Simplified Methodology for Fatigue Analysis of Reinforced Asphalt Systems

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Abstract

Fatigue analysis has an important role in evaluating the durability and performance of asphalt pavements, especially when new or alternative materials are used. Numerous laboratory studies have investigated fatigue performance with the aim to estimate field behavior as closely as possible. Therefore, there are currently many different testing methods and data analysis approaches that can be used. One of the most common laboratory test methods is the four-point bending beam (4PBB) test, which results are usually analyzed using the so-called traditional approach (where 50% of stiffness reduction is considered as failure criterion) or the energy ratio (ER) approach. However, outcomes from previous studies have shown that these approaches may not be appropriate and reliable if geogrids are used as a reinforcement. As a possible solution, this study proposes a new Simplified Flex Point (SFP) approach that considers the flex point of the strain amplitude curve, measured during 4PBB fatigue tests, to calculate the number of cycles to failure. These three approaches were applied on four sets of double-layered asphalt samples: one unreinforced and three reinforced with geogrids of different strength (50, 100 and 200 kN). The impact of reinforcement on the fatigue life was evaluated by comparing the critical strain values ($\varepsilon_{6}$) of reinforced and unreinforced sets through fatigue resistance improvement factor (FRIF). The research findings showed that the use of geogrids improves fatigue life when the SFP and ER approaches are applied and that the traditional approach might not always be appropriate for assessing the fatigue resistance of reinforced asphalt mixtures.

1 Introduction

The first use of textiles in roads dates back to 1926, when a heavy cotton fabric was placed below asphalt layers, that led to improved cracking resistance, decreased localized road failures and reduced raveling [1]. Since then, geosynthetics (fabrics, composites, membranes, grids, etc.) have been widely utilized for different purposes within a road construction, namely: for separation, filtration, stiffening, drainage and reinforcement [2]. The use of geogrids for reinforcement of asphalt layers within pavement structure is likely the most recent application of geosynthetics that started since early 1980s, when geogrids were used to mitigate reflective cracking and to prolong fatigue life [3]. Since then, numerous investigations involving geosynthetics have been carried out in both the laboratory [3–9] and the field [10–12], concluding that they can successfully slow down reflective cracking propagation [13, 14] and improve fatigue [9, 15–17] and rutting resistance [4, 18], even though they may affect shear bond strength [4, 11]. The beneficial effects of geogrids on the pavement structure have also been assessed through the life cycle cost analysis (LCCA) [4]. The results showed that sections reinforced with geogrids can significantly reduce maintenance and construction costs during a 20-year service period when compared to the section without reinforcement. In another study it was further claimed that grid reinforcement has a potential to structurally reduce the required thickness of the asphalt layers [19].

There are several types of geogrids used for pavement reinforcement, where some of them are woven from glass fibers of polymeric filaments, whereas others can be cut or pressed from plastic sheets and then post tensioned to maximize strength and modulus [20]. Grids typically have square, hexagonal or rectangular open mesh shape, with opening from 6 to 50 mm, which ribs can be made of materials with different strength in two perpendicular directions. Fiberglass yarns used for production of geogrids can be coated with bitumen based or polymer-based coating (to protect them and to reach an effective bonding between asphalt layers). As interlayer system, a reinforcement can be in form of geogrid or also contain a layer of light or heavy non-woven fabric. They can be placed at different positions and depths within a pavement structure – below or between asphalt layers, when
aiming to reduce permanent deformation and/or differential settlement or to mitigate reflective and fatigue cracking [3]. In some cases, if the reinforcement is located at the interface of two asphalt layers, the use of a tack coat can be required to enhance their performance. This may cause construction delay because of a tack coat breaking time, or even compromise the grid efficiency [12, 21], therefore some of them can be self-adhesive or contain a thin layer of modified bitumen.

During recent years, many studies have been conducted to evaluate the impact of geogrids on pavement performance. Among the frequently utilized laboratory tests are: Three Point Bending Beam – 3PBB [11, 22, 23], Four Point Bending Beam – 4PBB [6, 15, 17, 24], ASTRA interface direct shear test [6, 11] and Overlay Tester - OT [14, 21]. The fact that some researchers had designed different types of testing configurations such as the shear-torque fatigue test [25] and anti-reflective cracking system [13, 26, 27] further illustrates how crucial it is to examine the impact of grids on pavement performance. However, one of the tests that has been employed most frequently in earlier studies is the 4PBB test, which accurately depicts the loading condition that would occur in the field under the impact of traffic and resulting tensile strains.

To better understand the mechanism of reinforcement in asphalt mixtures and to examine its impact on fatigue performance, a variety of testing samples for the 4PBB test have been used in previous studies. Only a small number of studies [24, 28] have been conducted using testing beams made of three asphalt layers with grids between them, below and above the neutral axis. Even fewer studies investigated samples made up from a single layer with a grid adhered to the sample’s bottom [7]. Most of testing samples typically consisted of two asphalt layers with a grid between them [3, 5, 6, 15, 29, 30], usually in the tension zone below the neutral axis, as suggested by Zofka et al. [3]. A more sophisticated approach has been used in other studies [8, 9, 17, 19], where notches of various dimensions were cut at the middle of the bottom sample's side to simulate the existence of cracks in the field. In one study [4] the grid was placed in the middle of the sample, i.e. in the neutral zone. Kumar and Saride [16] went further in simulating field conditions and produced testing samples with a lower layer of old asphalt that was excavated from the field on top of which was placed geogrid and a thicker layer of new asphalt in the laboratory.

The method by which the effectiveness of the grid will be assessed should be chosen after the testing method and the type of testing sample have been chosen, even though the officially accepted term for that lacks current usage. There are several terms that serve the similar purpose: Traffic Benefit Ratio – TBR [31], Effectiveness Benefit Ratio - EBR [21], Grid Efficiency Factors - GEF [4], Improvement Ratio - IR [30], Improvement Factor - IF [15], Interlayer Crack Performance Factor – PCPF [19] and Performance coefficient – \( k \) [10]. Each of them is based on the same principle, comparing the various properties of grid-reinforced asphalt mixtures/samples to those of unreinforced mixtures/samples (such as rutting, cracking, or fatigue resistance).

If fatigue resistance is selected as the performance based on which the effectiveness of the network is assessed, the methodology and established criteria used to analyze the test results can have a significant impact on the outcomes. There are several criterions described in the literature to accomplish that: stiffness reduction criterion (classical criterion of 50% [32] or even 90% reduction [33]), phase angle criterion [34] and dissipated energy criterions [35–37]. Similarly to the case of conventional (unreinforced) testing samples [38], the application of different criteria on the same dataset can result in even more varied fatigue laws when the asphalt samples incorporate a grid reinforcement [39]. In one study, it was even suggested that when grid reinforcement is utilized, a new analysis criterion of failure should be developed and used instead of the classical approach (50% stiffness reduction) [28]. To overcome the shortcomings due to the unreliable selection of the number of cycles to failure, Virgili et al. [30] used the Permanent Deformation Evolution Model – PDEM to define the permanent deformation
evolution of a specimen during a repeated load test, from which the number of loading cycles corresponding to the flex point of the curve was selected as the failure criterion. This approach is very reasonable, because it has been proven that the reduction of pavement deflections due to the geogrid application might lead to a significant extension of pavement fatigue life [3]. However, when geogrids are used as reinforcement, none of these criterions have yet been broadly adopted and standardized.

Consequently, the paper presents a newly developed approach for estimating the fatigue life of testing samples collected utilizing the 4PBB test. The developed methodology based on the flex point approach was investigated by testing four different double-layered sets. In addition to one unreinforced, tests were carried out on three sets reinforced with various geogrids. Fatigue lives of all sets were determined using the developed approach and then compared with the results obtained by using some of already existing criterions: 50% stiffness reduction (traditional approach) and energy ratio (considering reduced energy ratio, i.e. normalized stiffness modulus x number of repetitions [33]).

2 Materials and method

The experimental program included four sets of testing samples: a set of double-layered samples without reinforcement and three sets with different geogrids applied between two layers. The first research stage consisted of sampling the asphalt mixture directly from an asphalt plant's hot storage bin, compacting the slabs, and then cutting the slabs to produce testing samples (beams). Volumetric properties and fatigue resistance of all samples were determined in the second stage, whereas data analysis was performed in the third stage utilizing three alternative approaches. The remainder of this chapter provides information related to materials’ properties and applied methodology, while Fig. 1 summarizes the whole experimental plan.

2.1 Materials

2.1.1 Asphalt mixture

A typical asphalt mixture for surface layers (AC 11 surf) prepared with plain 50/70 penetration grade bitumen was selected for the experimental program. To minimize potential variability, the entire amount of material needed for the study was sampled on the same day from a single hot storage bin of an asphalt plant. Table 1 shows the components of asphalt mixtures along with their proportions, whereas Table 2 shows the physical-mechanical properties of the asphalt mixture.

<table>
<thead>
<tr>
<th>Material type</th>
<th>Amount [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Limestone filler</td>
<td>5.5</td>
</tr>
<tr>
<td>Limestone aggregate fraction 0/2 mm</td>
<td>27.6</td>
</tr>
<tr>
<td>Igneous aggregate fraction 2/4 mm</td>
<td>15.7</td>
</tr>
<tr>
<td>Igneous aggregate fraction 4/8 mm</td>
<td>25.6</td>
</tr>
<tr>
<td>Igneous aggregate fraction 8/11 mm</td>
<td>20.6</td>
</tr>
<tr>
<td>Bitumen BIT 50/70</td>
<td>5.0</td>
</tr>
</tbody>
</table>
### Table 2
Physical-mechanical properties of the asphalt mixtures.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Unit</th>
<th>Standard</th>
<th>Results</th>
<th>Criterion¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stability – S</td>
<td>kN</td>
<td>EN 12697-34</td>
<td>10.4</td>
<td>min 8</td>
</tr>
<tr>
<td>Flow – F</td>
<td>mm</td>
<td></td>
<td>3.5</td>
<td>-</td>
</tr>
<tr>
<td>Marshall quotient – S/F</td>
<td>kN/mm</td>
<td></td>
<td>3.0</td>
<td>min 2</td>
</tr>
<tr>
<td>Bulk density</td>
<td>Mg/m³</td>
<td>EN 12697-6</td>
<td>2.428</td>
<td>-</td>
</tr>
<tr>
<td>Maximum density</td>
<td>Mg/m³</td>
<td>EN 12697-5</td>
<td>2.558</td>
<td>-</td>
</tr>
<tr>
<td>Air void content</td>
<td>% [v/v]</td>
<td>EN 12697-8</td>
<td>5.1</td>
<td>4.5–5.5</td>
</tr>
<tr>
<td>Voids in mineral aggregated filled with binder</td>
<td>% [v/v]</td>
<td>EN 12697-8</td>
<td>69.9</td>
<td>66–78</td>
</tr>
<tr>
<td>Voids in mineral aggregate</td>
<td>% [v/v]</td>
<td>EN 12697-8</td>
<td>16.9</td>
<td>-</td>
</tr>
</tbody>
</table>

Note: ¹SRPS U.E4.014: Technical specifications for asphalt concrete pavements

### 2.1.2 Reinforcement

Three polymer-coated fiberglass geogrids (Fig. 3) with different longitudinal and transversal strengths (50 x 50, 100 x 100, and 100 x 200 kN/m coded as G1, G2 and G3, respectively), were used in this study. The mesh size of the first two geogrids was 25 x 25 mm, whereas the third one had an opening of 25 x 19 mm. Each grid had an adhesive layer on the bottom side, which secures the adhesion of the grid to the surface during installation and paving.

Bitumen emulsion KN-60 (cationic bitumen emulsion with 60% residual binder) was used as a tack coat in this study, even though manufacturer recommends the use of emulsion with minimum 65% residual binder. Regardless of whether the grid was used or not, 300 g/m² of the tack coat was applied between the upper and the lower AC layer.

### 2.2 Methods

#### 2.2.1 Samples’ preparation

After sampling the asphalt mixture from the asphalt plant, a 1-ton roller was used to compact twelve slabs (three per each set), with dimensions of 50 × 50 × 7 cm, in metal molds. Slab compaction was performed in two stages. In the first stage, the 3-cm thick bottom layer was compacted first and after the asphalt mixture had been cooled down, bitumen emulsion was applied and let to break. When geogrids were used, they were placed on and pressed by several roller passes to ensure adhesion between the grid and the asphalt surface. In the second stage, the 4-cm thick upper layer was paved. The day after compaction of the second layer, slabs were removed from molds and sawed in order to obtain six beams from each slab (in total 18 beams). Beams were 6 cm wide and 40 cm long. The total height of each beam was 5 cm, including 2 cm of the bottom layer and 3 cm of the upper layer, so the geogrids were below the neutral zone (in the tension zone). The whole procedure of samples’ preparation is shown in Fig. 4.
2.2.2 Performance evaluation

Before testing, bulk density of saturated surface dry specimen was determined (EN 12697-6:2013, Procedure B), and consequently air void content was calculated in accordance with EN 12697-8.

The initial stiffness modulus and phase angle of each testing beam were measured using a 4PBB device in accordance with EN 12697-26, Annex B. The tests were performed at temperature of 20°C and at frequencies of 0.1, 1, 5, 8 and 10 Hz. Samples were subjected to 100 sinusoidal load cycles with a constant strain amplitude of (50 ± 3) µε.

Fatigue resistance of all sets was determined using 4PBB test, at a single temperature of 20°C and at a frequency of 10 Hz, according to EN 12697-24/Annex D. Before being loaded, the specimens were conditioned for at least 2h at a testing temperature. Tests were performed in the stress-controlled mode because of the rapid strain increase during the test that causes faster crack propagation, consequently allowing easier determination of the failure occurrence [15]. Tests were carried out at three stress levels, where six beams of each set were tested per each level, so that all fatigue failures occur in the range from $10^4$ to $10^6$ loading cycles.

2.2.3 Data analysis

The results of each individual sample from a certain set (number of loading cycles and initial strain value) were fitted together and presented in the form of a power (fatigue) function:

$$\log \left( N_{i,j,k} \right) = A_0 + A_1 \cdot \log (\epsilon_i) \text{ Eq. 1}$$

where $i$ is the specimen number, $j$ is the chosen failure criteria, $k$ is the set of test conditions (20°C and 10 Hz), $\epsilon_i$ is the initial strain amplitude measured at the 50th or 100th load cycle (µm/m), depending on the failure criteria, $A_1$ is the slope of the fatigue function in the log-log plot, and $A_0$ is the fitting parameter.

In this study, three different failure criteria (approaches) were used to determine fatigue lives: traditional approach (50% reduction in initial stiffness), the Energy Ratio (ER) approach and newly developed approach (SFP). Fatigue laws were obtained using Eq. 1, from which critical strain $\epsilon_6$, that leads to fatigue failure after $10^6$ cycles, was calculated and used for comparison of the fatigue lives among different sets and approaches applied.

2.2.3.1 Conventional approach

Van Dijk and Visser [40] defined the failure under cyclic loading as the point at which the stiffness drops to 50% of its initial value, which is typically regarded as the stiffness at the 100th cycle ($N_{f,50\%}$, Fig. 5a). Although this method is straightforward, it has some limitations. The estimation of the initial value based on the number of cycles may be affected by nonlinearity [41], irreversible damage and thixotropy [42]. Furthermore, true failure of a testing sample often occurs between 35% and 65% stiffness decrease, although it can occur as low as 20% of initial stiffness for heavily modified materials [43]. Despite its limitations, this approach has often been used in previous studies [44, 45], and it is still a part of European standard for the fatigue resistance EN 12697-24, therefore it was selected as one of the approaches in this study.

2.2.3.2 Energy ratio approach
Hopman et al. [46] proposed the failure in a strain-controlled testing mode as the number of cycles (N1) up to the point at which cracks are considered to initiate and defined the Energy Ratio (ER) as:

\[
R_E = \frac{nW_0}{W_n} = \frac{n[\pi\sigma_0\epsilon_0\sin\phi_0]}{\pi\sigma_n\epsilon_n\sin\phi_n} \quad \text{Eq. 2}
\]

where \( n \) is the number of cycles, \( W_0 \) and \( W_n \) is the dissipated energy in the first and \( n \)-th cycle, respectively, \( \sigma_0 \) and \( \sigma_n \) are stress levels in the first and \( n \)-th cycle, respectively, \( \epsilon_0 \) and \( \epsilon_n \) are strain levels in the first and \( n \)-th cycle, respectively, and \( \phi_0 \) and \( \phi_n \) are phase angles in the first and \( n \)-th cycle, respectively.

Rowe [33] stated that the change in \( \sin \phi \) is small compared to the change in the complex modulus (\( E^*_i \)) and therefore simplified equation for calculating the ER (\( R_\sigma \)) in a stress-controlled mode:

\[
R_\sigma \approx nE^*_i \quad \text{Eq. 3}
\]

where \( n \) is the number of load cycles and \( E^*_i \) is the complex modulus in the \( n \)-th cycle [MPa].

Slightly modified approach is adopted in standard ASTM D8237-21, where the failure (\( N_{f,ER} \)) is defined as the maximum value of normalized stiffness x normalized cycles versus number of cycles plot (Fig. 5b), that is calculated according to following equation:

\[
\hat{S} \times \hat{N} = \frac{S_i \times N_i}{S_0 \times N_0} \quad \text{Eq. 4}
\]

where \( \hat{S} \times \hat{N} \) is normalized beam stiffness x normalized cycles, \( S_i \) is flexural beam stiffness at cycle \( i \) (MPa), \( N_i \) is cycle \( i \), \( S_0 \) is initial flexural beam stiffness (MPa), estimated at approximately 50 cycles, and \( N_0 \) is actual cycle number where initial flexural beam stiffness is estimated.

The calculated normalized stiffness data can be fit to a best-fit six-order polynomial curve or Logit model, ensuring easy determination of the failure. Therefore, it was decided to employ this method as the second approach in this study since it is frequently used to evaluate the fatigue failure of 4PBB samples (ASTM D8237-21).

### 2.2.3.3 Simplified Flex Point (SFP) approach

The curve \( \epsilon (n) \) representing the strain amplitude evolution in control load conditions consists of a succession of experimental data in terms of number of loading cycles and corresponding deformation level (Fig. 5c). The acquired loading cycles are numerically very close at the beginning of the test and then become progressively more distant, even irregularly, during the test, mostly because of the machine limitations. This condition is detrimental to the application of a finite difference method (both linear and non-linear).

The experimental curve of strain amplitude evolution under repeated loading cycles (Fig. 6) has three typical stages (primary, secondary and tertiary stage) with completely different experimental trends. In these stages, the strain amplitude rate (slope of the curve) is always positive and in the primary stage, it decreases rapidly. In the second stage, the strain amplitude evolution curve has an inflection, namely flex point (\( N_{f,SFP} \)), which is assumed as a reference for identifying the fatigue resistance of the material tested. In the tertiary stage of the curve, the deformation rate increases rapidly till the physical failure of the specimen is reached.

From these considerations, it can be concluded how difficult is to find a robust and simple interpolation method to identify the flex point of the strain amplitude curve, which is the main outcome of the so-called Simplified Flex
Point (SFP) approach. An interpolation method using a non-linear polynomial of suitable order (single or segmented) is not helpful in this case, given the fact that the curve in the secondary stage theoretically could have a waving trend with a certain number of flex points instead of the single flex point suggested by the experimental data (except for their small intrinsic scattering). Furthermore, a high-order polynomial (up to 7th order) would be required to adequately model the primary and tertiary stages. To solve the above computational issues, a dedicated non-linear interpolation method was developed, based on the main characteristics of the experimental strain amplitude evolution curve.

This curve always has the following characteristics:

- the curve is strictly increasing, therefore the slope is always positive;
- the second derivative (related to the curvature) is always negative for the points preceding the flex point and positive for the subsequent ones;
- the third derivative is positive along the whole curve (i.e. the curvature is increasing).

Based on these features, a high-order nonlinear polynomial can be used to set up an interpolation method that complies with the characteristics of the experimental curve by imposing some unilateral and bilateral constraints to its constant parameters.

The theoretical model of the strain amplitude ε (n) can be described by the following polynomial of N-order, where n indicates the generic position along the curve and n_f denotes the location of the flex point:

$$\epsilon(n) = \sum_{i=0}^{N} K_i (n - n_f)^i \quad \text{Eq. 5}$$

where $K_i$ indicates the constants of the model of $N$-order, which are equal to $N + 1$.

The model is completed by adding to Eq. 5 the following conditions:

I. The slope is non-negative for any value of n;

$$\frac{d\epsilon(n)}{dn} = \sum_{i=1}^{N} iK_i (n - n_f)^{i-1} \geq 0 \quad \text{Eq. 6}$$

II. The curvature is non-negative for values of n greater than $n_f$ and negative for the n values lower than $n_f$;

$$\frac{d^2\epsilon(n)}{dn^2} = \sum_{i=2}^{N} i(i-1)K_i (n - n_f)^{i-2} \geq 0 : n \geq n_f \quad \text{Eq. 7}$$

III. The third derivative is non-negative for any value of n.

$$\frac{d^3\epsilon(n)}{dn^3} = \sum_{i=3}^{N} i(i-1)(i-2)K_i (n - n_f)^{i-3} \geq 0 \quad \text{Eq. 8}$$

From a theoretical point of view, the problem is solved by determining the constants $K_i$ in Eq. 5 by using the least squares method and satisfying the unilateral constraints (Equations 6–8). For this purpose, a constrained least squares method is used, so these constraints are polynomial inequalities of $N - 1$, $N - 2$ and $N - 3$ order, respectively. By calculating them in the flex point $n_f$ it is obtained:

$$\frac{d\epsilon(n_f)}{dn} = K_1 \geq 0 \quad \text{Eq. 9}$$
Eq. 10

\[
\frac{d^2\epsilon(n_f)}{dn^2} = 2K_2 \geq 0 : n \geq n_f \rightarrow K_2 = 0 \text{ Eq. 10}
\]

Eq. 11

\[
\frac{d^3\epsilon(n_f)}{dn^3} = 6K_3 \geq 0 \text{ Eq. 11}
\]

Therefore, both \(K_1\) and \(K_3\) must be non-negative, whereas \(K_2\) must be equal to zero.

By replacing Eq. 10 in Eq. 7 and taking the term \((n - n_f)\) out of the summation, constraint from Eq. 7 can be written as:

\[
\frac{d^2d(t)}{dt^2} = (n - n_f) \sum_{i=3}^{N} i (i - 1) K_i (n - n_f)^{i-3} \geq 0 : n \geq n_f \text{ Eq. 12}
\]

which can be simplified by dividing by \((n - n_f)\), thus obtaining:

\[
\sum_{i=3}^{N} i (i - 1) K_i (n - n_f)^{i-3} \geq 0 \text{ Eq. 13}
\]

In summary, the algorithm that solves the problem consists in the search for a constrained minimum. The minimum of the sum of the squared deviations between the values \(\epsilon(n)\) provided by the model given in Eq. 5 and the corresponding experimental values, will be sought, in compliance with Eq. 10 and inequalities provided in Equations 6, 8, 9, 11 and 13.

### 2.2.4 Fatigue Resistance Improvement Factor (FRIF)

The impact of grid reinforcement on the fatigue evaluation was assessed using the newly introduced Fatigue Resistance Improvement Factor (FRIF), given that critical strain was employed as an indicator of the fatigue resistance of the asphalt mixtures. Positive FRIF values, calculated according to Eq. 14, mean that reinforced asphalt samples have improved fatigue resistance when compared to the unreinforced samples, and reverse.

\[
FRIF = \frac{\epsilon^R_6 - \epsilon^UR_6}{\epsilon^UR_6} \times 100 \text{ Eq. 14}
\]

where \(\epsilon^R_6\) is the critical strain value of reinforced specimens and \(\epsilon^UR_6\) is the corresponding critical strain value of unreinforced specimens.

### 3 Results and discussion

#### 3.1 Basic properties of asphalt samples

The average air void content of eighteen test samples of each mixture, as well as minimum and maximum values measured, are given in Fig. 7. Although the UR set had the biggest difference in measured values, average values were within the range of \(7 \pm 1\%\), ensuring a trustworthy comparison of the test results. It can also be observed that the use of geogrid lead to slight increase of air void content, confirming the results from previous study [28].

When stiffness values are considered (Fig. 8), it can be observed that using geogrid reduces specimen rigidity, where the grid with the highest thickness and strength (G3) led to the lowest stiffness of samples investigated. These results are in agreement with a recent finding [28] that stiffness increases as air void content decreases, regardless of the testing frequency. Moreover, it should be taken into account that in the case of double-layered specimens air voids are not uniform with higher values at the interface [47] and the effect is even amplified in
presence of geogrids leading to the debonding effect with direct influence on the overall specimen stiffness. The testing results further demonstrate that the stiffness and the variation in measured values were unaffected by the strength of the geogrid.

3.2 Fatigue laws of investigated samples

The number of cycles to failure calculated with the different approaches at the selected stress levels were fitted with the power function (Eq. 1). Regression coefficients $A_0$ and $A_1$, as well as coefficient of correlation $R^2$ were also calculated for each approach (Table 3). Then, critical strain values $\varepsilon_6$ were calculated for comparison purpose among different approaches and geogrid types (Fig. 9).

Table 3
Regression coefficients of fatigue laws and coefficients of correlation.

<table>
<thead>
<tr>
<th></th>
<th>UR</th>
<th>G1</th>
<th>G2</th>
<th>G3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>50%</td>
<td>ER</td>
<td>SFP</td>
<td>50%</td>
</tr>
<tr>
<td>$A_0$</td>
<td></td>
<td>16.48</td>
<td>16.72</td>
<td>16.33</td>
</tr>
<tr>
<td>$A_1$</td>
<td></td>
<td>-5.26</td>
<td>-5.38</td>
<td>-5.34</td>
</tr>
<tr>
<td>$R^2$</td>
<td></td>
<td>0.98</td>
<td>0.98</td>
<td>0.98</td>
</tr>
</tbody>
</table>

The critical strain value calculated using the SFP approach is always the smallest, whereas the values obtained using the conventional and ER approaches are comparable, apart from samples reinforced with G2 grid. The correlation coefficient estimated using the traditional approach was reasonably high (above 0.8) but not comparable to those obtained using the other two approaches, providing a substantially lower $\varepsilon_6$ value. Nevertheless, it is well known that laboratory conditions never equal real scale pavement performance and the use of fatigue cracking transfer functions [48] is always necessary to adjust laboratory-determined $\varepsilon_6$ values of reinforced asphalt systems for pavement design purposes, regardless of the approach applied.

Testing results, except those obtained using traditional approach for fatigue analysis of set reinforced with G2 grid, show that reinforcement improves fatigue resistance. When considering the traditional approach, critical strain $\varepsilon_6$ values of set reinforced with G3 grid was higher for roughly 9% compared to that of G1 set. According to the results of the ER analysis, the critical strain value rises as grid strength increases, whereas in the case of the SFP approach, the highest critical strain value was found in the G2 set, just slightly higher than that of the G3 set.

However, when looking at the G2 and G3 results shown in Fig. 9, it can be seen that the differences between $\varepsilon_6$ values for both ER and SFP approach are quite low (ER: 114.6 Vs 116.9 µm/m; SFP: 105.9 Vs 103.2 µm/m) and could be within the experimental uncertainty range. In general, based on the research outcomes, the maximum strength of the geogrid able to increase the fatigue performance seems to be 100 kN (i.e. G2). The higher benefit of using the strongest grid (i.e., G3) is most likely limited due to shear bond. Since this grid is the stiffest of all the grids used in this study, it would be more advantageous to apply a tack coat with polymer modified bitumen and a higher residual bitumen percentage than the one used in this study to completely utilize its efficacy. [49]. Moreover, the cross-dimensional area of 200 kN geogrids could also be detrimental for the interface bonding between asphalt layers with negative impact on the overall fatigue performance of a layered pavement, highlighting the importance...
of using appropriate tack coat. These conclusions could explain the decrease of the critical strain $\varepsilon_6$ values emerged with the SFP approach when comparing G2 and G3 results.

### 3.3 Fatigue resistance improvement factor

The results of fatigue resistance improvement factor (FRIF) are displayed in Fig. 10. In general, the FRIF values of all sets were positive, meaning that reinforcement improves fatigue resistance, as it was proven in previous studies [3, 4]. However, when fatigue results of G2 set were analyzed using the traditional approach, results showed that reinforcement has negative impact on the fatigue resistance, i.e. it decreases fatigue life.

Average improvement in fatigue resistance of the G1 set was around 5.8%, regardless of the approach applied. The highest discrepancy between the FRIF values was found in the case of the G2 set, where was a clear improvement in fatigue life from 17.1% (ER approach) to 23.5% (SFP approach) depending on the approach used, even though the 50% traditional approach showed no improvement but rather a worsening of fatigue resistance. Finally, grid G3 caused improvement of at least 16% in the case of the traditional approach, followed by 19.4% and 20.3% when the ER and SFP approaches are used, respectively.

One possible reason for the unreliability of the 50% traditional approach can be related to the damage condition associated with this method that is stress-sensitive as opposed to the other two approaches. For example, looking at Fig. 10, it is clear that the number of cycles to failure related to the SFP approach are always close to the midrange of the secondary phase (Fig. 6), regardless of the stress level, whereas in the case of the 50% traditional approach the damage associated to the number of cycles to failure is stress sensitive. Specifically, for the 50% traditional approach the output of the fatigue failure becomes closer to the tertiary phase for lower stress levels (Fig. 11b), when compared to the higher stress level (Fig. 11a). This has already been identified as a potential problem with this method [33], especially when highly modified bitumen is used [43].

### 4 Conclusions

The behaviour of reinforced double-layered asphalt samples has been a topic of numerous research studies because of their complexity and various grid types. The approach that should be utilized fatigue analysis is not yet established, in contrast to single layer samples made of asphalt mixtures with neat binder, where the traditional (50% reduction in initial stiffness) and the energy ratio (ER) approaches are recommended for use in suitable standards. Therefore, in this study is developed the Simplified Flex Point (SFP) approach that analyses the strain amplitude curve obtained during the fatigue test, and obtained results are further compared to those obtained using standardized approaches. The most important conclusions are as following:

- The grid reinforcement improves the fatigue resistance in the term of critical strain in range of 5.7–22.3%, depending on the grid type and approach applied. The only exception appeared in case of the traditional approach, which showed that grid G1 (100 kN) decreases fatigue resistance.
- Critical strain values obtained using SFP approach are lower than those obtained using the traditional and ER approaches.
- The Fatigue Resistance Improvement Factor (FRIF) showed that the newly developed SFP approach has quite comparable results with those from the ER approach.
- When testing reinforced samples, the traditional approach (a 50% stiffness reduction) should be avoided because it may underestimate grid efficiency.
The newly developed approach could be utilized to examine the effectiveness of the various geogrids (for example, geocomposite), testing temperature and tack coat type and content on the fatigue resistance. Additionally, the behavior of asphalt mixtures comprising grid reinforcement, polymer modified bitumen and polymer modified tack coat may be much more complex, thus the applicability of this approach should also be investigated.

References


49. Bohus S, Sperka P, Kudrna J (2023) Investigations on shear bond characteristics of grid reinforced asphalt concrete. In: XXVIIth World Road Congress. PIARC -World Road Association, Prague, Czech Republic

**Figures**

- **Figure 1**

  Experimental plan of the study.
**Figure 2**

The gradation curve of the asphalt mixture.

**Figure 3**

The fiberglass geogrids used in the study: a) G1, b) G2 and c) G3.
Figure 4

Preparation of the testing samples.

Figure 5

Failure criteria used for fatigue analysis: a) traditional approach (50% stiffness reduction), b) ER approach and c) SFP approach.
Figure 6

Three-stages experimental curve of the strain amplitude evolution.

Figure 7

Air void content of the testing samples.
Figure 8

Stiffness of the testing sets at different frequencies.

Figure 9
Critical strain values obtained using different approaches.

Figure 10

Fatigue resistance improvement factors of testing sets.

Figure 11

Stress sensitivity of traditional approach (50%) compared to the SFP approach.