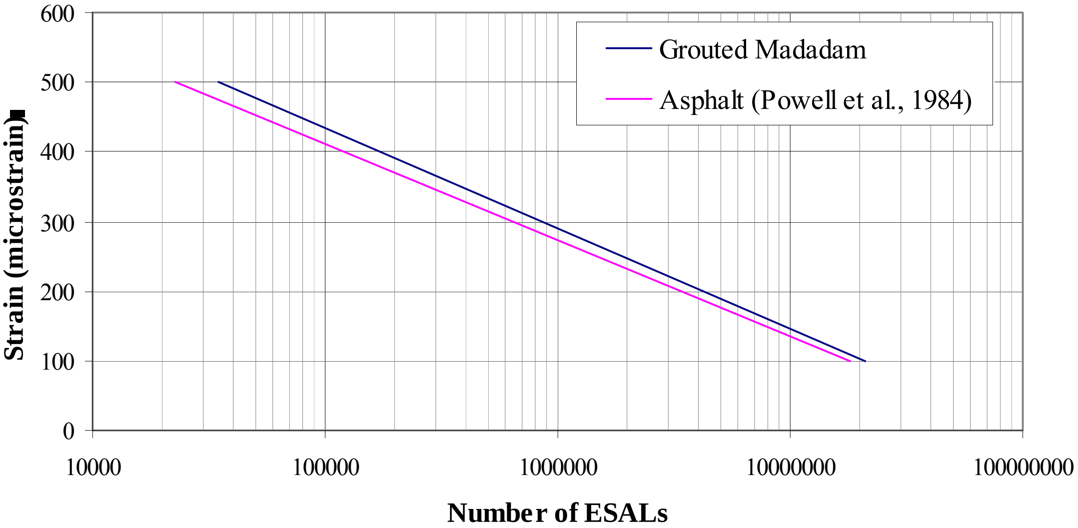

Figure 7. Fatigue criteria for grouted macadams and traditional asphalt

4 CONCLUSIONS

According to what was discussed above, some conclusions can be drawn, as follows:

- a shift factor of 45 was determined for grouted macadam mixtures, which should be multiplied by the fatigue life obtained in the laboratory, in order to predict the actual pavement fatigue life more realistically;
- the shift factor suggested is still considered a conservative value, since it does not include results from tests with very long rest periods between each load application;

- a fatigue criterion was proposed for pavement design when using grouted macadams, which was based on the shift factor determined by using rest periods on four-point bending fatigue tests.

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