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Fatigue Life Evaluation of Flexible Pavement

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Abstract: Predicting the fatigue life or remaining life of existing roads will lead to greater opportunities to use contracts related to performance-based parameters (mechanical properties of pavement layers). In 1996, a test road was built on the E6 motorway with several observation road sections. After 10 years of traffic, two pavement structures with different types of bituminous layers were evaluated in regard to fatigue cracking. One of the structures is based on the idea of using the stone mastic asphalt (SMA) principle for all bituminous bound layers, while the other is a reference section with a conventional road base mix. A procedure for fatigue life prediction was developed based on the stiffness and fatigue properties of cored samples, falling weight deflectometer (FWD) deflections, field temperature data, and traffic monitoring at the site. It was concluded that the procedure can be useful for evaluating the material characteristics' impact on the fatigue life of flexible pavement and in turn the connection between mix properties and pavement design. It is demonstrated that pavement performance can be significantly prolonged by choosing bituminous layers with adequate mechanical properties. It is also shown that a reasonable estimation of the remaining life of flexible pavement can be forecast.

Key words: *Fatigue life; Flexible pavement; FWD; Residual value; Stiffness modulus.*

Introduction

Between 1994 and 1996, a test road was built on the E6 motorway in the west of Sweden. The test road consists of several sections comprising of different types of bituminous pavement, with the purpose of evaluating the performance of alternative pavement designs. The client requested analytical methodologies to evaluate new techniques, among other things for use in function-based contracts. The test road has been in use and studied since 1996 [1]. This paper is limited to the evaluation of the fatigue properties of two flexible structures. Tensile strains in the bottom surface of the bituminous layers are defined as critical for fatigue evaluation in this work; the structures are, therefore, relatively thin and bottom-up cracking is normally reported in Sweden. Typical asphalt layer thicknesses are between 75 and 130 mm for Swedish structure.

Important parameters in evaluating existing flexible pavements in regard to cracking are the characteristics of the asphalt concrete layers, more precisely stiffness modulus, fatigue resistance, and layer thicknesses. Layer thickness influences the resultant strain in the bottom surface of bituminous layer and time for crack propagation to the pavement surface. Stresses and strains at the bottom surface of the asphalt concrete layer under traffic loading are essential for the resistance of the asphalt concrete layer to cracking. It is well known that pavement service life is sensitive to changes in climatic parameters. The most important climatic factors are temperature, moisture, and frost. The stiffness and fatigue characteristics of bituminous layers are very sensitive to changes in temperature and the influence of the temperature variations must be carefully considered when predicting cracking. Moisture and frost primarily influence the properties of the subgrade and the unbound layers and indirectly influence the critical strain at the bottom of the bituminous layer. The effect of moisture and frost on the critical strain at the bottom of the bituminous layer can be evaluated by calculating the strain using for example the BISAR software for stress analysis in roads, or preferably based on FWD measurements under various conditions encountered over a year. Performing FWD measurements during different climatic periods to predict strain is believed to be adequate for calculation of the strains in the bottom surface of the asphalt layer in order to determine the fatigue life of the pavement with respect to cracking.

The main purpose of this work is to quantify the effect of using alternative bituminous pavements and to present an evaluation methodology with relevant criteria concerning the remaining service life of existing roads with regard to fatigue cracking.

Methodology

The course of action has been to calculate fatigue life depending on the traffic-induced deterioration of the pavement. Deterioration of the pavement was predicted by studying the characteristics of the cores taken from existing pavement layers, chiefly the stiffness modulus and fatigue characteristics of road base layers, and by FWD measurements, as well as the actual temperatures encountered in the field. The FWD deflections were analyzed as indicators of the structural bearing capacity of the pavement in order to calculate critical strains in the bottom surface of the road base layer. Top-down cracking is not considered here.

A condition in this work for using the methodology is that the bituminous layers are not cracked; otherwise, it is not appropriate to measure stiffness modulus and fatigue properties of bituminous

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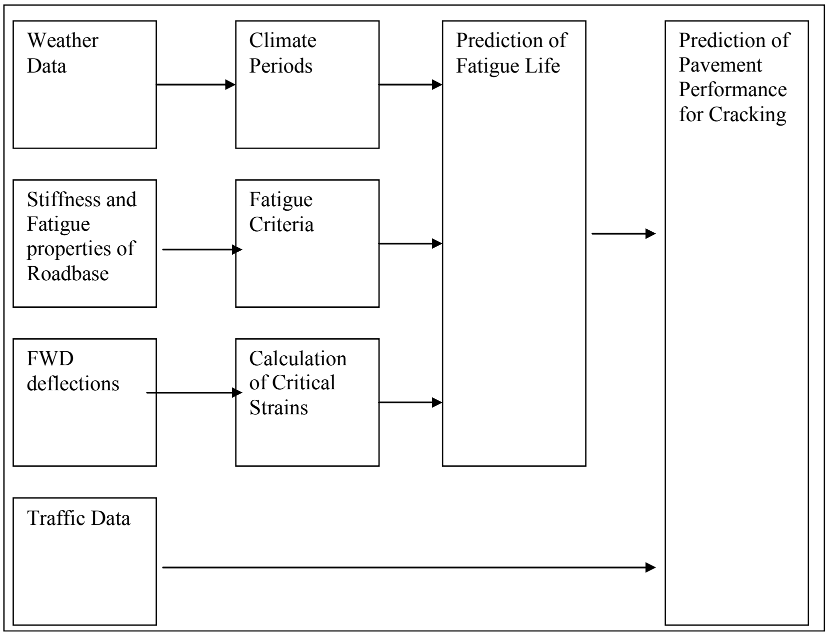

Fig. 1. Illustration of Performance Model.

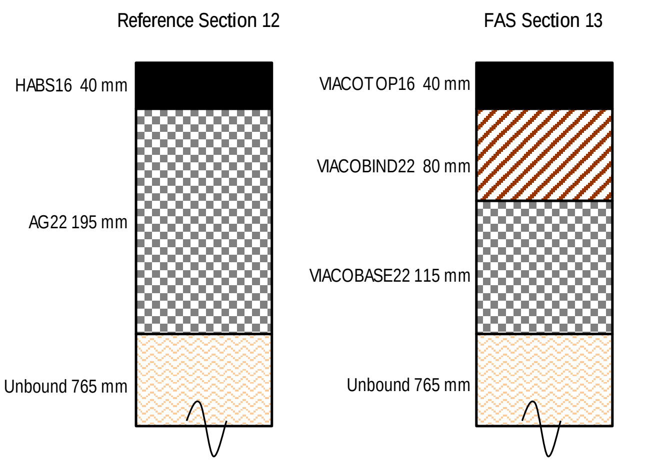

Fig. 2. Pavement Structures of the Reference Section and the FAS Road Sections on the E6 Motorway.

layers by testing cores. Since the road sections had been in service for 10 years, with a consequential obvious risk of cracking, the stiffness moduli and fatigue properties were studied in comparison with an area normally not used to traffic (area in-between wheel paths). The fatigue properties of the wearing and binder courses of the structures are not considered other than in respect of the effect of the layer thickness on crack propagation time (described later). The variations in temperature in the bitumen-bound road base layer over a year were calculated using temperature measurements made over a three-year period at a nearby weather station. Traffic counts are based on traffic monitoring performed close to the test road. As the purpose is to evaluate two bituminous structures on identical underlying layers, the effects of the unbound layers and the subgrade have not been taken into account other than when performing the FWD measurements. A further limitation is that the FWD measurements are performed only during the autumn. The effect of seasonal climatic variation on calculated strains was estimated based on the literature.

The plausibility of the fatigue life predictions was verified by means of comparisons with calculated fatigue lives using a reliable linear elastic model [2]. The methodology is illustrated in Fig. 1.

Full-scale Test Sections

Two full-scale test sections, each with a length of 200 m, were incorporated in the E6 motorway between Fastarp and Heberg. Except for the type of bituminous bound layer, these sections are similar in structure. The reference section (section 12) is one of the most common types of pavement structure in Sweden, i.e., gravel-bitumen pavement. In this case, it consists of a 40-mm conventional wearing course type SMA16 and a 195-mm layer of a typical road base mix called AG22 160-220. The FAS structure (section 13) has the same thickness as the reference section. However, all the bitumen-bound layers in the FAS structure are based on the idea of using a type of SMA mix called the VIACO concept, a trademark of the NCC construction company. The wearing course consists of a 40-mm SMA16 mix, called VIACOTOP. The binder layer consists of an 80-mm SMA mix called VICOBIND22 and a 115-mm SMA mix called VIACOBASE22. The unbound pavement layers of both sections are identical. The structures are illustrated in Fig. 2. The adopted road base thicknesses for the trial sections are somewhat thicker than the typical road base layer for a Swedish pavement. Traffic volume and climate at E6 motorway are described later.

Pavements Structures

The asphalt mixture recipes and the results from quality control of the bituminous layers during construction are reported by Ulmgren *et al.* [3]. Road base mix VIACOBASE22 pen 70/100 has a binder content of 5% and an air void content of 2%. Conventional road base mix AG22 pen 160/220 has a binder content of 4.2% and an air void content of 5.2%. A 0.8% additional binder content with only a 2% air void content should make the mix much more favorable in fatigue resistance in spite of using a slightly harder binder type in the VIACOBASE22 mix. It is worth noting that an increasing fatigue life should not be pursued at the cost of a higher rut potential. However, rutting is not the objective of this work. The FAS structure has a binder layer made of bitumen of pen 70/100 with 10% Uintaite® (natural bitumen) of bitumen weight. This can be compared with the upper part of the road base of the reference structure, which is conventional AG22 mix with binder type of pen 160/220. Using a stiff binder layer should give rise to better load distribution in the structure and therefore lower stresses in the pavement. The aggregate type is quartzite with 100% crushed aggregate. Further details can be found in references [3] and [4].

Stiffness Modulus of Base Course Layers

A number of cores with a diameter of 100 mm were drilled from road base layers in 2006 for laboratory measurements. Chiefly stiffness modulus and fatigue properties were determined at various temperatures using the Indirect Tensile Test (ITT) according to the Swedish Standard FAS Method 454. Five specimens from the lower part of each road base layers were used to determine the stiffness modulus at three temperatures (2°C, 10°C, and 15°C). Eqs. (1) and (2) are relationships between stiffness moduli of road base mixes and temperature [4], which are needed to predict fatigue life at various climates. The correlation coefficient (R^2) of the road base mix for the reference section is only 0.75, which is normal for this mix [5]. This has an influence on the accuracy of predicting fatigue life. Preferably more specimens should have been tested.

$$E_{AG} = 17780 \cdot e^{(-0,054 \cdot T)} \quad (R^2=0.75) \qquad (1)$$

$$E_{VIA} = 16720 \cdot e^{(-0,069 \cdot T)} \quad (R^2=0.90) \qquad (2)$$

where,
T = asphalt concrete temperature in °C,
E_{AG} = stiffness modulus of road base mix AG22 in MPa, and
E_{VIA} = stiffness modulus of road base mix VIACOBASE22 in MPa.

Fatigue Characteristics

Eqs. (3) and (4) are fatigue relationships based on fatigue testing about 40 specimens per mix at different temperatures for road base mixes AG22 and VIACOBASE22. Fatigue tests were performed using the ITT according to EN 12697-24 Annex E. The fatigue relationships were determined by testing cores after testing that there was no risk that fatigue cracks were present in the pavement [4]. The relationships can then be used to calculate fatigue life during various climate periods. It is worth indicating that the AG22 mix with the poorer E_{AG}-T correlation [Eq. (1)] was shown to have better correlation coefficient (R2 = 0.9) on fatigue life prediction [Eq. (3)] than that for the VIACOBASE22 [Eq.(4)]. This confirms the earlier conclusion that more than five specimens should have been tested for stiffness measurements, which might have effect on the fatigue life estimation.

$$N_f = 2.21 \cdot 10^{19} \cdot \varepsilon^{-4.28} \cdot E_{AG}{}^{-1.343} \quad R^2=0.90 \qquad (3)$$

$$N_f = 7.52 \cdot 10^{17} \cdot \varepsilon^{-3.18} \cdot E_{VIA}{}^{-1.423} \quad R^2=0.85 \qquad (4)$$

where,
N_f= the number of load applications to failure,
E_{AG} = stiffness modulus of roadbase mix AG22 in MPa,
E_{VIA} = stiffness modulus of roadbase mix VIACOBASE22 in MPa, and
ε = the tensile strain in μm/m.

Shift Factor

Laboratory-determined fatigue life normally underestimates the fatigue life of asphalt concrete layers in the field [6-8]. This is due to the fact that the laboratory tests do not simulate the actual field conditions in respect of crack propagation time, effect of frequency of loading pulses, loading mode, ageing, and healing effects. To overcome the uncertainty in the estimation of pavement performance, the investigators used an adjustment factor, called a shift factor, when predicting pavement performance from laboratory-based fatigue criteria. Suggested values for shift factors are normally between 20 and 100 [6], depending on test conditions. The shift factor for typical Swedish pavement structures using the Indirect Tensile Test to characterize bituminous mixes was reported to be 10 [5]. This is based on laboratory-determined fatigue criteria at 10°C on core samples from a number of road sections. Testing at 10°C is supposed to be standard temperature for evaluation of fatigue cracking in respect of Swedish climate. The laboratory fatigue criterion was then calibrated against the field criterion based on deterioration of the road sections, strain from FWD measurements, and traffic counting [5]. The total thickness of the bitumen-bound layers (consisting of road base and wearing course) included in the study was on average about 100 mm. It is logical that the thickness of a pavement's bituminous layers, in addition to the fatigue properties of a mix, has a crucial effect on the propagation time of cracks from the bottom to the surface of the bituminous layers. In this work, the total thickness of the bituminous layers is 235 mm, thus the shift factor needs to be adjusted in respect to the structure. A theoretical calculation of fatigue life was made in respect of change in thickness of pavement according to the Swedish code [2, 9] using the general road base fatigue relationship for the conventional road base mix, Eq. (5). This formula [Eq. (5)] was arranged conducting the same standard methods mentioned earlier, namely the FAS Method 454 for stiffness modulus and EN 12697-24 Annex E for fatigue cracking. Fig. 3 illustrates the effect of asphalt layer thickness on the calculated fatigue life of the pavement. The fatigue life is increased by a factor (called Thickness Factor – TFt) of 28 when the thickness of the road base mix layer is changed from 100 mm to 235 mm.

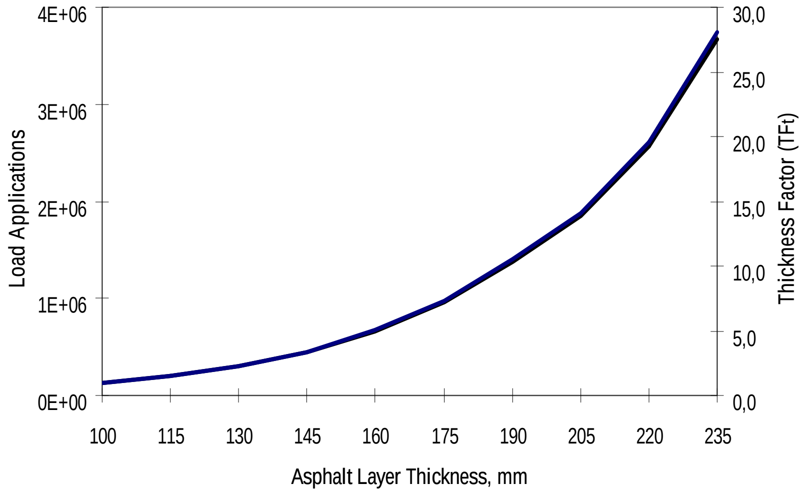

Fig. 3. The Influence of Asphalt Layer Thickness on Fatigue Life.

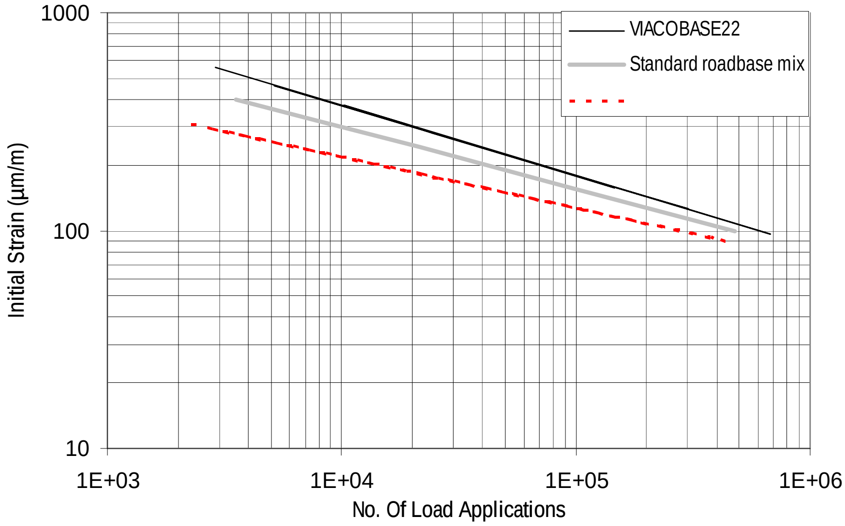

Fig. 4. Fatigue Relationships at 10°C.

$$N_f = 4.37 \cdot 10^{21} \cdot \varepsilon^{-3.53} \cdot E_{C-AG}{}^{-2.28} \quad (5)$$

where,

N_f = the number of load applications to failure,

$E_{C\text{-}AG}$ = stiffness modulus of the conventional roadbase mix in MPa, and

ε = the tensile strain in µm/m.

Another parameter that should have an effect on the shift factor is the slope of the fatigue relationship related to mix properties. Fig. 4 illustrates fatigue relationships at 10°C using Eqs. (3), (4), and (5). The slopes (n) of the relationships are 4.28 and 3.18 for the AG22 and the VIACOBASE22 mixes, respectively. However, the slope for the general road base fatigue relationship, Eq. (5), is 3.53. This indicates the higher sensitivity of the AG22 mix compared to the general fatigue relationship for the strain level. The VIACOBASE22 mix is less sensitive than the general fatigue relationship to the strain level. A ratio of the slope of a fatigue relationship of a mix to the slope of the general road base mix was used to adjust the shift factor in respect of mix resistance to fatigue cracking. Eq. (6) was used to determine the shift factor in respect to asphalt layer thickness and the fatigue properties of a mix. Using Eq. (6) will result in a shift factor of 46 and 34, respectively, for the pavement structures with the AG22 and the VIACOBASE22 mixes in this study. The pavement performance prediction for cracking is then estimated by means of Eq. (7). However, it is worth noting that the drawback of Eq. (7) is that the influence of the fatigue properties of other mixes (i.e., VIACOBIND22, VIACOTP16, and SMA16) rather than road base mixes are ignored. Further investigations would be useful for determining the correlation between laboratory and field criteria, preferably based on fracture mechanics [10].

$$SF = (SF_{100} + TF_t) \cdot \frac{n}{n_s} \quad (6)$$

$$N_{f(field)} = N_{f(lab)} \cdot SF \quad (7)$$

where,
SF = calculated shift factor,
TF_t = thickness factor (=28 when t=235 mm),
SF_{100} = shift factor for a structure with 100 mm thick bituminous layers (SF100 =10),
n = slope of the fatigue relationship of a mix,
n_s = slope of the fatigue relationship of the standard mix,
$N_{f\,(field)}$ = predicted in-situ fatigue life in ESALs, and
$N_{f\,(lab)}$ = measured fatigue life in the laboratory.

Determination of Temperature Periods

Regarding the climate conditions, the geographical location of the road section and the placement of the bituminous layer in the structure could be determining factors for the fatigue cracking of an asphalt layer and deterioration of a pavement [11]. Temperature measurements between 2003 and 2006 from a weather station (VViS1336) close to the road sections were therefore analyzed. Air and wear surface temperature data, at a frequency of 1 measurement per hour, were used in this work. Fig. 5a illustrates an example of temperature measurements for September 2005 to June 2006.
Hermansson's model [11] has been used to calculate temperature at the mid-depth of the road base layer, i.e., 177 mm from the pavement surface. Fig. 5b illustrates the average temperature distribution in the road base layer based on three years of measurements. This results in 10 periods of 5°C intervals. Shorter temperature intervals, for example 2.5°C, would be more appropriate and further investigation will be useful for determining the best interval.

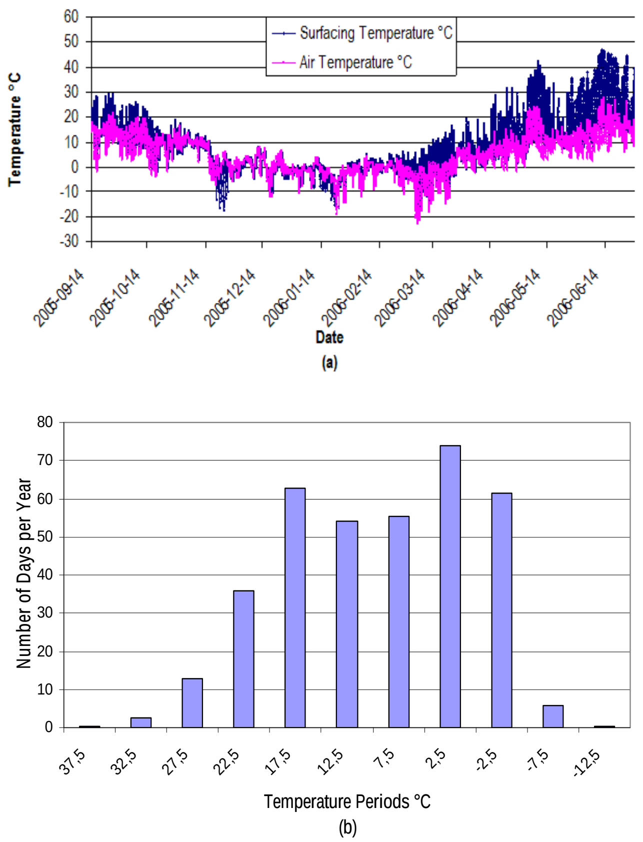

Fig. 5. Temperature Data: (a) Measurements from 2005 to 2006 and (b) Average Temperature Distribution in Road base Per Year.

Evaluation of Fatigue Life

Traffic Load Consideration

For an existing road, it is crucial for pavement performance evaluation to consider actual loads with respect to climatic conditions. Traffic-induced loading in the pavement is affected by such factors as axle load, wheel configuration, tire pressure, lateral traffic distribution, and traffic speed. In addition to this, the influence of traffic loading must be considered with climatic variations. To simplify the influence of traffic load, a standard load of 100 kN for axle load has been used according to the Swedish code [9]. To estimate traffic volume, the vehicle load is converted to a particular axle load (100 kN) called equivalent standard axle load (ESAL) using an equivalent axle load factor (*B*) that is the number of standard axles per heavy vehicle. The total number of ESALs is calculated using Eq. (8) according to the Swedish code [9], which is described by Winnerholt [2]. The most critical factor when evaluating ESALs is *B*. The default value has been set to 1.3 [2].

$$ESAL = AADT_l \cdot 3.65 \cdot A \cdot B \cdot \left(1+\frac{100}{k}\right) \cdot \left(\left(1+\frac{k}{100}\right)^n - 1\right) \tag{8}$$

where,
$ESAL$ = Equivalent Standard Axle Load,
$AADT_l$ = Average Annual Daily Traffic per lane,
A = heavy vehicle as a percentage of $AADT_l$,
B = equivalent axle load factor,
k = traffic growth per year in percent, and
n = design life in years.

Traffic has been monitored in-situ since 1996 [12]. The measured traffic data was converted to 100 N ESAL using Eq. (8). The forecast development in accumulated ESALs was calculated using the growth factor (*k*). The predicted traffic is used later in the prediction of remaining life for comparison with the estimated design life of each structure.

Critical Strains

Usually, two pavement-critical strains are considered when evaluating a pavement structure: the tensile strain at the bottom of the bituminous layer and the compressive strain at the top of the subgrade. This work is limited to forecasting critical strain at the bottom of the bituminous layer in view of the fact that the purpose of this work is to evaluate fatigue life with regard to cracking. Limiting the evaluation in respect of critical strain is partially due to the fact that the adopted structures in this work are assumed to have very good bearing capacity based on Swedish practice and partially the fact that the unbound layers and the subgrade are intended to be identical for both structures. Only critical strain in the bottom surface is thus needed to predict the remaining fatigue life of the pavement structures related to repeated traffic loading. The critical strain at the bottom of the bituminous layer at a specific axle load can be deduced from FWD deflections at actual climatic conditions in the field. The critical strain is needed for the prediction of fatigue life described later and used in Eqs. (3), (4), and (15).

FWD (Falling Weight Deflectometer) Measurements

In order to determine the relationships between strain and temperature for each of the structures, the FWD measurements were

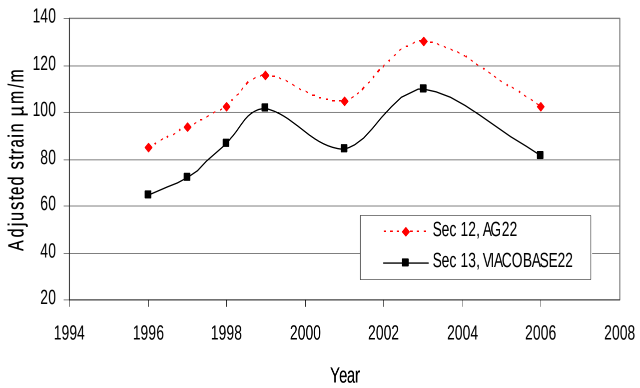

Fig. 6. Adjusted Strains for Reference Temperature 10°C.

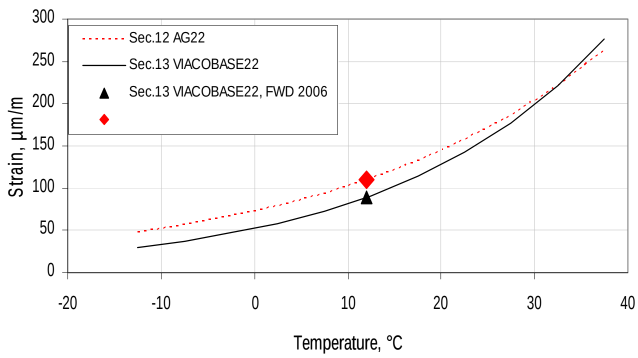

Fig. 7. Correlations between Adjusted Strains and Temperatures Based on FWD Measurements.

planned to be performed during various climatic periods. Unfortunately, due to a limited budget, the FWD measurements could only be performed during the autumn season [12]. The FWD measurements were performed using KUAB 50 kN FWD equipment, corresponding to a standard axle load of 100 kN. The measurements were made in the right wheel path, with 18 measurements per test section. Deflection measurements were adjusted to 10°C, the reference temperature normally used in Sweden. APLCAP algorithms [13] were used for adjustment of strains in respect of temperature. Due to the lack of FWD data at a wide range of field temperatures, relationships between stiffness moduli and temperatures were determined based on stiffness modulus (E_{ac}) measurements in the laboratory on cores at various temperatures (T) and expressed as in Eq. (9) [13]:

$$\text{Log}\,(E_{ac}) = a - b*T \tag{9}$$

Eqs. (1) and (2) are rewritten as Eqs. (10) and (11) for the road base mixes used in the structures.

$$\text{Log}\,(E_{AG}) = 4.250 - 0.0233*T \tag{10}$$

$$\text{Log}\,(E_{VIA}) = 4.223 - 0.0300*T \tag{11}$$

where,
T = asphalt concrete temperature in °C,
E_{AG} = stiffness modulus of roadbase mix AG22 in MPa,
E_{VIA} = stiffness modulus of roadbase mix VIACOBASE22 in MPa, and
a and b = constants related to the properties of asphalt concrete mixes.

The b value is used in Eq. (12) for calculation of correction factor (α) for adjustment of strain (ε) in pavement to a reference temperature of 10°C according to APLCAP [13]. The adjusted strain value for the reference temperature is calculated by Eq. (13).

$$\alpha = 10^{-0.6411*b*(T_r - T_m)} \tag{12}$$

$$Adjusted\varepsilon = \frac{Measured\varepsilon}{\alpha} \tag{13}$$

where,
T_r = reference temperature of 10°C, and
T_m = measured asphalt concrete layer temperature in °C.

Eq. (14) that is according to the Swedish Road Administration (SRA) Standard Method VV 114:2000 [14] was used to calculate the strains in the bottom surface of the bituminous layers. Jansson [15] developed the relationship [Eq. (14)] based on calculations of surface deflections and horizontal strain in the asphalt layer using a CHEVRON program. Pavement structures with various layer thicknesses and stiffness moduli were simulated. Eq. (14), based on multiple linear regression, has been found to be reliable with R2 = 0.93 for pavements with asphalt layer thicknesses larger than 75 mm [15].

$$\varepsilon = 37.4 + (988 \cdot D_0 - 533 \cdot D_{300} - 502 \cdot D_{600})/1000 \tag{14}$$

where,
ε = the tensile strain at the bottom of a bituminous layer in µm/m, and
D_0, D_{300} and D_{600} = deflections in mm at 0, 300, and 600 mm from the center of the loading plate in µm.

Strains were calculated using Eq. (14) from FWD data at mid-depth pavement temperatures. Fig. 6 illustrates calculated strains after adjustment, using Eq. (13), for the reference temperature (10°C). Decreasing strain in 2001 and 2006 is unlikely. This may be due to variation in climate such as differences in underground water levels that are not known or shortcomings in the adjustment procedure. It is possible that the strain levels do not increase after the initial period, which is a good indication that no damage has occurred in the pavements. Based on best practice, the strain levels in both structures are far lower than critical strain level [12]. The laboratory results that show no damage has occurred in the structures are also confirmed.

As a consequence of only being able to perform FWD measurements during the autumn (in practice at only one temperature), the strains during different climatic periods for both structures have to be estimated. Strains at various temperatures were calculated using Eqs. (12) and (13) based on adjusted strain at 10°C. The correlation between calculated adjusted strains and temperature is illustrated in Fig. 7 for both structures. The conventional structure (with AG22 road base mix) shows higher strains than the FAS structure (with VIACOBASE22 road base mix) except at elevated temperatures.

Prediction of Fatigue Cracking

In order to specify the differences between the FAS and the conventional structure's remaining life, the fatigue life was predicted with regard to damage caused by traffic loading. Fatigue life was predicted using fatigue criteria Eqs. (3) and (4) for conventional and FAS structures, respectively, during each climate period. Input data to determine fatigue life of pavement are given in Table 1 and described below.

The temperature of each period represents the temperature at the mid-depth of the road base layer. The number of days in each period was calculated as described earlier.

Stiffness moduli of the road base layers in each temperature period are predicted based on reported laboratory measurements on cores using Eqs. (1) and (2).

The tensile strains in the bottom surface of the bituminous road base layers during various temperature periods were estimated from the FWD measurements described earlier.

Prediction of fatigue life, fatigue criteria in Eqs. (3) and (4), were used to calculate damage per passage in each temperature period. Input data are adjusted strains from FWD measurements and stiffness moduli of road base mix described earlier. The fatigue damage at critical strain, corresponding to standard load, was calculated for each temperature period and the sum was reported using Miner's law.

As mentioned above, the laboratory-determined fatigue life underestimates fatigue life in the field. A shift factor is used to overcome the uncertainty in the prediction of pavement performance. The shift factors for the AG22 and the VIACOBASE22 structures were calculated to be 46 and 34, respectively. For the pavement performance prediction, the fatigue life is multiplied by the shift factor to estimate the remaining life of the pavement in respect of cracking using Eq. (7). Table 1 shows that the predicted number of 100 kN ESAL repetitions to failure after 10 years in service for conventional mix AG22 is 8.4 million repetitions and for the VIACOBASE22 mix is 52.4 million repetitions.

It is evident from Table 1 that the FAS structure (VIACOBASE22) shows a remaining fatigue life that is approximately 6 times longer than the remaining life of the conventional structure (AG22). The effect of appropriate mix and pavement design is unavoidable in this evaluation. The road base mix VIACOBASE22 used in the FAS structure has a lower void content and higher binder content than the conventional mix AG22. This change in mix design should have given rise to a longer fatigue life [16]. Using a binder course with high stiffness, as in the FAS structure, should have given better load distribution and in turn resulted in lower critical strains at the bottom of the road base layer. These conclusions are confirmed from the laboratory results and the FWD measurements, where the VIACOBASE22 mix shows better resistance to repeated loading than the AG22 mix in the laboratory tests, and the FAS structure shows significantly lower critical strains than the conventional structure.

The above methodology for prediction of fatigue life of a flexible pavement, based on laboratory measurement of the characteristics of the asphalt concrete mixes, has been verified by the fatigue cracking model, Eq. (15), used in the Swedish code for estimation of fatigue life of flexible pavements [2]. This model is based only on temperature and strain in the pavement but has proven to be reliable for practical use [2]. The predicted number of 100 kN ESAL repetitions to failure after 10 years in service for the structure with conventional mix AG22 is 18.8 million repetitions, and for the FAS structure with VIACOBASE22 mix is 62 million repetitions, marked as theoretical values in Table 1. The difference in the predictions of fatigue life is remarkable for the conventional structure. However, using a bearing capacity factor (fs) less than 1 (1 is for new construction) should result in better agreement between the fatigue lives calculated using the different methods.

Table 1. Prediction of Pavement Performance for Cracking.

T	Climate period	AG22				VIACOBASE22			
°C	Days/Year	E_{AG} MPa	ε µm/m	$N_{f(field)}\times10^6$ Laboratory	$N_{f(field)}\times10^6$ Theoretically	E_{VIA} MPa	ε µm/m	$N_{f(field)}\times10^6$ Laboratory	$N_{f(field)}\times10^6$ Theoretically
-12.5	0.2	34796	47			39660	30		
-7.5	5.8	26602	56			28074	38		
-2.5	61.4	20338	66			19873	47		
2.5	73.8	15549	79			14067	59		
7.5	55.3	11888	94	8.4	18.8	9958	73	52.4	62.0
12.5	54.2	9088	111			7049	91		
17.5	62.8	6948	132			4990	114		
22.5	35.7	5312	157			3532	142		
27.5	12.8	4061	186			2500	177		
32.5	2.7	3105	221			1770	221		
37.5	0.4	2374	263			1253	276		

$N_{f(field)}$ is number of equivalent single-axle loads (ESAL).

The FAS structure shows a remaining fatigue life which is about three times longer than the remaining life of the conventional structure, which is a smaller difference compared to the methodology based on characteristics of asphalt mixes. Otherwise, the result of the laboratory-based evaluation, i.e., that the FAS structure shows significantly longer fatigue life, is verified. The laboratory procedure based on asphalt mix properties can thus be useful for evaluating the impact of a mix on pavement performance.

$$N_{bb,i} = f_s \frac{2.37 \cdot 10^{-12} \cdot 1.16^{(1.8 \cdot T_i + 32)}}{\varepsilon_{bb,i}^4} \tag{15}$$

where,
$N_{bb,i}$ = allowable numbers of standard axles for the bitumen-bound, road base during climatic period *i,*
f_s = bearing capacity factor = 1 (1 is for new construction),
T = pavement temperature in °C, and
$\varepsilon_{bb,i}$ = strain calculated at the bottom of the bitumen-bound road base.

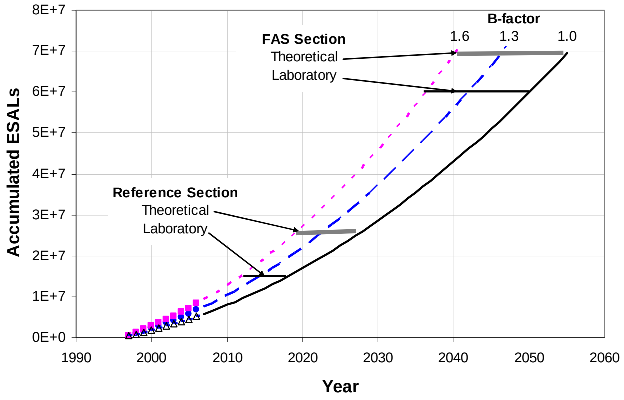

Fig. 8. Predicted Accumulated Equivalent Standard Axle Loads (100 kN ESAL) with Predicted Remaining Life for the Conventional and the FAS Structures at Different Equivalent Axle Load Factors (B-factor).

Remaining Life Prediction

Fig. 8 illustrates the accumulated 100 kN ESALs based on the traffic monitoring between 1996 and 2006, which was discussed earlier. The forecast for development of the accumulated ESALs is also presented in the figure. The prediction of ESAL is strongly related to the equivalent axle load factor (B-factor). In this work, the accumulated ESALs have been shown with three different assumed values for the B-factor, due to the uncertainty when estimating it [2]. The effect of uncertainty in the growth factor is ignored here. Based on laboratory measurements, Fig. 8 shows that the conventional structure is predicted to withstand the traffic loading until between 2013 and 2018, and the FAS structure should withstand traffic loading until some time between 2035 and 2050, depending on the equivalent axle load factor. However, the reliable model (marked theoretical in Fig. 8) shows that the conventional structure should withstand traffic loading until between 2019 and 2027 and the FAS structure until between 2041 and 2055.

In practice, this could mean that the road base layer in the FAS structure will never crack from repeated loading and can thus be classified as "long life pavement."

Conclusions

It is concluded that the road base mix VIACOBASE22 using the SMA principle shows better fatigue resistance than the conventional AG22 mix. The FAS concept, which implies that material with good mechanical characteristics is chosen and that the stresses and strains on the structure are dimensioned, has shown considerably better pavement performance than the conventional structure in respect of fatigue cracking. It is calculated that the number of years to failure for the FAS structure will be more than twice as long (in years) as for the conventional structure.

A procedure is presented for the prediction of the remaining fatigue life of flexible pavements using laboratory tests and field measurements. The performance model (methodology) for fatigue cracking is based on the stiffness and fatigue properties of mixes determined on samples from existing pavement, the critical strains that occur in various climatic conditions in the field, and the predicted traffic loading. The procedure has proven to be effective in the evaluation of the impact of a mix on pavement performance with regard to fatigue cracking. The procedure gives an overall evaluation of a bituminous mix in a pavement and in turn the connection between mix and pavement design.

A procedure for predicting the remaining life of flexible pavements with regard to fatigue cracking is also presented in this work based on characteristics of pavement materials and structural condition with regard to in-situ conditions. Therefore this procedure is valuable for performance-based contract for evaluation of the rest value (remaining life) at the end of the contract period. In addition, the evaluation based on asphalt mix properties is verified through a reliable prediction model with a reasonable conclusion. However, validation of the procedure with actual fatigue cracking of the pavement would be valuable. Further analytical investigation would be useful for studying crack propagation in pavement.

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