FLEXIBLE PAVEMENT WITH SMA AS AN ANTI-FATIGUE LAYER

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Abstract

Asphalt Pavement Alliance has defined the perpetual pavement as ″an asphalt pavement designed and built to last longer than 50 years without requiring major structural rehabilitation or reconstruction and needing only periodic surface renewal…″. The perpetual pavement design approach assumes that one can design against certain types of failure or distress by choosing the right materials and layer thicknesses. This can be achieved by providing enough stiffness in the upper pavement layers to preclude rutting and enough total pavement thickness and flexibility in the lowest layer to avoid fatigue cracking from the bottom of the pavement structure. One way to reduce the bottom up fatigue cracking in pavement structure is to add an additional anti-fatigue layer to standard asphalt layers. This layer can be an extra layer that increases the total asphalt layers thickness, or it can be layer separated from the standard asphalt base layer by reducing its thickness. The presented research aimed to evaluate the suitability of application, Croatia traditionally used asphalt mixtures within the concept of perpetual pavements. Among traditional asphalt mixtures, the stone mastic asphalt was selected as a mixture for the anti-fatigue layer. The analysis was carried out for proposed perpetual pavements of different thicknesses and/or position of stone mastic asphalt anti-fatigue layer. Calculation of pavement layers stresses and strains was done in CIRCLY software, taking into account the seasonal variations in asphalt layers properties. The analyses have shown that the addition of stone mastic asphalt layer as an anti-fatigue layer can extend flexible pavement design life.

Keywords: flexible pavement, anti-fatigue layer, stone mastic asphalt, fatigue life, horizontal tensile strain

1 Introduction

In recent decades, we are facing accelerated pavement deterioration due to increasing axle loads, increase in heavy vehicles and age of existing pavements. Accelerated pavement deterioration leads to frequent rehabilitation, which increases pavement cost, reduces level of road service, is impractical and inefficient. Therefore, from a life cycle cost perspective, longer pavement service life is of great interest [1]. The traditional approach to pavement design is based on empirical methods in which a greater number of heavy vehicles results in a greater pavement thickness [2, 3]. While it is undeniable that pavement thickness plays an important role in bearing the load, it does not necessarily follow that insufficient thickness is the underlying cause of pavement damage. In addition to insufficient thickness, pavement damage can also be due to environmental conditions, material properties, or construction errors [1]. Understanding the pavement's response to traffic loading and the potential causes of damage and distress mechanisms is the basis for developing a perpetual pavement design.

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The perpetual pavement design is based on mechanistic-empirical concepts. The basic idea is that pavement failure can be avoided if the pavement responses under load are kept below the respective thresholds values [1, 4]. Currently, most approaches to the perpetual pavement design focus on limiting pavement responses associated to structural rutting and bottom-up fatigue cracking. The vertical compressive strain on the top of the subgrade should be limited to 200 με [2, 4, 5] to prevent pavement failure due to structural rutting. This is achieved by proper pavement foundation design and construction [1]. To prevent pavement damage due to fatigue cracking, the value of horizontal tensile strain at the bottom of asphalt layers must be limited. Although the hypothesized value of 70 με has been used in perpetual pavement design for several years [4, 5], the literature review has not revealed a consistent value for this limit. Most researchers refer to a range between 60 and 100 (150) με (microstrain) depending on the mix type [1, 5, 6]. This can be achieved by choosing the right asphalt mixture and the thickness of the asphalt layers, taking into account that each layer has a specific function. In perpetual pavement, three asphalt layers are combined: a rut-resistant, impermeable, and wear-resistant surface layer, a rut-resistant and durable intermediate layer, and a fatigue-resistant and durable bottom layer, i.e., an anti-fatigue layer [7, 8]. Compared to the traditional flexible pavement, the main difference in the composition of the layers is the addition of the anti-fatigue layer. Thesphaltt mixture for the anti-fatigue layer has a higher asphalt content, which allows the material to be compacted to a higher density and provides the necessary flexibility to prevent the formation and growth of bottom-up fatigue cracks [1]. The anti-fatigue layer can be introduced to the traditional flexible pavement as a layer separate from the standard asphalt base layer by reducing its thickness. It can also be an additional layer that increases the overall thickness of the pavement [9].
Although many positive examples prove the benefits of introducing an anti-fatigue layer, this layer is not used in Croatia. This can be attributed to the higher initial construction costs and resistance to the introduction of new materials and methods. Therefore, the purpose of this paper is to investigate the possibility of introducing an anti-fatigue layer into the pavement design methods and asphalt mixtures traditionally used in Croatia.

2 Research methodology

In order to evaluate the suitability of asphalt mixtures and design methods traditionally used in Croatia within the concept of perpetual pavements, a reference pavement was designed in accordance with the HRN U.C4.012 standard [10] and the technical requirements for asphalt pavements [11]. The reference pavement (RP) was designed for a traffic load of $2.5*10^6$ ESAL (equivalent standard axle load), a design period of 20 years and a California Bearing Capacity (CBR) of the subgrade of 15 %. The anti-fatigue layer was added to the reference pavement as an additional layer (AF1) and by reducing the thickness of the base layer (AF2) (Fig. 1).

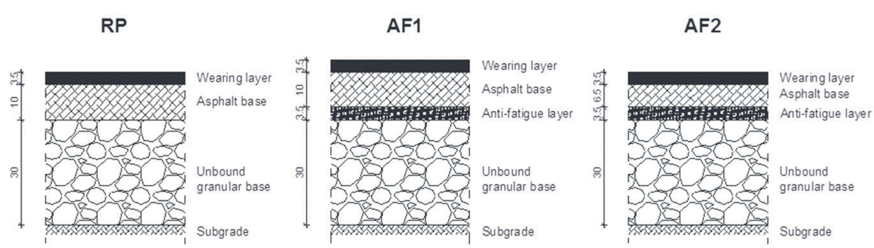

Figure 1 Analysed pavement structures composition and layers thickness

Among the asphalt mixtures traditionally used in Croatia, stone mastic asphalt (SMA) with a relatively high bitumen content and a lower air void content meets the requirements for anti-fatigue asphalt mixtures. The thickness of the anti-fatigue layer for SMA 11 surf 45/80-55 was chosen in accordance with [11].

2.1 Material characteristics

The material characteristics of each layer are taken into account through their elastic properties, i.e. modulus and Poisson's ratio. For the subgrade, a CBR value of 15 % was assumed and the modulus is determined according to the empirical relationship 10*CBR, so a modulus value of 150 MPa was adopted. The Poisson's ratio of 0.35 representative of non-cohesive materials, was used. Regular standard crushed stone with a corresponding presumptive modulus value of 500 MPa and Poisson's ratio of 0.35 was chosen as the material for the unbound granular base layer. The asphalt mixture AC 22 base 50/70 was selected for the base and SMA 11 surf 45/80-55 for the wearing and anti-fatigue layer. The properties of asphalt mixture, i.e. bitumen content, air voids, modulus and Poisson's ratio in relation to seasonal variations, were taken from [12]. The properties of the asphalt mixtures are listed in Table 1.

Table 1 Asphalt mixtures properties

Layer	Asphalt mixture	Bitumen content [% v/v]	Air voids [% v/v]	Modulus [MPa]/Poisson's ratio		
				winter	spring-autumn	summer
wearing	SMA 11 surf 45/80-55	14.6	4.2	15940/ 0.31	5163/ 0.45	1238 / 0.49
base	AC 22 base 50/70	8.3	6.2	27014 / 0.31	10307 / 0.45	2462 / 0.49
anti-fatigue	SMA 11 surf 45/80-55	14.6	4.2	15940 / 0.31	5890 / 0.45	1451 / 0.49

2.2 Pavement analysis

To determine the allowable number of load repetitions and the cumulative damage factor, a pavement analysis was performed using CIRCLY 7.0. The pavement load was assumed to be a single axle load of 80 kN with dual tyres and a vertical static wheel load of 20 kN distributed uniformly over a circular area with a pressure of 800 kPa.

In the pavement with an anti-fatigue layer, the fatigue cracks may occur at the bottom of anti-fatigue layer or at the bottom of the asphalt base [9]. Therefore, stresses and strains were calculated at the bottom of the asphalt base and anti-fatigue layer and at the top of the subgrade pavement, i.e. in the critical cross-sections (Fig. 2).

The allowable number of load repetitions was determined for two modes of pavement failure: fatigue cracking and structural rutting.

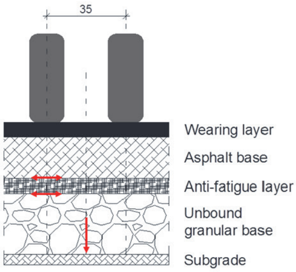

Figure 2 Pavement critical cross-section

The Shell asphalt fatigue criterion with a project reliability of 95 % was used to calculate the allowable number of load repetitions to fatigue failure, eqn. (1):

$$N_f = \left[\frac{6918\left(0.856 V_b + 1.08\right)}{E^{0.36} \mu\varepsilon} \right]^5 \tag{1}$$

where:
N_f – allowable number of load repetitions to fatigue failure,
V_b – volume percentage of bitumen (%),
E – asphalt modulus (MPa)
με – horizontal tensile strain at the bottom of asphalt layer (microstrain) [13].

The allowable number of load repetitions until structural rutting failure was calculated for the Shell rutting criterion according to eqn. (2):

$$N_d = 6.15 \cdot 10^{-7} \left(\varepsilon\right)^{-4} \tag{2}$$

where:
N_d – number of load repetitions to structural failure (rutting equal to 13 mm)
ε – vertical compressive strain at the top of the subgrade [14].

Pavement damage is traditionally defined as the ratio between the actual number of traffic load repetitions and the allowable number of load repetitions that a pavement structure can support. Since pavement material properties vary with the season, it was necessary to calculate the cumulative damage factor, as shown by eqn. (3):

$$D = \sum_{i=1}^{3} \frac{n_i}{N_i} \tag{3}$$

where:
D – cumulative damage factor,
n – actual number of load repetitions in pavement design period,
N – allowable number of load repetitions,
i – season (winter, spring-autumn, summer) [14].

The distribution of traffic load was assumed to be 15 % in winter (W), 50 % in spring-autumn (S-A), and 35 % in summer (S). The corresponding number of ESALs in the design period was $0.375 \cdot 10^6$ for winter, $1.25 \cdot 10^6$ for spring-autumn, and $0.875 \cdot 10^6$ for summer.

3 Results and discussion

The results of the pavement analyses in critical cross-sections are shown in Table 2. For all pavements, the lowest values of strains were obtained in winter and the highest in summer. For all seasons, the highest values of horizontal tensile strains at the bottom of the asphalt base were obtained for RP, and the highest values of vertical compressive strains were obtained for pavement AF2. The lowest values of horizontal tensile and vertical compressive strains were obtained for pavement AF1. This was to be expected since AF1 is the pavement with the largest thickness of the asphalt layers, i.e. with the largest total pavement thickness.

Table 2 Results of pavement analyses

Strain	**Horizontal tensile** [με]						**Vertical compressive** [με]		
Layer	**base**			**anti-fatigue**			**subgrade**		
Season	**W**	**S-A**	**S**	**W**	**S-A**	**S**	**W**	**S-A**	**S**
RP	49.08	86.83	186.00	/	/	/	159.10	221.10	309.30
AF1	26.10	49.93	127.10	43.58	77.60	162.20	125.70	180.40	266.80
AF2	30.83	59.04	152.30	61.29	106.40	211.00	172.70	235.00	317.80

None of the analysed pavements meet the requirements of the limits for horizontal tensile and vertical compressive strain set in perpetual pavement design. It can be concluded that a pavement designed in accordance with HRN U.C4.012 [10] cannot be classified as perpetual. The allowable number of load repetitions until fatigue failure at the bottom of the base and anti-fatigue layer, and until structural rutting failure at the top of the subgrade is given in Table 3.

Table 3 Allowable number of load repetitions

	Allowable number of load repetitions $*10^6$								
Layer	**base**			**anti-fatigue**			**subgrade**		
Season	**W**	**S-A**	**S**	**W**	**S-A**	**S**	**W**	**S-A**	**S**
RP	21.59	7.05	2.06	/	/	/	959.83	257.35	67.20
AF1	507.68	112.19	13.80	1267.03	424.95	132.68	2463.39	580.67	121.38
AF2	220.76	48.53	5.59	230.29	87.69	35.62	691.36	201.65	60.29

From the results, it can be concluded that for all pavements and seasons, pavement life is higher for structural rutting than for fatigue cracking (except for pavement AF1 in summer). The lowest value for the allowable number of load repetitions, i.e. the shortest pavement life, is obtained for the reference pavement and the asphalt base layer. The addition of the anti-fatigue layer resulted in a significant increase in the fatigue life of the asphalt base.
The cumulative damage factor is calculated for all analysed pavements in the critical cross-sections, and the results are shown in Fig. 3. The value of the cumulative damage factor is less than one for all the scenarios considered, indicating that the analysed pavements would exceed their design life.

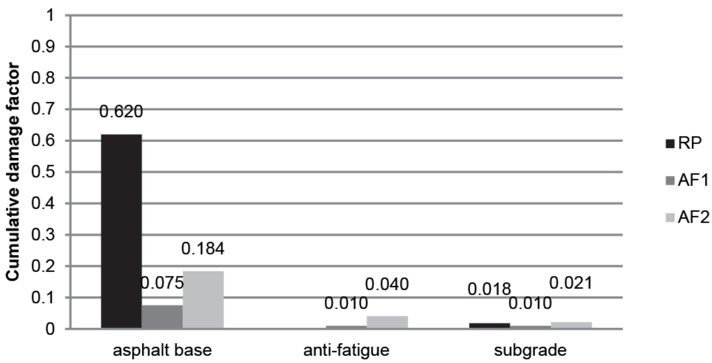

Figure 3 Cumulative damage factor in critical cross-sections

An additional asphalt layer of 3.5 cm has a positive effect on reducing pavement damage in all critical cross-sections. The addition of 3.5 cm resulted in an 87.9 % reduction in cumulative damage for the fatigue criteria and a 44.4 % reduction for the structural rutting criteria. The highest value of the cumulative damage factor according to fatigue criteria is obtained for RP and according to subgrade rutting criteria for AF2. The lowest value for both failure criteria is obtained for pavement AF1. Replacing 3.5 cm of the asphalt base with an anti-fatigue layer decreased fatigue cumulative damage factor for the base layer by 70.3 % and increased subgrade cumulative damage factor by 16.6 %.

4 Conclusions

The introduction of an anti-fatigue layer to traditional flexible pavement contributes to prolongation of pavement design life. Three pavement structures were analysed to investigate the possibility of using stone mastic asphalt (SMA) as a mixture for an anti-fatigue layer. A reference pavement (RP) was designed according to the Croatian regulations as well as two additional pavements with SMA as an anti-fatigue layer. The anti-fatigue layer was introduced as an additional layer by increasing the thickness of the RP by 3.5 cm (AF1), and as a separated layer from the asphalt base by reducing the thickness of base layer by 3.5 cm (AF2). The contribution of SMA as an anti-fatigue layer was evaluated in terms of fatigue cracking and structural rutting failure, based on the calculated strains, allowable number of load repetitions, and cumulative damage factor.
The values obtained for horizontal tensile strain at the bottom of the asphalt base and anti-fatigue layer, and for vertical compressive strain at the top of the subgrade, were higher than limiting pavement response values used in perpetual pavement design. For all pavements, the lowest value for the allowable number of load repetitions was obtained for fatigue failure at the bottom of the asphalt base. The shortest pavement life was obtained for RP and the longest for AF1. The addition of an anti-fatigue layer resulted in a significant increase in fatigue life for both AF1 and AF2 pavements. Based on the cumulative damage factor values, all pavements would exceed their design life. The lowest value of the cumulative damage factor for both failure criteria was obtained for pavement AF1. The highest value of the cumulative damage factor according to the fatigue criteria was obtained for RP and according to the structural rutting criteria for pavement AF2.

In relation to the obtained values of strains in the critical cross-section, it was concluded that the pavements designed according to the Croatian regulations cannot be classified as perpetual. The addition of SMA as an anti-fatigue layer resulted in a significant increase in the pavement design life according to the fatigue criteria. From the perspective of the pavement engineer, the use of SMA as an anti-fatigue layer is justified. However, for its application in practice, the economic viability of the proposed solution should be proven as well.

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