How may the variation of traffic loading effect measured asphalt strains and calculated pavement service life?

P. Ekdahl
Ramböll RST & Lund University, Malmö, Sweden

R. Nilsson
Skanska, Malmö, Sweden

ABSTRACT: Service life testing of asphalt specimen in laboratory frequently uses a highly specified and constant load. Real roads experience a considerable distribution of both placement and size of load which leads to a variety of material responses. Fatigue criteria derived from lab tests often need a large shift factor in order to match the experience on real roads. Data from an instrumented test site in southern Sweden (E4, Eket) has been used for analysis of how the variation in load placement, load size and response direction may contribute to the shift factor. The variation in measured strains at the bottom of the AC-layer has been compared with the Swedish design code ATB Road and has been used as input to the asphalt strain criterion in this code. The results are discussed with use of other contributions to the shift factor such as healing.

KEY WORDS: Shift factor, strain criterion, load distribution, pavement service life, test site Eket.

1 INTRODUCTION

In most pavement design codes a major criterion for defining technical service life is the asphalt strain at the bottom of the AC-layer. However asphalt strain criteria are often based on laboratory tests and frequently use a rather large shift factor to get a reasonable correlation with experience from real roads and full-scale tests. The need of shift factors is a complicated matter. Apart from variation in load placement, healing and other climatic effects they are effected by variation in vehicle loads and tire pressures. The desire is to minimize the influence and use of shift factors.

The test site E4 Eket (4-lane highway) in Sweden has been used for registration of longitudinal and transversal asphalt strains at the bottom of the AC-layer under real traffic use and FWD testing. In particular data from May 1998 has been selected for this study. The data has been used in combination with the Swedish design code, ATB Road, in order to get an indication of the effect on the technical service life from 1) the transversal distribution of the vehicle placement on the road and 2) load distribution on vehicles. The road structure at Eket is; 140 mm AC, 80 mm granular base and 470 mm granular subbase on a moraine subgrade. In addition to test data from Eket, information from two other test sites in Sweden has been used (test site E6 Uddevalla and Borrebackevägen). Furthermore, laboratory tests regarding the influence of shift factors and the effect from healing have been used to put results from the test sites into perspective.

2 LAB TO FIELD SHIFT FACTOR

Over the years several fatigue criteria have been developed worldwide. The most well known are the Asphalt Institute (AI) fatigue criterion and the Shell criterion developed by Bonnaure et al. (1980). In Sweden the ATB Road asphalt criterion (see equation 2) is used. This criterion was developed mainly from laboratory tests on base course materials called AG16, AG22 and AG25 containing a penetration grade binder 160/220 and from empirical data from long time pavement performance projects in Sweden. The Swedish National Road and Research Institute (VTI) has also derived fatigue criteria for the same mixtures, (Said et al.). These criteria can be found in ATB Road, Section C5, and are to be used if it is not possible to measure the mixture properties. VTI has also developed a methodology, based on Indirect Tension Fatigue Tests, that must be used if fatigue properties for alternative mixes are needed in the design process (Said, F. Safwat, 1995).

In figure 1 the different field fatigue criteria are compared. It is clear that there is a large difference between the criteria and this has a huge impact on the design life of the pavement. According to VTI their fatigue criterion correlated well to field performance when a shift factor close to 10 was used. These two criteria are derived from the same mixtures and, in theory, the lines should coincide or at least be very close.

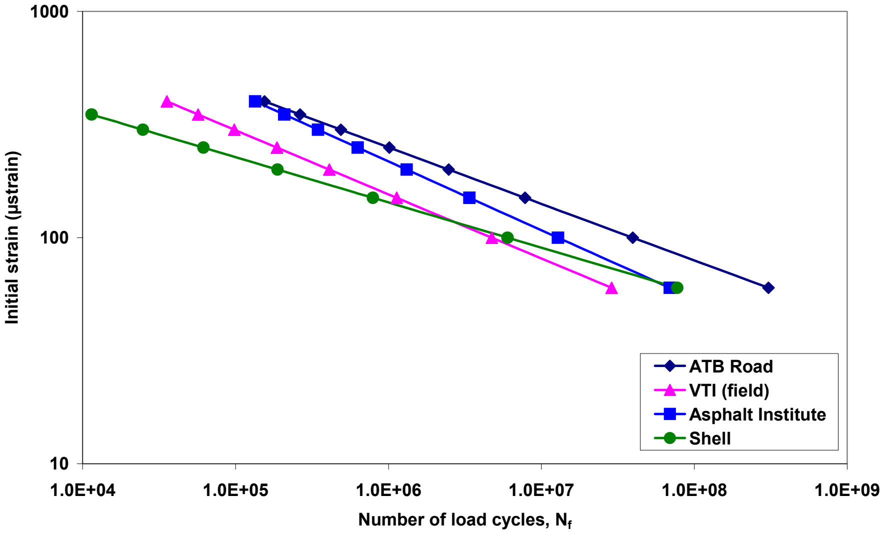

Figure 1: Comparison between different field fatigue criteria (10°C)

The fatigue tests in figure 1 were performed using the Indirect Tensile Fatigue Test according to Said (1995). A lab to field shift factor equal to 10, according to instructions in ATB Road, was used. The three mixes had the same gradation. The only difference was the type of binder used. The 160/220 and 70/100 are non-modified standard binders while the 100/150-75 PMB is polymer-modified (SBS). The AG22, 100/150-75 PMB mix is optimized for good fatigue resistance (Nordgren, 2004).

From figure 2 it is clear that using a shift factor equal to 10 will not show the positive effects from the polymer modified binder. In this case the asphalt mix containing a polymer-modified binder has almost the same fatigue characteristics as a standard mix. Also in this case there is a large difference between the ATB Road criterion and the AG22, 160/220 mix. In theory, the lines should coincide or at least be very close. Hence, the result is not completely logical and it might indicate that the lab to field shift factor of 10 is not large enough.

In figure 3 the same data as in figure 2 is shown. The only difference is that in this case a shift factor equal to 42.4 was used instead of 10. The new shift factor was derived by minimizing the error between the AG22, 160/220 fatigue criterion and the ATB Road fatigue criterion. When using the new shift factor it is possible to benefit from the modified mix in the design process, i.e. it has a longer life compared to a standard mixture. It also makes sense that a stiffer mix (AG22, 70/100) has a shorter fatigue life than a more flexible mix. One conclusion from these tests is therefore that the frequently mentioned shift factor of 10 could be much larger.

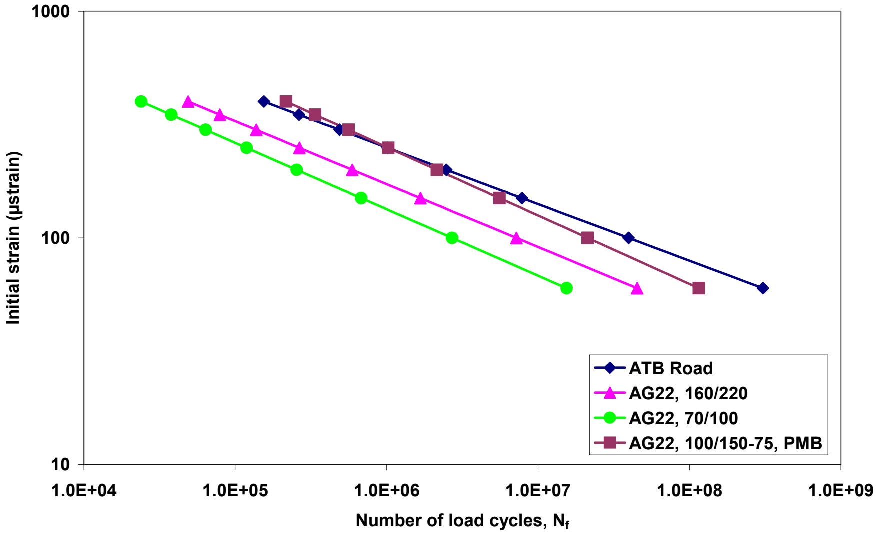

Figure 2: Laboratory fatigue data for different asphalt mixes converted to field criteria using a shift factor equal to 10 according to ATB Road instructions (10°C)

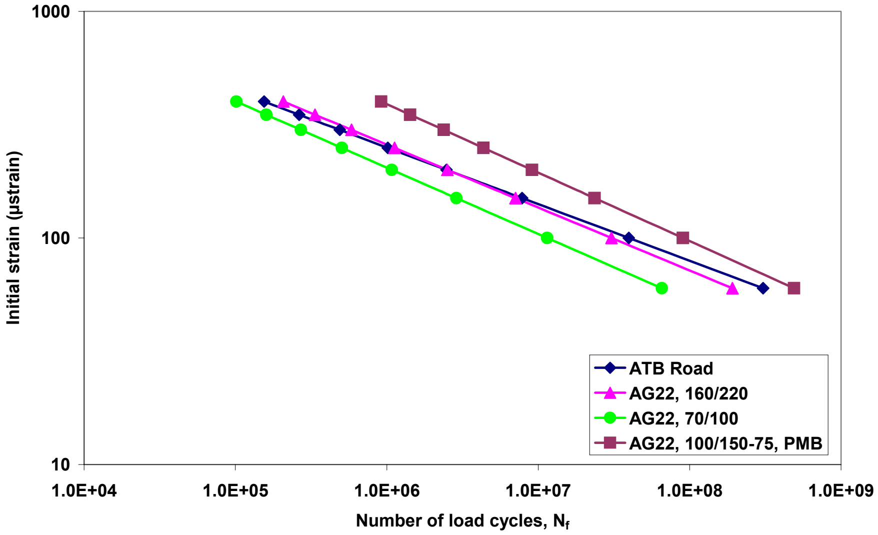

Figure 3: Laboratory fatigue data for different asphalt mixes converted to field criteria using a shift factor equal to 42.4 (10°C).

3 EFFECT FROM TRANSVERSAL DISTRIBUTION

At the test site Eket asphalt strain gauges were placed in three lines in the supposed outer (right) wheel path during construction. There is approximately 230 mm between each line of gauges (across the wheel path). Line A is closest to the road edge and line C closest to the centerline of the road. Each passage of a heavy vehicle produces a series of asphalt strains, one strain cycle for each axle (see figure 5). The longitudinal strain cycle consists of three phases (compression-tension-compression) for each axle passage. Since the distance between the gauges is known in both directions the vehicle speed and distance between axles may be calculated. By combining the results from ordinary traffic with FWD tests and tests using trucks with a specified load, the exact load and strain relationship under normal traffic may be analyzed.

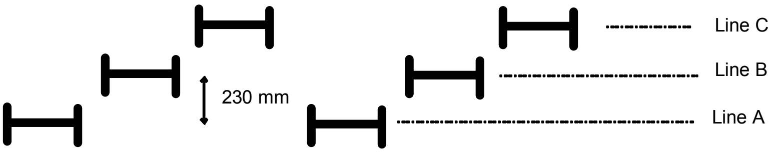

Figure 4: Placement of longitudinal AC strain gauges in outer (right) wheel path (Ekdahl, 1997).

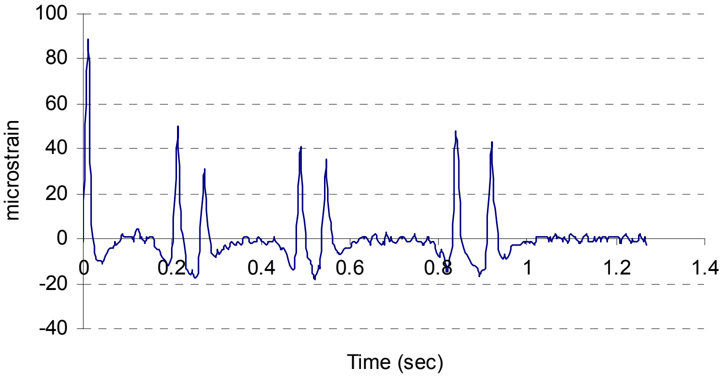

Figure 5: Typical longitudinal asphalt strain signal at Eket.

By studying which line of gauges (A, B or C) that gave the highest strain signal from a wheel passage, the conclusion was drawn that this line was closest to the major loading wheel. Table 1 shows the distribution over the wheel path for max AC-strain/vehicle passage. The table shows that approximately 33% of the vehicles passages are on one and the same line while the design codes often assume 100%.

Table 1: Transversal distribution of heavy vehicles

Line of max loading	Line A	Line B	Line C
	38%	29%	33%

The load transfer means a reduced material response in adjacent points. If the load is supposed to be positioned on the exact line where the maximum measured AC-strain is (a rough simplification) the two other gauge lines at E4 Eket registered strains signals that were about 15% and 55 % less respectively (stdev=11 and 23 %) at 230 and 460 mm distance from the maximum strain (see figure 6). In the case of real traffic the most exposed line of loading is line B according to figure 4. Approximately 2/3 of the wheel passages results in a 15 % reduction in asphalt strain in line B (i.e. when the load is closer to line A or C) and the remaining 1/3 of the wheel passages will be directly on line B. Line B in figure 4 will therefore experience the maximum strain (for 1/3 of the passages) or a 15% reduced strain for each wheel passage for a heavy vehicle (for 2/3 of the passages).

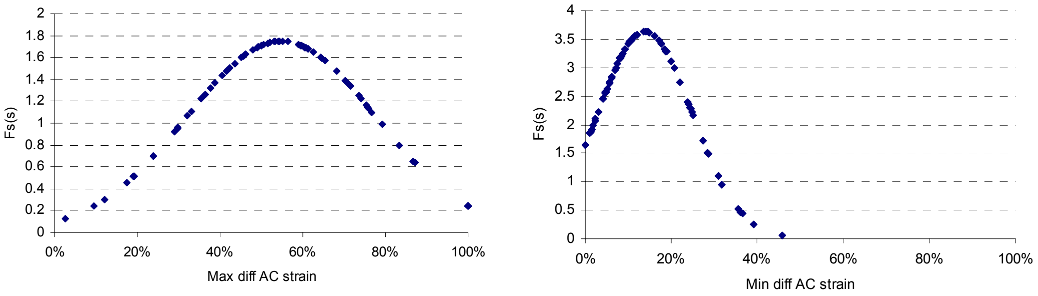

Figure 6: Distribution of max and min strain differences between gauge lines (A-B and A-C).

This means that any point in line B will experience a (somewhat simplified) mean longitudinal AC-strains as

$$\left(\frac{1}{3}\cdot 1+\frac{2}{3}\cdot 0.85\right)\cdot \varepsilon_{\max} \tag{1}$$

By developing this and combining it with the strain criterion in ATB Road

$$N_{bb,i}=\frac{2.37\cdot 10^{-12}\cdot 1.16^{(1.8\cdot T+32)}}{\varepsilon_{bb,i}{}^{4}} \tag{2}$$

where

$N_{bb,i}$ = critical (permissible) number of standard axle loads
T_i = AC-temperature for season i
$\varepsilon_{bb,i}$ = calculated AC-strain under an axle load in season i

we then get

$$N_{bb,i}=\frac{2.37\cdot 10^{-12}\cdot 1.16^{(1.8\cdot T+32)}}{\frac{1}{3}\cdot\left[\left(\varepsilon_{bb,i}{}^{4}\right)+2\cdot(0.85\cdot\varepsilon_{bb,i})^{4}\right]} \tag{3}$$

$$N_{bb,i}=1.47\cdot\frac{2.37\cdot 10^{-12}\cdot 1.16^{(1.8\cdot T+32)}}{\varepsilon_{bb,i}{}^{4}} \tag{4}$$

This means that the number of permissible passages of a standard axle is multiplied by a factor of about 1.47 as a rough estimate in this case (i.e prolonged service life). This contribution is a rather small part of the total shift factor mentioned in section 2. One may therefore speculate about the healing effect from the two compaction phases at each wheel passage at high AC temperatures. Logically, a combination of warmer and therefore softer bitumen and two compression phases for each wheel passage could mean a considerable healing effect where micro cracks are sealed.

4 EFFECT FROM VARIATION IN AXLE LOAD

According to the Swedish design code (ATB Road) the total traffic loading during the service life may be calculated as

$$N_{ekv}=\text{ÅDT}_k\cdot 3.65\cdot A\cdot B\cdot n \quad \text{(yearly traffic change is set to 0.)} \tag{5}$$

and

$$N_{bbi}\geq N_{ekv} \tag{6}$$

where

A = percentage (%) of heavy vehicles (>3.5 ton)
B = equivalent number of standard axles (10 ton, dual wheel) per heavy vehicle (normally 1.3)
n = service life (years)

The variation in axle load has been investigated in Sweden using WIM tests (Weigh In Motion). The WIM measurements have shown that the previously recommended factor of 1.3 standard axles per heavy vehicle quite often is underestimated, thus the normal axle loads frequently exceeds what is expected. Therefore the Swedish Road Administration (SRA) has published revised instructions in ATB

Road regarding the factor B containing guidelines for the normal magnitude of B for various road types. On roads like the one used in the study (Eket) a factor B between 1.3 and 4.0 is recommended. Normally a factor B of approximately 2 is chosen. When using a factor 2 the previous effect (from transversal distribution of the load) is reduced.

If we assume that a FWD load with 50 kN corresponds to the standard axle load in the design code (100 kN) and compare measured asphalt strains under both the FWD and the vehicle passages we get a factor B equal to 4.3 for the test site Eket in May 1998 which is slightly higher than the recommended 1.3 - 4.0.

5 THE EFFECT FROM STRAIN DIRECTION (TRANSVERSAL VERSUS LONGITUDINAL ASPHALT STRAIN)

The previous sections 3 and 4 concern longitudinal asphalt strains. At Eket the transversal asphalt strains were measured in the same way as the longitudinal ones. For the transversal direction the strain pattern is more complicated under traffic use. While the longitudinal strains display a homogeneous pattern with a response in three phases (compression-tension-compression) the transversal strains are much more dependent on the distance to the load.

The axle configuration has a clear effect since the center point of load varies between axles on one and the same vehicle. When looking at vehicle passage #21 for May 13, 1998 it can be seen that one and the same vehicle passage will cause a different strain pattern on gauge ASG8 compared to gauge ASG10 (see figure 7) since they are in adjacent lines. Since gauge #10 is closer to the loading line it has a tension phase for one of the axles, while gauge # 8 only has compressions. This means that the loading centre is closer to gauge #10. This illustrates the fact that the loading centers for all wheels on one and the same vehicle are not concentrated on one line. The axle width differs and the centre on dual and single tires varies. FWD tests at various distances from the measurement point shows that if the load is more than approximately 300 mm away it will cause a compression (see figure 8).

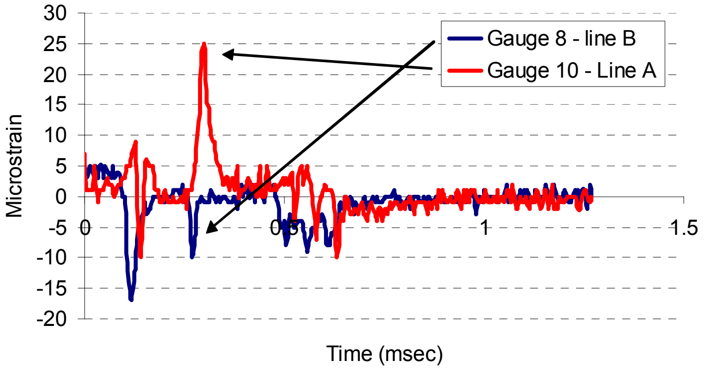

Figure 7: Example on transversal asphalt strains at Eket (T=20 deg C), adjacent lines A and B.

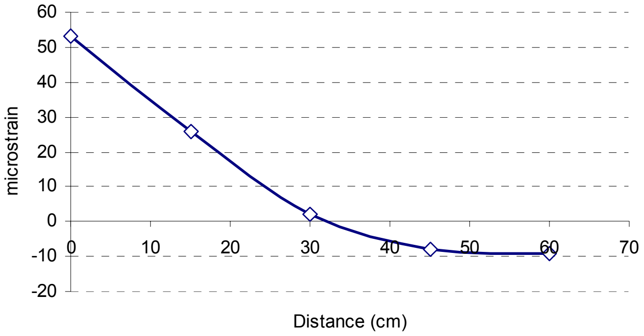

Figure 8: Asphalt strain at various distances from FWD load 700 kPa (Ekdahl, 1998)

When using this information and the same approach as in section 3 for the differences between loading lines, the data shows that the adjacent line (23 cm from the loading) roughly experience a 75% reduction in asphalt strain. This leads to the following strain criterion

$$N_{bb,i} = 2.98 \cdot \frac{2.37 \cdot 10^{-12} \cdot 1.16^{(1.8 \cdot T + 32)}}{\varepsilon_{bb,i}^{\;4}} \tag{7}$$

Hence, the transversal strains are more sensitive than the longitudinal ones. This then means a large impact on the strain criterion and the number of permissible standard axles (i.e pavement service life). In this case we see an improvement in service life by a factor of about 2 for the transversal strains compared to the longitudinal strains.

Besides the fact that the strain phases are different by shape there seems to be a more viscous and additive response in the transverse direction (see figure 9). However this effect is not investigated in this paper. The phase difference in time between ASG 1 (longitudinal) and ASG 10 (transversal) is due to the distance of approximately 3.25 m between the gauges in the travel direction. The vehicle speed can thereby be calculated to 82 km/h since the time difference (Δt) between the strain peaks for axle #2 is 0.142 s.

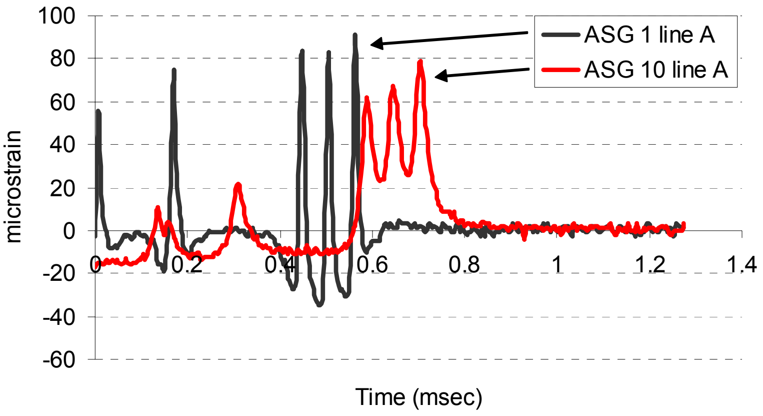

Figure 9: Example on longitudinal and transversal asphalt strains at Eket (T=20 deg C).

6 REST PERIODS BETWEEN LOADS (HEALING EFFECTS)

Literature tells us that it is mainly the time between rest periods that affect the magnitude of the shift factor (NVF committee 33, 1992). The rest period has a large impact on the healing of the asphalt mixture. This was reported by Bazin et al. 1967, Van Dijk 1972, Raithby et al. 1972, Verstraeten 1982, Kim et al. 1997 Si, Z. et al, 2002 and Nilsson B.R. et al. 2005.

Raithby et al. (1972) have showed that a sinusoidal shape got a relative fatigue life equal to 1.0. If a square wave form was used the fatigue life became much shorter (0.42); the longest fatigue life was obtained with a triangular wave form (1.45). Raithby et al. (1972) concluded that if a rest period was added to a sinusoidal wave, the fatigue life was up to 25 times longer than without rest periods. It was also concluded that the length of the maximum beneficial rest period was temperature-dependent; above 25°C the effect of rest periods seems to decrease. They also studied how state of stress affected fatigue life. Five different loading sequences were compared. If tension/compression, followed by a rest period, was compared to compression/tension, also followed by a rest period, fatigue life was approximately 1.5 times longer in the first case. When pure tension was compared to compression, it was no surprise that compression resulted in a fatigue life much longer than for pure tension.

It is a well-known fact that asphalt pavements heal during the summer which was demonstrated in a paper by Kim et al., 1997. They studied damage growth during loading cycles and healing during rest periods using viscoelasticity and continuum damage mechanics theory. Kim et al. suggest three explanations for the difference in stiffness modulus before and after a rest period. One explanation is relaxation in the material due to its viscoelastic behavior. During the rest period, the deformation recovers and the microstructure of the asphalt mixture changes; this probably contributes to the change in stiffness modulus. Another explanation is steric hardening of the binder due to molecular restructuring during rest periods. The third explanation is healing of micro cracks, which is a well-known phenomenon in polymer engineering.

Si, Z. et al. 2002 developed a healing index (HI), based on Schapery's pseudostrain concept, that can be used to describe the healing characteristics of an asphalt mixture. The same methodology was later used and confirmed by Nilsson B.R. et al. 2005. During a fatigue test the stiffness is continuously decreasing. If a rest period is introduced the stiffness will increase when the test is started again. An example is shown in figure 11 below.

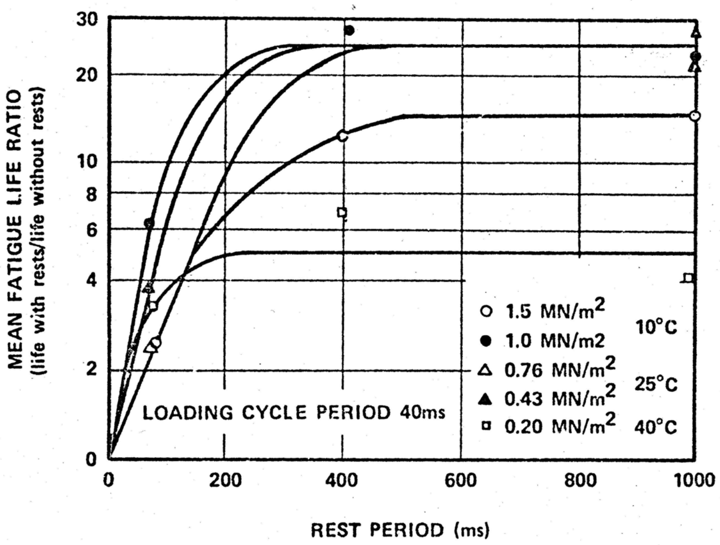

Figure 10: Effect of rest periods, Barksdale et al. (1977)

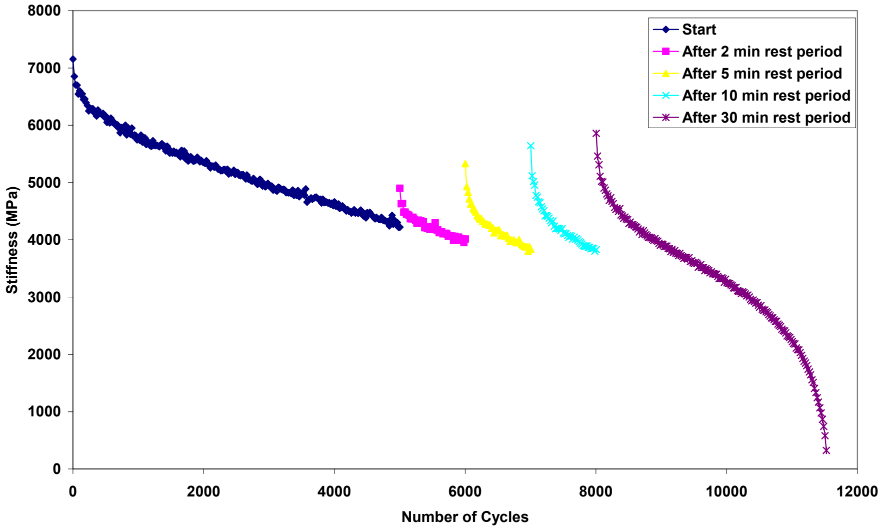

Figure 11: Stiffness before and after rest periods with different durations (AG16, 160/220)

In Figure 12 a healing index (HI) is shown (example chart) for an AG16, 160/220 mix. This curve is unique for this type of mixture. Similar types of curves can be derived for other types of mixes and then be used for comparison of the healing characteristics. The optimal mix has a high initial value and a steep increase as the rest period becomes longer. The healing effects during rest periods might be one explanation to the large difference between lab performance and field performance for most mixes. If the healing effects were considered during the design it would probably produce a more reliable result.

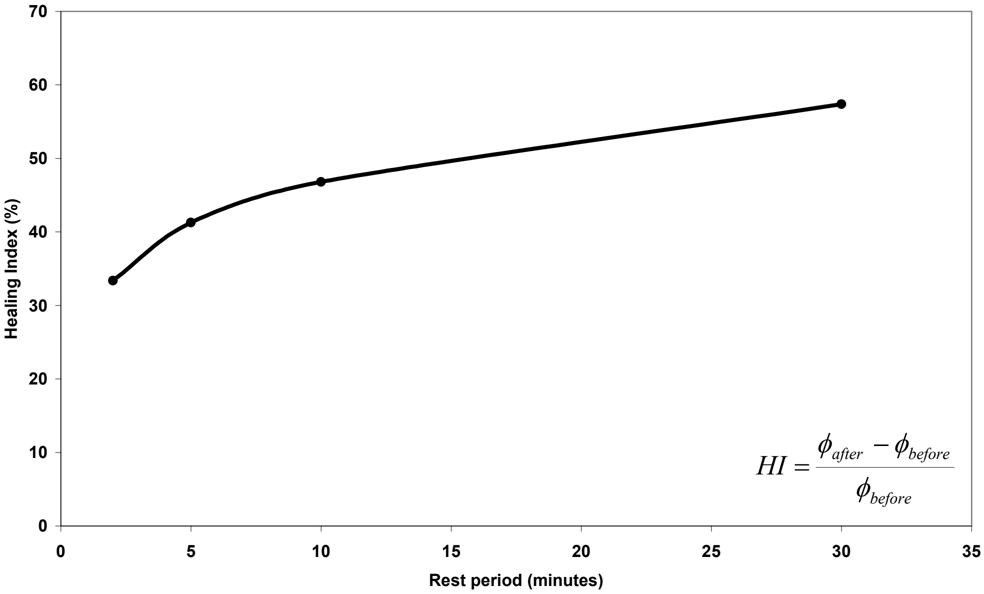

Figure 12: Healing index (HI) for AG16, 160/220 mix.

7 CONCLUSIONS

Shift factor may vary a lot and studies have shown shift factors varying between 10 and 40 from laboratory to field studies. Obviously, these large shift factors have to be explained in order to achieve a transparent and reliable design procedure. It seems like the transversal distribution of traffic placement and load size has a noticeable impact on the shift factor. It also seems like there is a clear difference between longitudinal and transversal asphalt strain in this matter. Furthermore, literature indicates that there is a large impact on service life (and thereby shift factors) from healing effects and varying load/response modes. This may serve as an indicator for further studies to focus on the combination of all the effects mentioned above. Pavement contracts with long warranties and performance contracts put higher demands on high precision fatigue criteria and reliable design models.

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