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Modelling of thin asphalt layer pavements considering the effect of non-uniform tire pressure loads

Modélisation des chaussées minces en asphalte en considérant l'effet des charges de pression non uniformes des pneus

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ABSTRACT: With the advent of new numerical models that predict the behavior of pavement structures in a robust and efficient manner, a new trend has been emerging in road authorities worldwide to move from the traditional empirically-based pavement design to a more advanced mechanistic design. In the mechanistic approach the in-pavement stresses and strains are determined numerically using the principles of engineering mechanics. Afterwards, pavement distresses are predicted using transfer functions to define a mapping from the stress-strain domain into the field space. Despite the radical changes that numerical modeling has introduced to pavement engineering, the mechanistic method has been implemented only to major pavements. Instead, the design of low volume roads, made mostly of thin flexible pavements, is almost always done empirically and the cross sections and construction materials of these roads are based on country specific experience in high-standard asphalt pavements. This paper presents a mechanistic design methodology targeted to thin asphalt layer pavements. The new approach considers the effect of non-uniform tire pressure loads on the road durability. Tire footprint measurements are inputted into a Fourier assisted finite element method to determine the stresses and strain in the different pavement layers. Two main distresses are studied: fatigue in the thin asphalt layer and permanent deformation originated in basecourse and subgrade.

RÉSUMÉ: Avec l'avènement de nouveaux modèles numériques permettant de prédire le comportement des structures de chaussée de manière robuste et efficace, les autorités routières du monde entier ont pris une nouvelle tendance: passer de la conception de la chaussée traditionnelle basée sur des données empiriques à une conception mécanistique plus avancée. Dans l'approche mécaniste, les contraintes et déformations dans la chaussée sont déterminées numériquement à l'aide des principes de la mécanique du travail. Ensuite, les contraintes de la chaussée sont prédites à l'aide de fonctions de transfert afin de définir un mappage du domaine contrainte-déformation dans l'espace. En dépit des changements radicaux introduits par la modélisation numérique dans l'ingénierie des chaussées, la méthode mécaniste n'a été appliquée qu'aux chaussées majeures. Au lieu de cela, la conception de routes à faible volume, principalement composées de chaussées minces et flexibles, est presque toujours faite de manière empirique et les coupes transversales et les matériaux de construction de ces routes sont basés sur l'expérience propre à chaque pays en matière de chaussées en asphalte de haut niveau. Cet article présente une méthodologie de conception mécaniste visant à fluidifier les chaussées en couches d'asphalte.

Keywords: Thin asphalt pavement, low volme road, tire footprint mechanistic design, Fourier assisted finite element.

1 INTRODUCTION

The European low volume road network (roads with less than 1000 AADT) consists, to a large extent, of relatively thin asphalt layer pavements (TAL pavements). This type of structure has been widely adopted because it is cost effective, requires fewer energy resources and it is fast to build compared with traditional thick asphalt pavements. TAL pavements are traditionally used in low volume road networks of scarcely populated areas. These roads are vital to providing the local permanent population and associated rural industry an all-year-round transportation solution. Furthermore, a well-maintained road network is essential in attracting tourist to these areas. TAL pavements commonly consist of an upper thin bituminous layer (25 mm to 120 mm thickness) over one or more unbound granular material (UGM) layers (base course and subbase) on top of a compacted soil subgrade (Arnold, 2006)(Werkmeister, 2006)(Canon Falla, 2012). The bearing capacity of this structure is provided to large extent by the UGM with the upper bituminous surfacing acting as a waterproofing layer.

Recent studies (Arnold, 2006)(Werkmeister, 2006)(Canon Falla, 2012)(Rahman 2004)(Wieman, 2008) brought up interesting findings of how the service life of these pavements is affected by the permanent deformation characteristics of the UGM. This permanent deformation is boosted when the granular basecourse materials are of poor quality and do not have enough plastic resistance to withstand the high imposed wheel loads or when a good quality aggregate is affected by aggressive environmental conditions (i.e. wetting or frost/thawing) and loses its load carrying capacity. All in all, it was concluded that management of the risk of permanent deformations due to traffic loads, especially during the periods with increased water content in the subgrade, is of vital importance in order to have durable roads with thin asphalt layers.

Recently, a research project aiming to understand the response of thin asphalt pavements under design conditions of Germany (Wellner, 2014) showed that a well engineered and constructed basecourse layer has the ability to carry repeatedly large loading pulses and can be durable enough to withstand German design conditions under low volume traffic for a period of 30 years.

Despite the above-mentioned findings, the design of TAL pavements worldwide is almost always done empirically and the cross sections and construction materials of these roads are based on country-specific experience in high-standard pavements. Such an empirically based design method has the disadvantage in that the materials and layer thicknesses are selected in accordance with very inflexible predetermined design inputs and extrapolation is required when the input parameters lay beyond the original interference space. In Germany, for example, all low volume roads (< 300.000 -10t standard axle load) are designed empirically with a minimum asphalt thickness of 120 mm. However, experience from other countries (i.e. Australia, New Zealand, USA, Sweden, Finland) showed that for low traffic volume it is feasible to have long service life roads with asphalt layers of less than 50 mm thickness.

A need was identified to develop a mechanistic framework for estimating realistically the performance of thin surfaced asphalt pavements in Europe. Mechanistic design allows a range of variables to be studied and manipulated in order to identify their combined influence over the appearance of pavement distresses. The variables that are usually controlled are the material properties, the thickness of the pavement layers, the effect of temperature changes and magnitude of the load. However, in the opinion of the authors, additional attention should be given to the potential impact of the effects of non-uniform tire pressure loads on the pavement performance.

2 MECHANISTIC DESIGN OF TAL PAVEMENTS

Most of the available M-E pavement design methods are intended to protect the structure from rutting originated in the subgrade, however, no considerations are made for the permanent deformation in the basecourse. Instead, it is assumed that no permanent deformation occurs if the basecourse granular material complies with some specifications that include criteria for aggregate strength, durability, cleanliness, grading, etc. This assumption is not valid for TAL pavements for which the lifespan is governed by the maximum rut depth derived from the permanent deformation development on the UGM near the load.

In a previous research by the authors, a simplified mechanistic design approach was developed with focused attention on limiting the main source of rutting of thinly sealed pavement structures: excessive plastic deformation in the granular basecourse and subgrade.

The proposed mechanistic procedure for TAL pavements is shown in Figure 1. The flow diagram of Figure 1 consists of a first loop in which the year is divided into two seasonal periods representing summer and spring thaw conditions. During spring thaw water content in the base UGM increases substantially. This increase leads to a loss of bearing capacity, which must not be ignored in the design process. Thereafter a second loop is used to sweep over the traffic loading. The traffic load has to be considered in the design process by an appropriate range of axle load groups in conjunction with their associated frequency of occurrence.

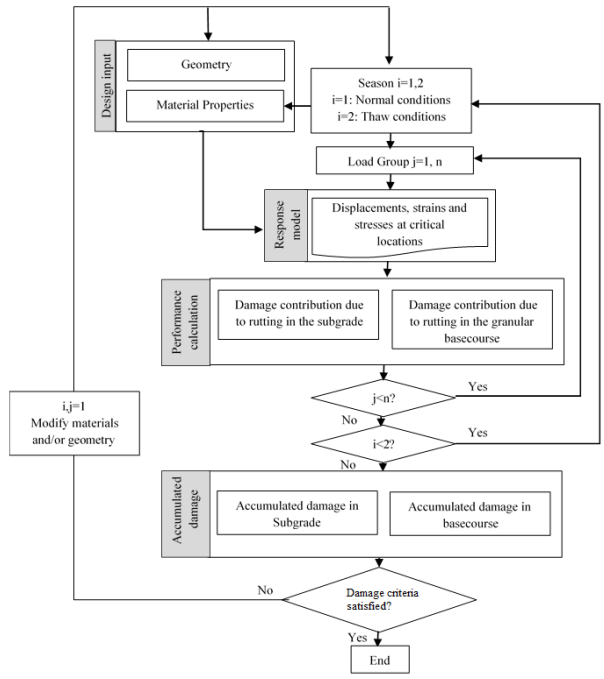


Figure 1 M-E design of thin asphalt pavements,

3 STRESS ANALYSIS USING FOURIER AIDED FINITE ELEMENT METHOD (FSAFEM)

A computational model to predict the evolution of pavement distresses is needed in the implementation of a mechanistic pavement design and performance evaluation. Studies using mechanistic approaches usually employ layered elastic analysis to determine the pavement response. Layered models, where the pavement is simplified as a multilayer elastic system, has been widely used because they are less computation-intensive than other numerical theories, such as the Finite Element (FE). However, a layered elastic analysis may lead to significant errors when the load is not axisymmetric.

Alternatively, one can use the three-dimensional finite element method (3D FEM). This model can include all the phenomena and characteristics of real pavements, including non-uniform tire pressure distribution, viscoelasticity of asphalt

layers, damage, the non-linear elasticity of unbound granular layers, etc. Such a model will be the most accurate, however, it requires a large amount of computer resources that may overtax the available computer capability. Furthermore, performing 3D-FEM analysis within a mechanistic pavement design framework would be not practical because of the numerous times that the FE analysis needs to be run.

Thus, it is needed to look for an alternative to reduce computational effort. One possible solution is to idealize the pavement as either plane strain or axisymmetric. Plane strain is a very rough approximation because the traffic has to be modeled as an infinite strip load along the longitudinal direction, which is definitely not appropriate. Axisymmetric approximation of the tire load may be an acceptable alternative for thick asphalt layer pavements, but for thin asphalt pavements will lead to considerable errors.

With the goal of overcoming the limitations of the multilayer elastic theory and Plane-strain/axisymmetric FEM and to reduce the computational effort of a full 3D-FEM, we have used an analysis technique called "Fourier series aided finite element method" (FSAFEM). In the FSAFEM a three-dimensional problem is reduced, in appearance, into a two-dimensional analysis. The main idea behind this method, as applied to pavement modeling, is to perform Fourier analysis in the longitudinal direction (traffic direction), and use finite elements in the cross-section. So, The transverse plane, x-y plane in Figure 2, is discretized using a 2D-finite element mesh and the variation of fields in this plane are described using nodal values and shape functions. In the z-direction (traffic direction) the distribution of variables is described by Fourier series. In the FSAFEM the pavement is considered straight and infinite in the longitudinal direction and the traffic load is approximated using periodic loading of constant shape. These two idealizations allow using Fourier series expansion to eliminate the spacial variable in the direction of traffic.

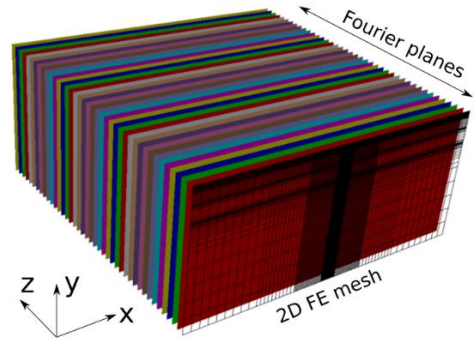


Figure 2 FSAFEM mesh and Fourier planes

4 NUMERICAL EXAMPLE

This section presents the numerical modeling of two pavements with different asphalt surface thickness under a representative tire load. The objective is to identify the impact of the non-uniform tire contact stresses on the useful life of the pavement. For this, the following approach was used:

1. Initially, the pavement structure, models and materials were defined.
2. With the finite element technique described in section 3, an analysis was performed in which the tire load was modeled using a non-linear stress distribution.
3. A similar analysis was performed with conventional elastic theory considering a constant circular stress distribution.
4. The results obtained in step (2) and (3) were compared and conclusions were drawn.

4.1 Pavement structures and materials

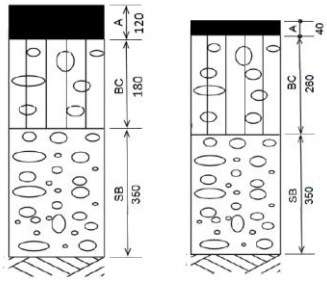
Two TAL pavements were investigated:

Structure 1: this pavement structure was selected to satisfy the basic requirements regarding traffic and frost conditions of a typical low volume road

near Dresden, Germany. For this, the traditional empirical design method of Germany (RSTO, 2012) was used. Seven traffic classes are considered in RSTO 12, depending on the number of equivalent standard axle load (ESAL) repetitions during the design life of the pavement. The less demanding traffic class, BK0.3, corresponds to ESAL repetitions of less than 0.3 million. Using the available materials and local conditions of a rural road in the vicinity of Dresden, the chosen pavement structure consisted of 12 cm of a bituminous surface layer, underlying by a granular basecourse of 18 cm and a frost protection layer of 35 cm thickness.

Structure 2: according to Dawson and Kolisoja (Dawson, 2006) a minimum asphalt surface thickness of 40 mm is needed in order to achieve effective load distribution and stress reduction in the lower aggregate base layer. Thus, the second structure consisted of a TAL pavement with an asphalt surface of 4 cm thickness on top of two granular layers: a base course layer of 28 cm and a frost protection layer of 35 cm.

Figure 3 shows the schematic representation of both pavements as well as the material properties for both design cases: summer and spring thaw.



Structure No. 1. Structure No. 2.

Layer	Thickness [mm] Structure 1	Structure 2	E-modulus [MPa] Summer	Spring thaw
Asphalt Surface	40	40	3000	10000
Asphalt basecourse	80	-	4000	12000
Granular basecourse	180	260	400	150[b]
Granular subbase	350	350	120	80
Subgrade	2000	2000	45	25

Figure 3 Pavement structures and material properties

4.2 Tire contact stresses

The load used in the numerical simulations was based on the vertical stress distribution measured under a 35 kN single wheel load with a tire inflation pressure of 900 kPa. The measurements were done with a wide base radial tire 385/65R22.5 at the Institute of automotive engineering of RWTH Aachen. This is a highly probable tire load that can be expected on a low volume road of Germany. It represents a typical European articulated truck with super-single trailer tires (equivalent axle load of approx. 7 tonnes). Figure 5 shows the variation of the vertical pressure over the contact area.

The measured contact area (45908 mm^2) and the applied tire load (35000 N) were used to represent the non-uniform contact pressure as an equivalent uniform stress distribution of 762 kPa over a circular patch of 121 mm radius. Figure 4 summarizes the two different tire load configurations investigated.

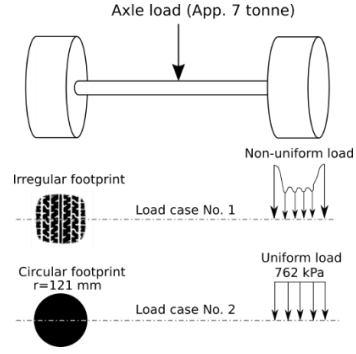


Figure 4 Load cases

The non-uniform tire load, defined at the element nodes, was expressed in the longitudinal direction (traffic direction) as a series of harmonic functions. Figure 5 shows the footprint discretization for different number of Fourier harmonics. It is clearly observed that as the number of frequencies increases, the Fourier series provides an accurate and reliable representation of the footprint measurement.

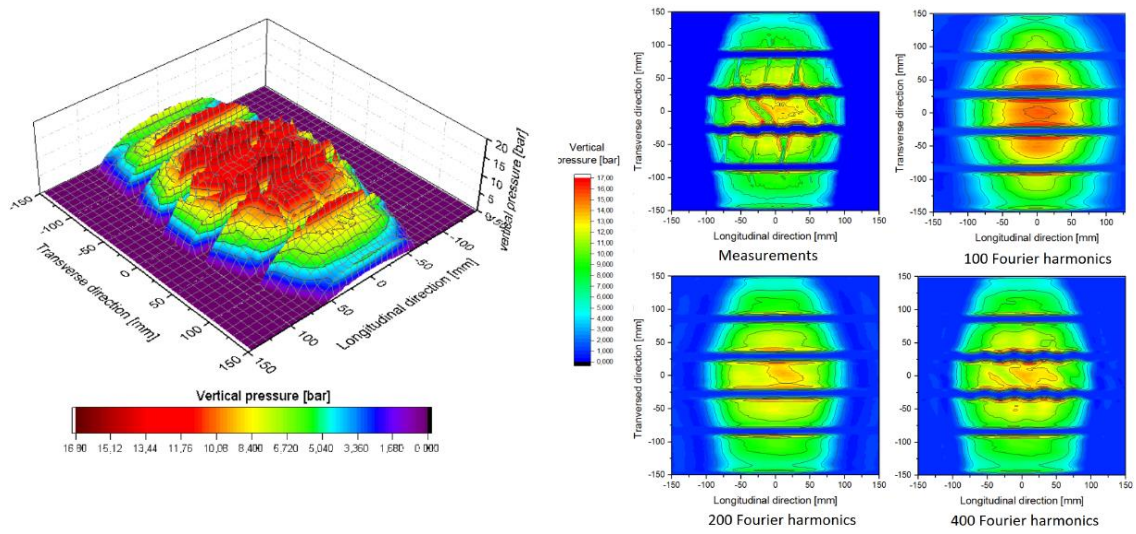
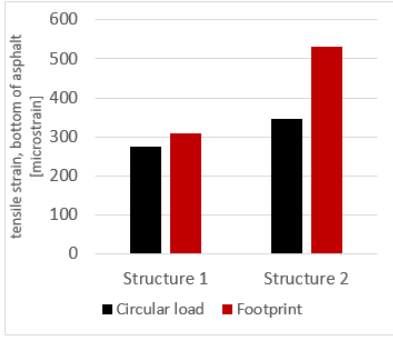


Figure 5 Tire foot-print. Right: measurements, Left: Fourier discretization

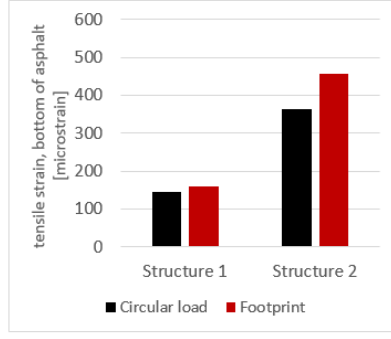
4.3 Results

The numerical simulations were analyzed with two performance aspects in mind, fatigue of the asphalt surface layer and rutting originated on basecourse and subgrade layers.

Fatigue of the asphalt layer: The parameter used for the analysis of the fatigue cracking in the asphalt was the tensile strain at the bottom of the layer. Figure 6 shows the results for both design conditions.



Summer conditions

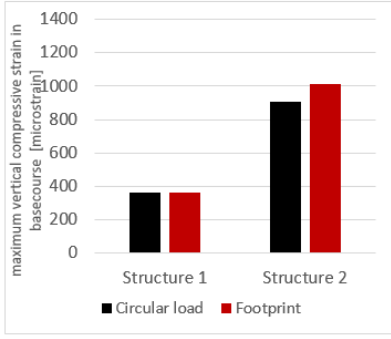


Spring thaw conditions

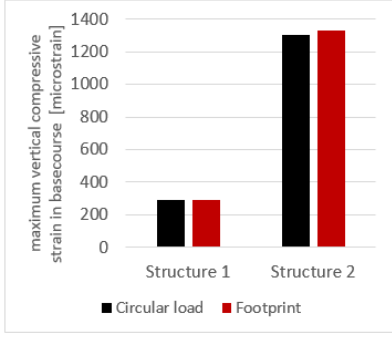
Figure 6 horizontal tensile strain at the bottom of the asphalt layer

It was observed that the second pavement structure showed a higher risk of failure due to fatigue in the asphalt layer. The most critical scenario was during summer of Structure 2. For this case, the difference between the strains calculated with the non-uniform pressure load and the strain determined with the uniform circular pressure load was more than 50%. This means that the tire pressure distribution plays an important role in the fatigue of the surface layer, especially when the asphalt layer is very thin.

Rutting originated in the basecourse: Unbound granular materials in the vicinity of the load are very prompt to deform permanently. Part of the energy during loading and unloading goes into a permanent plastic strain that accumulates with the time. In order to account for this source of rutting, the authors propose a strain-based "routine level" approach, in which the reference parameter is the maximum vertical elastic strain in the basecourse layer (Figure 7).



Summer conditions

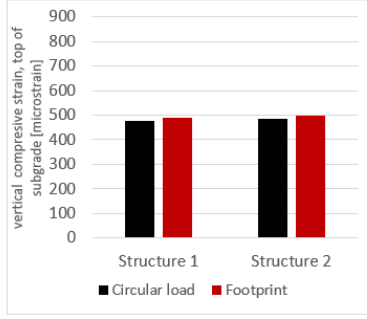


Spring thaw conditions

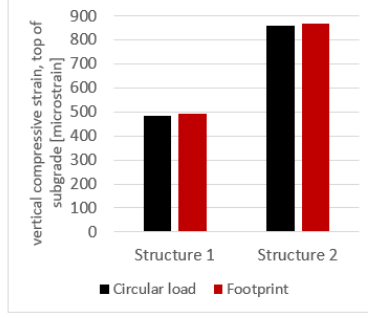
Figure 7 maximum vertical compressive strain in the basecourse layer

The results of the FE calculation showed that the tire footprint did not affect substantially the calculated maximum vertical strain. The difference between both load modes (footprint and circular load) was found during summer of Structure No. 2 (around 10% difference). As expected, the maximum risk of permanent deformation was in the spring thaw of the pavement structure No. 2. The results showed that the thickness of the asphalt layer governs the susceptibility of rutting originated in the basecourse. It is concluded that for very thin asphalt layers or for chip seal surfacings it is necessary to use very high-quality aggregates to be able to withstand the high traffic stresses in the basecourse.

Rutting originated in the subgrade: In most of the analytical pavement design methods, the design against permanent deformation in the subgrade is done with empirical transfer functions that correlate the maximum number of load cycles before failure with an indirect index that assess the permanent deformation propensity. This index is usually the vertical elastic strain at the top of the subgrade (Figure 8).



Summer conditions



Spring thaw conditions

Figure 8 vertical compressive strain at the top of the subgrade

The results showed that the non-uniform tire footprint did not affect the vertical strains. So, it was concluded that a simplification of uniform circular stress distribution is valid for this failure mechanism. It was observed that the spring thaw condition doubled the risk of permanent deformation in the subgrade of Structure No. 2.

5 CONCLUSIONS

A large part of the European road network consists of relatively thin pavements. Their design is mainly carried out by an empirical approach that is obscure with little transparency and therefore involving difficulties when applied in new situations (new materials, different climate conditions, higher traffic loads etc.). A more rigor mechanistic approach in their design process will, therefore, improve the transparency of the process and allow carrying out distress prediction of how performance changes with time.

A new mechanistic design method focused on thin asphalt layer pavements for low volume roads was presented. The results of Fourier assisted finite element calculations showed that the non-uniform tire pressure plays an important role in the fatigue life of the asphalt layer. As expected, it was found that the highest risk of permanent deformation in the granular layers took place during the spring thaw period.

With the help of advanced numerical models and the experience of other countries, it appears possible to have durable pavement structures with thin asphalt layers. However, there are quality requirements that stipulate the type of materials that can be used in the base course. Only high-quality UGMs that have high stiffness and low susceptibility to plastic deformation may be used.

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