Accepted Manuscript

Main flexible pavement and mix design methods in Europe and challenges for the development of an European method

Paulo Pereira, Jorge Pais

PII: S2095-7564(16)30300-2

DOI: 10.1016/j.jtte.2017.06.001

Reference: JTTE 145

To appear in: *Journal of Traffic and Transportation Engineering (English Edition)*

Received Date: 28 November 2016

Revised Date: 31 May 2017

Accepted Date: 2 June 2017

Please cite this article as: Pereira, P., Pais, J., Main flexible pavement and mix design methods in Europe and challenges for the development of an European method, *Journal of Traffic and Transportation Engineering (English Edition)* (2017), doi: 10.1016/j.jtte.2017.06.001.

Reviews

Main flexible pavement and mix design methods in Europe and challenges for the development of an European method

Paulo Pereira*, Jorge Pais

Centre for Territory, Environment and Construction, University of Minho, Guimarães 4800-058, Portugal

Highlights

- This article analyzes the main flexible pavement design methods in use in Europe.
- This article analyzes the main asphalt mix design methods in use in Europe.
- This article presents the recent developments related with pavement design.
- This article discusses the main challenges for the development of a pavement design method.

Abstract

Pavement and mix design represent one of the key components within the life cycle of a road infrastructure, with links to political, economic, technical, societal and environmental issues. Recent researches related to the characteristics of materials and associated behavior models both for materials and pavement, made it appropriate to consider updating current pavement design methods, and especially in the USA this has already been in process while in Europe uses of the methods developed in the early 1970s. Thus, this paper firstly presents a brief historical overview of pavement design methods, highlighting early limitations of old empirical methods. Afterwards, French, UK and Shell methods currently in use in Europe will be presented, underlining their main components in terms of methodology, traffic, climatic conditions and subgrade. The asphalt mix design and modelling in Europe are presented with their inclusion in the pavement design methods. Finally, the main challenges for the development of a European pavement design method are presented as well as the recent research developments that can be used for that method.

Keywords:

Road pavement; Pavement design; Mix design; Future challenges.

*Corresponding author. Tel.: +351 253 510240; fax: +351 253 510217.
E-mail addresses: ppereira@civil.uminho.pt(P. Pereira), jpais@civil.uminho.pt (J. Pais).

1 Introduction

According to the European Union Road Statistics (EURF, 2015), and European Commission (EC, 2015), 50% of the employment in companies of all transport modes lies in activities related to roads. In the period from 1995 to 2007, the movement of passengers experienced an increase of 21% and the movement of goods had an increase of 37%, which were in accordance with the GDP increase of 34% in the same period. This growth was interrupted by the 2008 crisis, mainly in the transportation of goods.

The predominance of goods transportation by roads is supported by a European road network of 6 million km (5.5 million km in the EU28). This number only compares with the road network length of USA plus Japan and Russia. The present value of this infrastructure reaches more than 20 billion Euros.

Presently, this road network implies costs of more than 10 thousand million Euros per year in maintenance activities to provide a high quality standard. In 2006, before the crisis, this value reached 30 thousand million Euros per year.

The quality of the European road network is also visible in terms of safety, namely accidents involving personal injury, which decreased by 28%in the period 2000-2012. In terms of road fatalities, in the same period, it faced a reduction of 51%. In spite of this reduction, the number of road accidents involving personal injuries in Europe continues to remain high level, reaching more than 2 per 1000 of the population in the EU28 (Fig. 1).

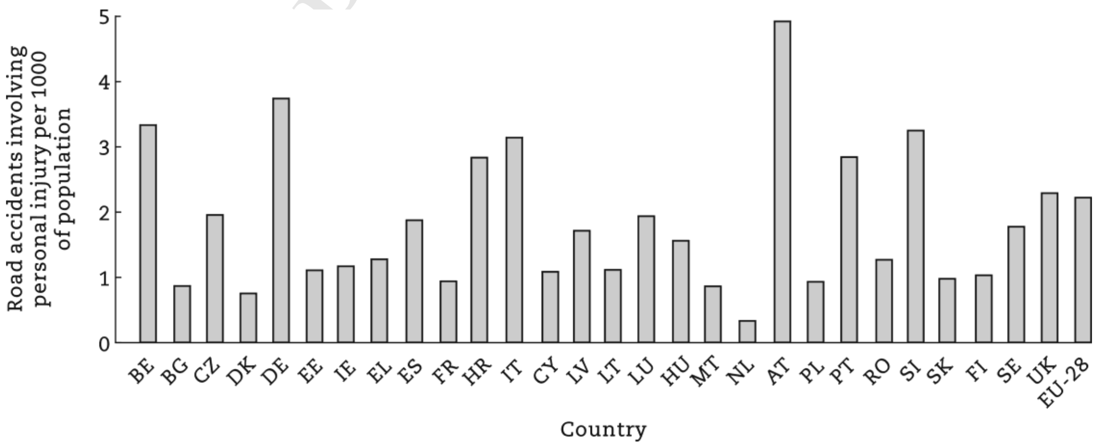

Fig. 1 Road accidents involving personal injuries in Europe (EURF, 2015).

The quality of life is also a concern of the European Union and, in relation to transportation, it has been expressed in terms of CO_2 emissions reduction for new passenger cars. In the period of 2005-2013, an average of 21% was reached that allowed the 2015 target to reach levels found in 2012.

Another concern in Europe is energy consumption Transportation is responsible for one third of the total energy consumed, even more than industry and households (Fig. 2).

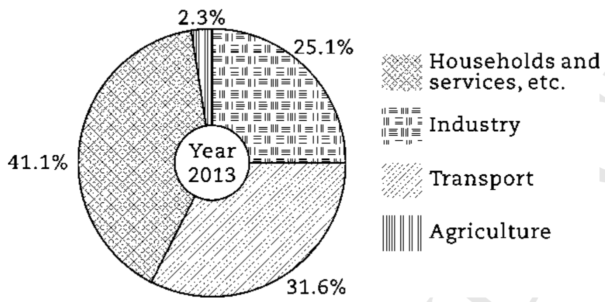

Fig. 2 Final energy consumption (EC, 2015).

The figures mentioned above are the results of an European road network which is responsible for high investments in their infrastructures and also with significant maintenance costs whereby this network must be preserved to allow a sustainable transportation of passengers and goods with the quality required by European citizens.

Road pavement (being flexible or asphalt pavement, predominant worldwide) is one of the most expensive element of road construction, apart from the bridges and viaducts. Also, during maintenance operations, road pavement is the element where more money is being spent, requiring that its design should be done with the most accurate methods considering existing conditions of traffic, climatic and materials.

Today, pavement and asphalt mix design represent a robust subject with a stable knowledge obtained after a long period of research, laboratory experimentation and field applications, from the 1950's until today.

However, the majority of pavement related factors have evolved over the years requiring continuous attention in terms of updating the quality of all processes, contributing to long-lasting road infrastructures, providing better investment results and quality in road engineering.

The overall purpose of this paper is to address an overview of the main pavement and mix design in Europe, highlighting the main challenges to be taken into account by researchers and practitioners in the near future.

Firstly, a brief historical overview of pavement and asphalt mix design is presented, including the main steps and contributions.

Regarding Europe, the most common pavement design methods are presented, in particular those developed and used by countries and institutions such as France (LCPC, at present IFSTAR), Shell and the UK (TRL). Main components of pavement design such as traffic, climatic conditions, materials and methodology which are adopted by those methods will be presented and discussed. As a very relevant component of flexible pavement design process, the design of asphalt mixes will also be highlighted.

Finally, this paper takes into account the present challenges for the important components of road infrastructure, pavement and asphalt mix design. This paper also presents challenges for pavement design and research needs of pavement design components.

2 From the past to the present in pavement design

Pavement design has evolved over the last decades from an empirical to a mechanistic-empirical approach. Empirical methods consider traffic input represented by a single wheel load as well as soil properties, with support from the observation of field pavement performance, in service roads or accelerated track test facilities with real pavement. The main objective consists of the determination of the thickness of pavement layers to be constructed over the subgrade, with the major objective of allowing traffic circulation before reaching a predefined failure condition at the end of its designed life.

The empirical approach started during the Second World War and represented the main design methods during almost three decades. At the same time, soil classification was also used as an input in design methods (Stock, 1979). All contributions for the empirical design methods came from the research carried out in the USA and Canada, without input from Europe.

The first empirical design method used worldwide was the one called CBR method (adopted by the U.S. Corps of Engineers (1945), and developed by the California Division of Highways in 1928, which used the CBR (California bearing ratio index) value of the subgrade material to assess the constitution of the pavement.

For the empirical methods, full-scale road tests presented a step forward in the pavement design by addressing some important pavement performances related factors such as traffic, climatic conditions and pavement distresses (Newcomb et al., 2001). However, the effects of the different traffic axle load and configuration on the pavement performance were the main achievements of the various full-scale road tests.

Full-scale road tests and deflection measurements have become the main support for the development of a new approach for pavement design, supporting a step forward in empirical design methods, which are applied to the main features that are still adopted in many pavement analyses and design methods today.

Tests on real roads started in the United States (Maryland road test) (HRB, 1952), where tests under controlled traffic were conducted in 1950, with the objective of determining the relative effects of different axle loadings.

The Maryland road test was followed by the WASHO (Western Association of State Highway Officials)road test, from 1952 to 1954, considering different thickness of the asphalt layer, where the effect of different axle loadings on the cracking of the pavement was investigated (HRB, 1954, 1955). In WASHO road test, the Benkelman Beam device was introduced, allowing for the measurement of the pavement deflection under slow moving wheel loads, providing an early indication of pavement performance.

The AASHO road test (HRB, 1962), undertaken from 1958 to 1960, represented a land mark for tests under real traffic conditions, contributing to the improvement of pavement design and providing the impetus for the development of many current analytically based design procedures. One of the major findings of AASHO road test was the development of the pavement serviceability concept, together with equations relating serviceability, load and thickness design of both flexible and rigid pavements which were used in the pavement design guides, mainly in the AASHTO design guide (1961, 1972, 1986) and Asphalt Institute (1970).

In Europe, after implementation of the AASHTO road test, the Road Research Laboratory (UK) implemented test sections in some major roads, with the objective of studying the long-term performance of pavement under real traffic loading in specific environment (Lee and Croney, 1962).

After thirty years of using empirical pavement design methods, the mechanistic-empirical design approach was conceived by Dormon and Metcalf (1965), essentially calculating the pavement structure response (stresses and strains) to one or more distresses (cracking and permanent deformation), as a function of the material's properties, layer thickness and loading conditions, corresponding to the mechanistic part of the method. These responses were then related to the observed performance of the pavement, corresponding to the empirical part of the method.

Mechanistic-empirical design methods represented a step forward from empirical methods. The induced states of stresses and strains in the pavement, due to traffic loading and environmental conditions, were predicted using the theory of mechanics (Burmister theory) implemented in several computer softwares.

Kerkhoven and Dormon (1953) were the first researchers suggested the use of vertical compressive strain on the top of the subgrade, as the failure criterion to reduce permanent deformation on the pavement surface. Saal and Pell (1960) proposed the use of the horizontal tensile strain at the bottom of asphalt layer to control the fatigue cracking. These were the first steps to produce an entire mechanistic-empirical design method that controlled permanent deformation and fatigue cracking and, that was implemented by Dormon and Metcalf (1965). Later, Claussen et al. (1977) in the Shell pavement design method, Shook et al. (1982) in the Asphalt Institute method, LCPC (1981) in the French method and Powell et al. (1984) in the English method represented the main contributions for the mechanistic-empirical approach.

Over the past twenty years, several projects have developed mechanistic-empirical pavement design guides. However, most of the work was based on variants of the same two strain-based criteria, previously developed by Shell and the Asphalt Institute.

The NCHRP 1-37A project (NCHRP, 2004) was the most recent mechanistic-empirical method, called Mechanistic-Empirical Pavement Design Guide (MEPDG) that incorporated US calibrated models to predict distinct distresses induced by traffic loads and environmental conditions. The NCHRP

1-37A methodology also incorporated vehicle class and load distributions in the design, a step forward from the equivalent single axle load (ESAL) approach, used in AASTHO design method. In the MEPDG method, pavement performance was calculated on a seasonal basis, representing an incremental approach, in order to incorporate the effects of climate conditions on the behavior of materials and to incorporate the evolution of the composition of materials and resulting behavior over time. Structural responses (stresses, strains and deflections) were mechanistically calculated based on the properties of materials, environmental conditions and loading characteristics. These responses were used as inputs in empirical models to compute distress predictions.

The MEPDG was based on an iterative process, in which predicted performance of a selected pavement structure was compared against the design criteria. The structure composition and material selection were adjusted until a satisfactory design was achieved.

Based on the design input data and importance of the project, MEPDG considered different approaches following three levels.

- Level 1–the properties of the material are required with laboratory tests, together with traffic data;
- Level 2–the properties of the material are obtained through empirical correlations with other parameters;
- Level 3–the properties of the material and vehicle class distribution are selected from an existing database.

For a better understanding of the evolution in the pavement design methods, Fig. 3 presents a timescale of the main methods and road tests in the history of pavement design.

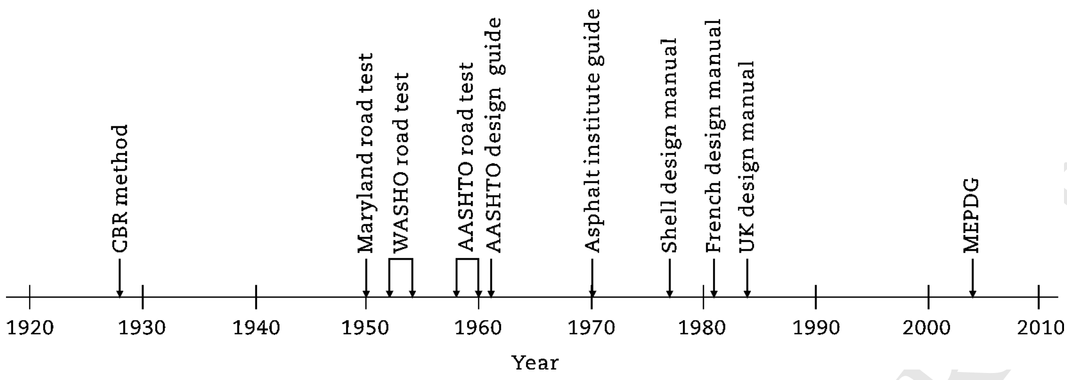

Fig. 3 Timescale of pavement design evolution.

Mechanistic-empirical methods are gaining more acceptance and uses all over the world, since they are more robust than traditional empirically-based design methods. Mechanistic-empirical methods can adapt to new design conditions (e.g., heavier loads, innovative pavement materials) by primarily relying upon mechanistic pavement modelling. Empirically-based procedures, however, are limited to the original test conditions encountered during procedure development (Timm et al., 1999).

However, even considering these advances offered by mechanistic-empirical based design methods, every model related to each component of the design (traffic, and climatic conditions, subgrade and material behavior) needs to be calibrated, as well as the pavement performance models. This in turn implies greater challenges in terms of investment in data collection, experimental research, in the laboratory and in the field, demanding greater cost-benefits analyzes, between data cost and quality of the design process.

3 Pavement design in Europe

In this section an analysis of the main pavement design methods in Europe, namely the French, UK, and Shell methods, is carried out focusing on the principal aspects that must be included in such methods of methodology, traffic, climatic conditions, subgrade, granular materials, asphalt mix design, and asphalt mix modeling.

3.1 Pavement design methodology

Since the introduction of the Shell pavement design method by Claussen et al. (1977) in Europe has been changed from the empirical to the mechanistic-empirical approach, where distresses in the pavement are correlated with the mechanical behaviour of the pavement materials, in specific points on the pavement. This design requires an analysis of the level of stress, strain and deflections, with the objective of controlling bottom-up fatigue cracking in the asphalt mixes and the permanent deformation due to subgrade soil contribution. Thermal cracking and permanent deformation in the asphalt mixes are controlled, indirectly, during the design of the asphalt mixes (Brovelli et al., 2015). Top down cracking is not controlled in the European mechanistic-empirical pavement design methods.

The pavement design through the mechanistic-empirical method is an iterative process with three parts (Fig.4), input, distress analysis,and design decisions.

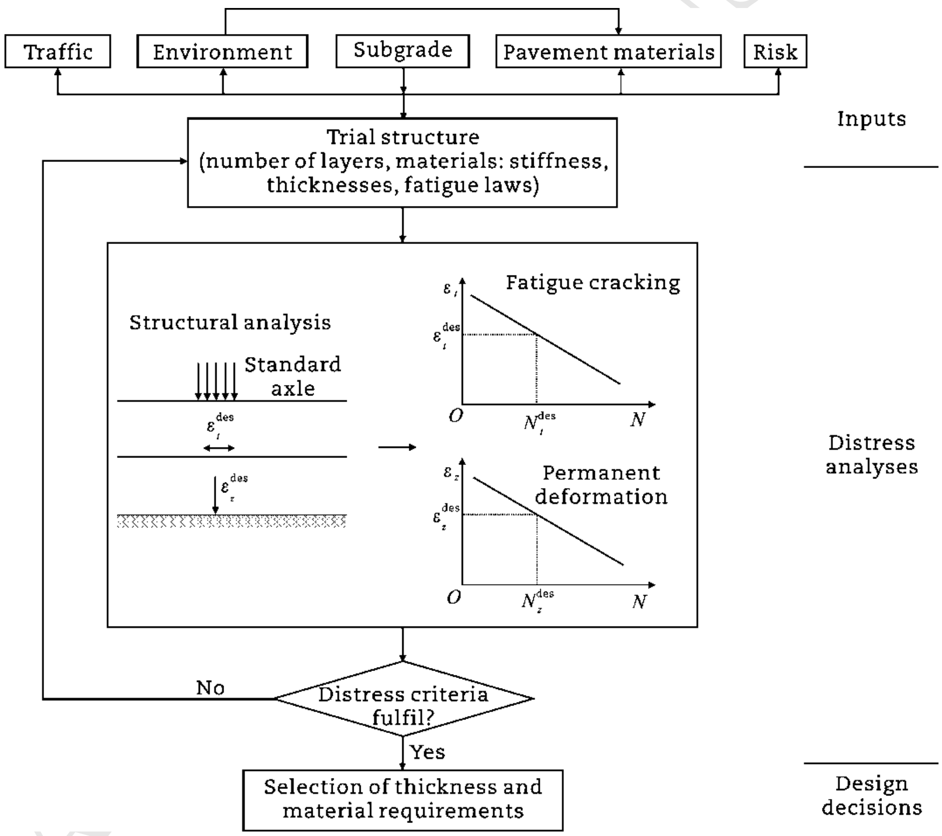

Fig. 4 Pavement design–a simplified design/analysis framework (Monismith, 2004).

The input part of the mechanistic-empirical method includes five groups of data to define a trial pavement structure, which composed of a given number of layers, each defined by its thickness and mechanical properties expressed by the stiffness and the Poisson ratio, as only linear-elastic analysis is considered. The main data for the definition of the trial structure is the traffic and the subgrade characteristics.

The traffic is expressed in terms of ESAL for a standard axle, usually 80 kN or 130 kN, depending on the design method. The conversion of the number of vehicles to ESAL is carried out with the AASHTO equation, derived from the AASHTO road test. The subgrade is considered by the CBR value of the soil, which is used to predict the stiffness of the pavement foundation.

The other factors include the climatic conditions, the degree of risk and the available materials. Climatic conditions take into account the temperature on the pavement, which is used to define the characteristics of asphalt mixes and the water for the definition of the drainage system of the road, as well as properties of granular materials, mainly the subgrade CBR. The degree of risk is assumed in the definition of the properties of the materials, as well as in the fatigue laws used to predict distresses in the pavement structure.

Available materials, associated with the importance of the road and the degree of safety and comfort, together with other factors (traffic, subgrade, climatic conditions, and degree of risk), allow for the defining of the trial pavement structure for the pavement design, composed by a number of layers of specific materials and their thicknesses and boundary conditions.

The second part of the pavement design process, the distress analysis, calculates the strains and stresses at specific points, related with the distresses considered in the design. Usually, two distress modes are considered in the design, i) fatigue cracking in the asphalt mixes and ii) pavement permanent deformation due to the subgrade soil. These distresses are considered in the design by controlling the horizontal tensile strain at the bottom of the asphalt layer and the vertical compressive strain at the top of the subgrade.

Prediction of pavement life is carried out through fatigue laws developed in laboratory and calibrated with in situ results. To consider the bottom-up fatigue cracking, fatigue law relates the horizontal tensile strain at the bottom of asphalt mixes, with the number of cycles to failure, which here considered as a given crack density. Permanent deformation due to the subgrade soil is controlled using fatigue laws, relating the vertical compressive strain at the top of the subgrade with the number of cycles responsible for a certain rut depth.

Typically, pavement damage, defined as the ratio between the expected traffic and the number of ESAL cycles applications that the pavement can stand, is used as the design criteria in the pavement design process. Depending on the pavement design method, different damage ratios are considered in the third part of the design.

The French pavement design method (LCPC, 1981) is the most comprehensive design method in use in Europe. A sound manual explains the procedure which includes i) an explanation of the basis of the pavement design method, ii) the relation between pavement design options and road management system, iii) the role of pavement surface course, iv) the role of pavement foundation, v) pavements material, and vi) design of new pavement.

Preliminary design consists of choosing the wearing course, according to the category of the road and weather conditions and then, making a preliminary design of the pavement, having as a reference comparable situation. The design of the wearing course follows the procedures used for asphalt mixes design. Aggregate gradation for wearing course is defined in the standards as well as the type of binder.

The control of the fatigue of the subgrade consists in the comparison between the calculated stresses/strains with the admissible values that are determined according to the expected traffic, the accepted failure risk, the strength of the materials, and thermal effects.

The adjustment of the pavement system and calculated layer thickness were taken into considerations, i) restrictions of minimum and maximum thickness of each material to achieve the compaction and evenness objectives, ii) risk of debonding by limitation of the number of interfaces, and iii) and the suitable protection of the base layers.

The last step in the pavement design according to the French method is the verification of the frost/thaw behaviour, which includes the following evaluations.

- The atmospheric frost index chosen as reference, IR, that characterizes the severity of winter against which the pavement is protected;
- The atmospheric frost index that the pavement is able to withstand, which defines the allowed frost index IA.

IR is evaluated according to the frost susceptibility of the subgrade, the thermal protection and mechanical function fulfilled by the pavement. The pavement structure is designed so that the allowed frost index (IA) of the pavement is higher than the reference frost index (IR).

IA is the calculated function of the susceptibility of the pavement foundation provided by the non frost-susceptible materials of the capping layer and of the subgrade. It is also the function of the quantity of frost that will be allowed to be transmitted through to the deeper, frost-susceptible layers of the underground.

The first version of the Shell pavement design procedure was published in 1963 and was updated and extended in 1978 (Shell International Petroleum Company, Ltd, 1978) to include additional design parameters such as the effect of temperature, different types of asphalt mixes and a procedure to estimate the rut depth in the asphalt layers, being presented in the form of a design manual for highway loading conditions. After a number of years of experience with the 1978 procedure, additional modifications were implemented in 1985, which also included the prediction of the permanent deformation of the asphalt layers.

The UK mechanistic-empirical pavement design method, developed by Powell et al. (1984), was updated by Nunn (2004) to improve its versatility. This modified method calculated pavement layer thicknesses that were compatible with existing methodology and methods of characterizing materials.

Different types of pavement structures are considered to design road pavement, which include flexible (the most representative in Europe and worldwide, rigid and composite pavement. Flexible pavement has two variants: pavements with granular base and full-depth asphalt pavement. Rigid pavement can have slabs or be constituted by continuous reinforced concrete. Composite pavement includes the use of asphalt layers and cement treated layers on base layers (LCPC, 1994).

3.2 Traffic

Traffic data constitutes one of the key elements required for the design and analysis of pavement structures. Except the Mechanistic-Empirical Pavement Design Guide (AASHTO, 2003), where traffic was defined by axle load spectra, the number of ESAL, as defined in the 1986 AASHTO design guide (AASHTO, 1986), was already a required traffic feature for most pavement structural design procedures, which used the concept of the equivalent load to transform the expected traffic into the designed traffic. The first equivalency factors used to determine the number of ESAL were based on the present serviceability index (PSI) concept.

The ESAL uses the concept of the equivalent axle load factor (EALF), which defines the ratio between the damage caused by the passage of an axle on a pavement and the damage caused by the passage of a standard axle on the same pavement. This EALF is used in pavement design to convert the spectrum of vehicles with different loads and types of axles (single, tandem, and tridem) into single axles with dual tires, i.e., the ESAL Eq. (1),where P_x is the actual axle load, P_{80} is the load of the standard axle (80 kN), and α is a coefficient function of the pavement stiffness.

$$\mathrm{EALF} = (\frac{P_x}{P_{80}})^{\alpha} \tag{1}$$

This equation fails to consider the type of axle (single, tandem, tridem) in the calculation of EALF, and only considers the total load of the axles.

However, the French pavement design manual (LCPC, 1994) considers the type of axles (Eq.(2)), where k is a coefficient function of the type of axle (single, tandem or tridem) (Table 1), P_{130} is the load of the standard axle (130 kN) adopted in the French pavement design manual.

$$\mathrm{EALF} = k(\frac{P_x}{P_{130}})^{\alpha} \tag{2}$$

Table 1 Values of the k and α coefficients for the French method (LCPC, 1994).

Pavement	α	k		
		Single axle	Tandem axle	Tridem axle
Flexible pavement	5	1	0.75	1.1
Rigid and semi-rigid pavement	12	1	12	113

The k coefficient does not take into account the variety of flexible pavement, both in terms of thickness and stiffness of the pavement layers. Another factor which is not taken into account is the distance between the axles (tandem and tridem axles), which has an important effect on the state of stress and strain on the pavement and thus has an important effect on the load equivalency factor.

In terms of standard axle, the French pavement design manual adopted the 130 kN standard axle, with dual tires of wheel loads, for both flexible and rigid pavement, which corresponds to the maximum legal limit in France. For analysis purpose, the load was applied on two circular loaded areas, each one with a radius of 12.5 cm and a center-to-center distance of 37.5 cm, which corresponds to a gap between the loads of 12.5 cm, adopting the uniform pressure of 0.662 MPa.

The Shell Pavement Design Manual used a different approach to consider the traffic for pavement design. The standard design single axle load adopted was 80 kN, applied through two wheels of 20 kN with a contact pressure of 0.6MPa and a radius of contact area of 10.5 cm. The gap between the two wheels was equal to the radius.

The calculation of the number of standard axles is made by the Eq.(3), where N is the number of standard axles and L is the axle load to be transformed (kN). This equation is equivalent to the Eq.(1), considering 4 as the exponent. The coefficient 2.2×10^{-8} corresponds to a standard axle of 82 kN.

$$N=2.2\times10^{-8}L^{4} \tag{3}$$

Tandem and tridem axles are treated as two and three separate axles. A loading time of 0.02 s is considered, which corresponds to a speed of 50-60 km/h.

Powell et al. (1984) and later Nunn (2004), in the English pavement design method, adopted the 80 kN as standard axle. The standard axle was represented by a single standard wheel load of 40 kN with a radius of 15.1 cm, corresponding to a uniform pressure of 0.558 MPa.

3.3 Climatic conditions

Climatic conditions are considered in pavement design by the effect of i) the temperature in both asphalt and cement treated materials, ii) the water in the subgrade and granular layers, iii) the frost and thaw in the all pavement layers.

The temperature influences on the behaviour of all different pavement types, namely.

- in flexible pavement, on the temperature affects the mechanical properties of the asphalt mixes;
- in composite pavement, cyclic thermal variation causes opening and closing of shrinkage cracks;
- in rigid pavement, the temperature produces thermal gradients causing stresses in the concrete slabs.

For flexible pavement, the temperature is considered by an equivalent constant temperature on pavement material, which produces the same annual damage as the hourly temperature during the year.

The French design method recommends the use of Miner's law to calculate the equivalent temperature. For a given number of temperatures t_i, the equivalent temperature t_{eq} is calculated through the Eq. (4).

$$\sum_i \frac{n_i(t_i)}{N_i(t_i)} = \frac{\sum_i n_i(t_i)}{N(t_{\mathrm{eq}})} \tag{4}$$

where t_i is an observed temperature, t_{eq} is the equivalent temperature, $N_i(t_i)$ is the number of loadings causing failure due to fatigue for the strain level, and $n_i(t_i)$ is the number of equivalent axle passages undergone on the pavement at temperature t_i. t_{eq} is obtained from the curve giving the variation in damage according to temperature. In France, in general, the temperature adopted for pavement design is 15 ℃.

In the Shell pavement design method, the temperature is incorporated through the use of a weighted mean annual air temperature, w-MAAT, which is derived from the mean monthly air temperatures, MMAT, from a given location and is related to an effective asphalt temperature and thus to an effective asphalt stiffness. Weighting factors have been derived by which the MMAT is multiplied so that a single temperature for the year will produce the same damage as that resulting for 12 monthly temperatures throughout the year. The pavement temperature at a given depth is calculated in function to the w-MAAT and the depth of the layer.

The UK pavement design method does not present any method to calculate the weighting air temperature and considers an equivalent temperature of 20 ℃.

In terms of hydric conditions, only the French manual presents information about the influence of the hydric conditions on the pavement foundation. This information is addressed to a separate manual about the construction of embankments and capping layer (LCPC, 1992), where different cases for the construction of the pavement foundation are defined based on the climatic conditions.

3.4 Subgrade

For any type of pavement, subgrade plays a major role on the pavement bearing capacity, influencing the final solution for the pavement structure. In general, subgrade strength is considered through a simplified approach where an equivalent subgrade modulus is related with its CBR. Only the French design method adopted a more robust approach, which utilized the information of the guide for the realization of embankments and capping layers (LCPC, 2003). This guide classified naturally-occurring soils on the basis of laboratory classification tests (chiefly with respect to their potential use as a filling material), specified the soil categories suitable for incorporation in embankments and the relevant conditions of use, and described the main methods for construction and any restrictions specific to the categories of foundations.

Based on this guide, the soils are classified into different classes (A to D) depending of the percent passing through the 80 µm, 2 mm and 50 mm sieve, which allows the separation among fine soil, sand, and gravel. The water sensibility of the soil is evaluated through the Methyl blue absorption (VBS, with the unit of methyl blue per 100g of soil) of the soil, measured on the 0-50mm fraction.

Additionally, soils have an indicator of the state when they are sensitive to water, based on their IPI value (immediate bearing index is immediate CBR test without surcharge) or their natural moisture content, w_n, at a given time, in relation to the optimum moisture content w_{OPN} determined from the standard proctor test, or on the value of the soil consistency index (I_c). To characterize the state of the soils, five hydrous states are considered, ts means very dry, s means dry, m means normal, h means wet, th means very wet. The normal state (m) of soil corresponds to the best condition for placement since it allows for appropriate compaction. Wet state (h) and very wet (th) state correspond to soils for which trafficability and compaction are difficult because very wet soil is not normally trafficable for a standard earthmoving plant. The dry (s) and very dry (ts) states are soils which are difficult to compact to form stable fill structures because a very dry soil is considered as being impossible to compact properly by standard methods. Example of this definition can be observed in Table 2.

Table 2 Example of the definition of the climatic condition for soil in the French method (LCPC, 1992)

Classification by type					Classification by state	
Type parameters first level classification	Class	Type parameters second level classification	Subclass by type	Principal features	Parameters and limit values	Subclass
$D_{max} \leq 50$ mm and percent passing 80 μm > 35%	Fine soils (A)	VBS ≤ 2.5 or Ip ≤ 12	A_1, low plasticity silts, loess, alluvial silts, dean fine sand, low plasticity granite sand.	Small changes in moisture content produce sudden changes in consistency, especially when w_n is dose to w_{OPN}. Relatively short reaction time to change in moisture and weather conditions but permeability may vary widely depending on grading, plasticity and compactness, so there can be a wide variation in reaction time. With low plasticity fine soils, it is frequently preferable to identifty them by their methyl blue VBS value because of the lack of precision in measuring Ip.	IPI≤ 3 or $w_n \geq 1.25\ w_{OPN}$	A_1th
					3 <IPI≤ 8 or $1.10\ w_{OPN} \leq w_n < 1.25\ w_{OPN}$	A_1h
					8 <IPI≤ 25 or $0.9\ w_{OPN} \leq w_n < 1.10\ w_{OPN}$	A_1m
					$0.7\ w_{OPN} \leq w_n < 0.9 w_{OPN}$	A_1s
					$w_n < 0.7 w_{OPN}$	A_1ts
		12 <Ip ≤ 25 or 2.5 < VBS ≤ 6	A_2, clayey fine sand, silt, low plasticity clays and marls, granite sand, etc.	The mid-range nature of this subclass means they are suitable for use with most types of constructional plant provided moisture content is not too high. Ip is the best identification criterion.	IPI≤ 2 or $I_c \leq 0.9$ or $w_n \geq 1.3 w_{OPN}$	A_2th
					2 <IPI≤ 5 or 0.9 <$I_c \leq 1.05$ or $1.1\ w_{OPN} \leq w_n < 1.3\ w_{OPN}$	A_2h
					5 <IPI≤ 15 or 1.05 <$I_c \leq 1.2$ or $0.9\ w_{OPN} \leq w_n < 1.1\ w_{OPN}$	A_2m
					1.2 <$I_c \leq 1.4$ or $0.7 \geq w_{OPN} \leq w_n < 0.9\ w_{OPN}$	A_2s
					$I_c > 1.4$ or $w_n < 0.7\ w_{OPN}$	A_2ts

For use in capping layers, soils have another classification index based on the FS (sand friability coefficient), the MDE (Micro-Deval coefficient in water measured on 10-14mm fraction, if unavailable, on 6.3-10mm fraction) or the LA (Los Angeles coefficient measured on 10-14mm fraction, if unavailable, on 6.3-10mm fraction).

For design purposes, the mechanical behavior of soils in the pavement foundation is characterized in a very simple way through the CBR value.

In the Shell pavement design method, the definition of the subgrade properties for pavement design consists in the determination of the subgrade modulus, which is considered in this method into two ways:

1. the CBR value of the subgrade soil;
2. the classification of the subgrade soil, either by the AASHO soil classification or by the Unified soil classification.

Subgrade modulus (Pa) is given by Eq.(5), which must be used with accuracy since the model has a factor of two between the values given by the model and current values (Claussen et al., 1977).

$$E = 10^{7}\,\mathrm{CBR} \tag{5}$$

where CBR is the bearing capacity of the subgrade (%).

In the UK method, the stiffness of the subgrade (MPa) is defined in function of the CBR through the Eq.(6).

$$E = 17.6\,\mathrm{CBR}^{0.64} \tag{6}$$

In this method, the pavement structure is also composed of a capping layer when the CBR of the subgrade is inferior to 5%, in order to provide a working platform on which sub-base construction can proceed with minimum interruption in wet weather and to minimize the effect of a weak subgrade on road performance. The capping layer reduces the risk of damage during construction operations to any cement-bound materials above the capping layer and thus improving the structural contribution of these layers.

In terms of permanent deformation, the different pavement design manuals have fatigue laws, which relate the strain level at the top of the subgrade with the number of loading cycles. Shell manual (Shell International Petroleum Company, Ltd, 1978) has different fatigue laws in function of the confidence interval, as indicated in Eq. (7), where a = 2.8x10^{-2} for 50% confidence, a = 2.1x10^{-2} for 85% confidence and a = 1.8x10^{-2} for 95% confidence.

$$\varepsilon_z = aN^{-0.25} \tag{7}$$

The permanent deformation in the UK design method is considered by the model presented in Eq.(8).

$$\log(N) = -7.21 - 3.95\log(\varepsilon_z) \tag{8}$$

In the French design method, the permanent deformation due to the subgrade is considered in function of the traffic volume through the Eq.(9), where a = 0.012 for traffic ≥T3 and a = 0.016 for traffic <T3.

$$\varepsilon_z = aN^{-0.222} \tag{9}$$

These models, for the definition of the subgrade modulus and the permanent deformation resistance of the pavement foundation, are easily applied due to their simplicity. However, due to their simplicity they include great simplifications by not including the effect of all variables inherent to the phenomenon that they try to simulate. Thus, their application must be done with all precautions because the obtained results may not represent the real behavior of the pavement.

3.5 Granular materials

In pavement, the granular layers have the following roles (Araya, 2011), the ability to carry a significant portion of the load applied by a vehicle (during construction and service time) and load spreading to a magnitude that will not damage the underlying layers, particularly the subgrade; resistance to the built up of permanent deformation within each layer; the provision of an adequately stiff layer on which the overlaying layers can be compacted; and the provision of an adequately durable and stiff layer to support any overlaying layers in the long term during in-service conditions.

Granular materials are used in pavement as capping layers, sub-base and base layers. Depending on the traffic level, not all of these layers are required, although they have significant importances for the pavement bearing capacity. In thin asphalt pavement, together with pavement foundation, they have the main contribution for the overall bearing capacity, reducing its importance as the asphalt layers present higher thickness.

These materials are chosen according to the gradation, hardness of the aggregates, cleanness of the sand and gravel, and angularity in the case of alluvial origin. The application of these materials is made at the optimum Proctor water content and compacted through procedures identical for soil compaction.

In the Shell pavement design method, the mechanical characterization of the untreated granular layers is done by the application of Eq.(10), where E_2 is the stiffness of the granular layer, E_3 is the modulus of the subgrade and k is a coefficient function of the thickness of the granular layer (h_2).Eq. (10)

could be calculated with Eq.(11), and was developed by Dormon and Metcalf (1965), applicable in the range $2<h_2<4$.

$$E_2 = kE_3 \tag{10}$$

$$k = 0.2h_2^{0.45},\ h_2(\mathrm{mm}) \tag{11}$$

The stiffness of the granular layers (base and sub-base) in the UK method is function of the underlying layer as indicated in Eq.(12), where E_{n+1} is the modulus of the underlying layer.

$$\begin{cases} E_n = 3E_{n+1} & E_{n+1} \le 50\ \mathrm{MPa} \\ E_n = 150 & E_{n+1} > 50\ \mathrm{MPa} \end{cases} \tag{12}$$

The method assumes 75 mm for rut depth of the sub-base, which is expressed by Eq.(13), derived from US Army Corps of Engineers experiments, where N_{75} is the number of standard axles of 80 kN, h is the thickness of the sub-base, CBR represents the bearing capacity of the subgrade.

$$\log(N_{75}) = \frac{h\mathrm{CBR}^{0.63}}{190} \tag{13}$$

Later, experiences in UK (Potter and Currer, 1981) have demonstrated a greater resistance to rut of good quality sub-base than that predicted by the above equation. Thus, the method has proposed Eq.(14) to define the thickness of the sub-base for a 40 mm rut depth.

$$\log(N_{40}) = \frac{h\mathrm{CBR}^{0.63}}{190} - 0.24 \tag{14}$$

In the French method, the modulus of the granular layers with untreated graded aggregates (GNT) is defined in function of the traffic volume, type of layer (base or sub-base) and type of material (Table 3).

Table 3 Design Young's modulus for untreated graded aggregates (GNT) layers (LCPC, 2003).

Low traffic pavement	
Road base	Category 1 • E_{GNT} = 600 MPa Category 2 • E_{GNT} = 400 MPa Category 3 • E_{GNT} = 200 MPa
Sub-base (GNT, sub-layers 0.25 thick)	$E_{GNT}(1) = kE_{\text{pavement foundation}}$ E_{GNT}(sub-layer i) = kE_{GNT} [sub-layer (i-1)] with k varying depending on the category of untreated granular material, for category is 1, 2, 3, k is 3.0, 2.5, 2.0, respectively. $E_{GNT}$is limited by the value indicated in the road base.
Medium traffic pavements: granular material and bitumen mix/untreated gravel structures	
Sub-base (GNT, sub-layers 0.25 thick)	$E_{GNT}(1) = 3\ E_{\text{pavement foundation}}$ E_{GNT}(sub-layer i) = 3 E_{GNT} [sub-layer (i-1)] E_{GNT}(1)is limited by 360 MPa

3.6 Asphalt mix design

The formulation of the asphalt mixes in Europe mainly adopts the Marshall method, which is specified in the European standard EN 13108-1 for both stability and flow. The ratio between stability and flow is also specified in the standard, as well as the volumetric parameters of the asphalt mix. France uses a different approach based on the Gyratory method (Fig. 5).

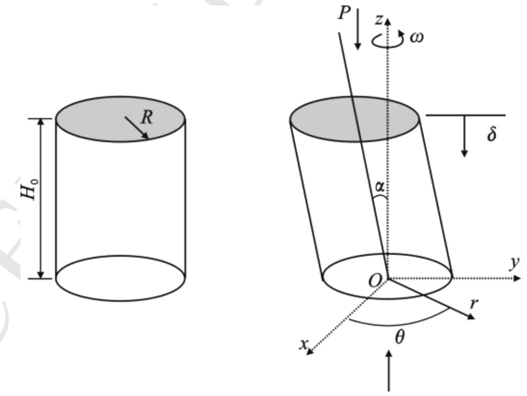

Fig. 5 Representation of the gyratory shear compaction (Guler, 2008).

However, the design of the asphalt mixes in Europe uses other tests to complement the design process as both the Marshall and the Gyratory methods do not assess the fundamental properties of the asphalt mixes, as well as performances related properties are important to predict pavement behavior. In this case, several complement tests are required to confirm the design of the asphalt mix. The main complementary tests are related to the water sensitivity and resistance to permanent deformation of the asphalt mixes, which are evaluated through the indirect tension strength ratio and the Hamburg Wheel-Track Device test or Wheel-Track test. In France, the asphalt mix design with the gyratory compactor is complemented with water sensibility through the Duriez test (Fig. 6), the permanent deformation resistance with the LCPC wheel track test, the stiffness assessment with the two-point trapezoidal bending beam and the fatigue resistance with the two-point trapezoidal bending beam as well. In the UK, complementary tests to assess water sensitivity, rutting, stiffness, and fatigue resistance are considered.

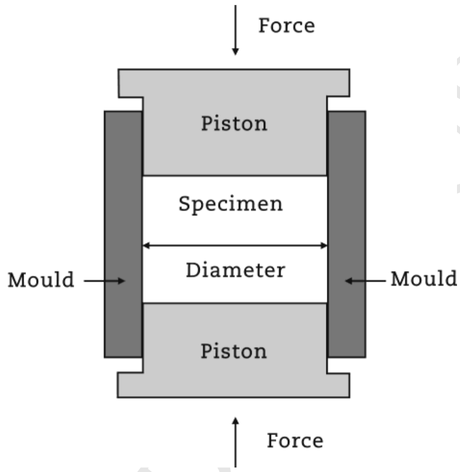

Fig. 6 Duriez test.

The asphalt mix design in Europe uses different types of tests for the preparation of the specimens and for assessment of their properties, which are used to select the main result of the mix design, the optimum binder content.

The main testing equipment used in the design is the Marshall device, which allows obtaining the stability and the flow of specimens compacted with the Marshall compactor. European standard EN12697-34 defined the procedure to perform the Marshall test and interpretation of the result.

The other mix design method uses gyratory shear testing, where a specimen is compacted in the gyratory compactor and the height of the specimen is monitored and correlated with its air-void content. The test consists of the application of a constant axial force, while the specimen rotates in turn of its axle that has a slight angle with the force that is responsible for the shear effect.

In the French method (LCPC, 2007), the asphalt mixes are designed based on their use, type of asphalt mix and traffic volume, by the implementation of design levels from the simplest (Level 0) to the most thorough (Level 4), with the higher levels always including the requirements addressed in the lower levels.

Level 0 corresponds to a description of the asphalt mixes according to a grading and binder content without any type of test. This is used only for asphalt mixes for non-trafficked areas.

The design in Level 1 must be able to satisfy a full range of void percentages for use in the gyratory compactor test, as well as water resistance. This level consists only a volumetric design of the asphalt mixes with the verification of the effect of the water in the asphalt mix.

Level 2 includes the tests from Level 1 (gyratory compactor and water resistance) together with the evaluation of resistance to permanent deformation through the Wheel-Track test. This level starts with the verification of the performance of the asphalt mix, in this case, the resistance to the permanent deformation.

Level 3, in addition to the specifications of previous levels, it includes the evaluation of the stiffness modulus of the asphalt mix. This design level is proposed whenever the stiffness is considered in the structural design of the pavement, which happens for major road pavement, corresponding to a level that is included in the fundamental approach of the European standards.

Level 4 includes the determination of the fatigue resistance of mix designs under previous levels, completing the fundamental approach of the European standards. This level must be considered when the asphalt mix is part of pavement for major roads and in a layer submitted to fatigue. The fatigue response is considered by the 6 parameters that represent the tensile strain for 1 million load cycles.

According to the definitions of EN 13108-1, Level 0, Level 1, and Level 2 are relevant for the "general + empirical" approach and Level 3 and Level 4 for the "general + fundamental", as indicated in Fig. 7.

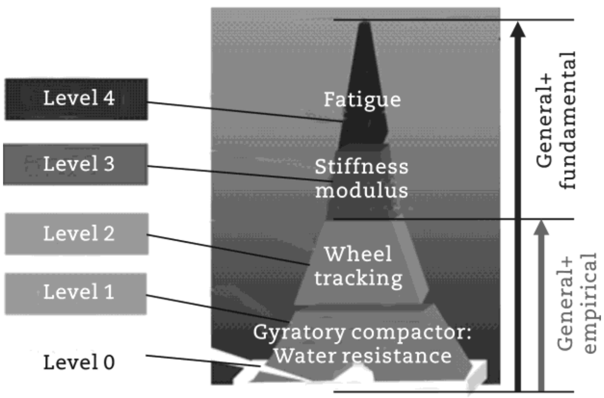

Fig. 7 Level of the French asphalt mix design (LCPC, 2007).

3.7 Asphalt mix modelling

The modelling of the behavior of asphalt mixes for pavement design comprises mainly the estimation or determination of performance related indicators, such as stiffness modulus, fatigue resistance, and permanent deformation resistance.

In Europe, the stiffness of the asphalt mixes is assessed through the EN12697-26 standard that specifies methods to characterize the stiffness of asphalt mixes by different procedures, including bending tests and direct and indirect tensile tests. In general, the tests are performed under a sinusoidal loading or other controlled loading, using different types of specimens (CEN, 2004a).

Different testing equipments are used to evaluate the stiffness of the asphalt mixes. In Europe these equipments include two-point bending with trapezoidal specimens (used only in the French methodology), four-point bending with prismatic specimens, indirect tension with cylindrical specimens, and direct tension with cylindrical specimens.

Fatigue resistance of asphalt mixes is defined in the European Standard EN12697-24 that specifies the methods for the characterization of the fatigue of asphalt mixes by bending tests and direct and indirect tensile tests, such as for stiffness assessment. Fatigue characterization is used to rank asphalt mixes, as a guide to relative performance in the pavement, to obtain data for estimating the structural behavior in the road and to judge test data according to specifications for asphalt mixes (CEN, 2004b).

Different approaches are used to evaluate the fatigue response of an asphalt mix. The main approach consists of performing fatigue tests at a specific strain level, which allows for the calculation of the corresponding fatigue resistance or fatigue life. If strain level installed in the pavement is known, with resulting fatigue law, it is possible to determine the corresponding fatigue life, as indicated in Fig. 8.

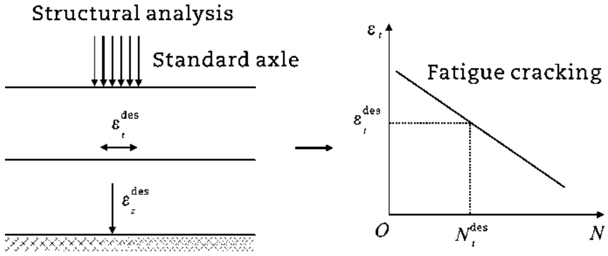

Fig. 8 Schematic representation of the assessment of pavement fatigue life.

However, in the assessment the usual procedure consists of the fatigue resistance of an asphalt mix by determining its fatigue law, allowing interpolating or extrapolating the fatigue resistance for the strain level installed in the pavement.

The determination of the fatigue law for an asphalt mix requires the testing of a large number of specimens due to the dispersion of the results of the fatigue tests. The European Standard EN12697-24 requires the testing of at least a total of 18 specimens at 3 different strain levels. ASTM standard (ASTM, 2010) requires only 6 specimens and AASHTO standard (AASHTO, 2003) does not define the number of specimens to be tested.

The rutting resistance is defined in the European Standards EN12697-22 as the susceptibility of asphalt mixes to deform under load and temperature, which is assessed by the rut formed by repeated passing of a loaded wheel at constant temperature. Three alternative types of equipment can be used according to this standard, large, extra-large, and small-size devices. With large and extra-large size devices, the specimens are conditioned in air during testing. With small-size devices, specimens are conditioned in either air or water (CEN, 2004c).

The stiffness modulus of the asphalt mixes is calculated through laboratory tests, previously referred to, which requires the production of an asphalt mix similar to that to be produced and applied in the real pavement.

Frequently, for assessment of pavement design, stiffness of the asphalt mixes is predicted using existing models that include the variables related to stiffness, i) binder, ii) service temperature, and iii) volumetric characteristics of the asphalt mix. The Shell monographs are the oldest models, and the first to predict the stiffness of the bitumen and second to predict the stiffness of the asphalt mix.

The stiffness of the binder can be calculated from the Van der Poel (1954) monograph developed by Shell Laboratory in Amsterdam (KSLA), which allows the prediction of the stiffness modulus of bitumen within a factor of two, which is remarkable in relation to the large range of the stiffness (Bonnaure et al., 1977). The monograph used the loading time, softening temperature, surface temperature and penetration index of the binder. Later, Ullidtz and Peattie (1982) developed an estimation model (Eq.(15)) for the computation of the stiffness of the binder that correlates the stiffness of the binder with the loading time, penetration index, softening temperature and service temperature, where S_b is the binder stiffness (MPa), t_c is the loading time (s), IP is the penetration index of the binder (Eq.(16)), T_{RB} is the softening temperature (℃) by the ring and ball method, T is the service temperature (℃). The penetration index is given in Eq.(16), where PEN_{25} is the penetration of the binder at 25 ℃.

$$S_{\mathrm{b}} = 1.157 \times 10^{-7} t_{\mathrm{c}}^{-0.368} 2.718^{\mathrm{IP}} (T_{\mathrm{RB}} - T)^5 \tag{15}$$

$$\mathrm{IP} = \frac{20T_{\mathrm{RB}} + 500\log(\mathrm{PEN}_{25}) - 1955.55}{T_{\mathrm{RB}} - 50\log(\mathrm{PEN}_{25}) + 120.15} \tag{16}$$

Brown et al. (1985), for asphalt mixes with more than 3% of air-void content, developed a model for the stiffness of the asphalt mix (Eq.(17)), where VMA represents the voids in mix of aggregates (%).

$$S_{\mathrm{m}} = S_{\mathrm{b}}[1 + \frac{257.5 + 2.5\mathrm{VMA}}{n(\mathrm{VMA} - 3)}]^n \tag{17}$$

However, the monograph developed by Shell researchers (Bonnaure et al., 1977) is still considered a reference for the prediction of the stiffness of the asphalt mix.

The influence of the temperature on the stiffness modulus of the asphalt mixes has been studied by several researchers, using results from pavement back calculation, obtained through data from falling weight deflectometer. The first model was developed by Ullidtz and Peattie (1982), as indicated in Eq. (18), where S_T and S_{15} are the asphalt moduli at temperatures of T (℃) and 15 ℃.

$$\frac{S_T}{S_{15}} = 1 - 1.384\log(\frac{T}{15}) \tag{18}$$

In the UK pavement design method, for the calculation of the stiffness of asphalt layers a frequency of 5 Hz is considered.

The fatigue resistance of an asphalt mix refers to its ability to withstand repeated bending without fracture. Fatigue, a common form of distress in asphalt pavement, manifests itself, in general, is in the form of cracking due to repeated traffic loading. It is important to have a measurement of the fatigue characteristics of specific mixes over a range of traffic and environmental conditions, so that fatigue results can be incorporated into the process of designing asphalt pavement.

The fatigue characteristics of asphalt mixes are usually expressed as the relationships between the initial stress or strain and the number of load repetitions to failure, determined by using repeated flexure, direct tension or diametric tests performed at several stress or strain levels (Tayebali et al., 1994).

Fatigue tests are carried out in two modes, controlled strain and controlled stress. In controlled strain mode, the strain is kept constant by decreasing the stress during the test, whereas in controlled stress the stress is maintained constant which increases the strain during the test. In general, controlled stress testing has been related to relatively thick pavement structures where high stiffness is the fundamental parameter that underpins fatigue life. Controlled strain testing, on the other hand, has been associated with thin conventional flexible pavement where the elastic recovery properties of the material have a fundamental effect on its fatigue life (Artamendi and Khalid, 2004).

The fatigue behavior of a specific asphalt mix can be characterized by the slope and relative level of the stress or strain versus the number of load repetitions to failure, and can be defined by a relationship proposed by Monismith et al. (1971) in Eq.(19), where N is the number of repetitions to failure, ε and σ are tensile strain and stress applied, a, b are experimentally determined coefficients.

$$N = a\left(\frac{1}{\varepsilon;\sigma}\right)^{b} \tag{19}$$

However, the fatigue response is dependent on the stiffness of the asphalt mix. Thus, Monismith et al. (1985) have proposed the Eq.(20), where E_{mix} is the stiffness of the asphalt mix, to express the fatigue response of asphalt mixes.

$$N = a\left(\frac{1}{\varepsilon;\sigma}\right)^{b}\left(\frac{1}{E_{\mathrm{mix}}}\right)^{c} \tag{20}$$

The stiffness at any number of load repetitions is computed from the tensile stress and strain. The fatigue life to failure is dependent on the mode of loading condition. For controlled stress tests, failure is well defined since specimens are cracked to the end of the test. In controlled strain testing, failure is not readily apparent. Accordingly, the specimen is considered to have failed when its initial stiffness is reduced by 50% (Tayebali et al., 1994).

Many fatigue laws have been developed during the last years, some of which were not only be used to compare materials, but also to be applied in pavement design. In Europe, the main fatigue laws used in pavement design include the Shell model, the UK model, and the French one.

The Shell fatigue law is defined in Eq.(21) and correlated the fatigue life (N) with the strain level (ε), stiffness of the asphalt mixes (S_{mix}) and volume of bitumen (V_{b}). This is the most used fatigue law in Europe, coming from an extensive laboratory testing program. This fatigue law was calibrated in order to be used in the pavement design to predict the pavement life.

$$\varepsilon = (0.856V_{\text{b}} + 1.08)S_{\text{mix}}^{-0.36}N^{-0.2} \tag{21}$$

The UK pavement design method uses a simple fatigue law which is only dependent on the strain level, as indicated in Eq.(22).

$$\log(N) = -9.38 - 4.16\log(\varepsilon) \tag{22}$$

In the update of the UK method, a different configuration for the fatigue law of the asphalt layers was introduced Eq. (23), where ε_{r} is the strain level for design, ε_6 is the strain for 1 million load cycles, N is the fatigue life, K_{flex} is a risk factor and K_{safety} is a security factor as defined below.

$$\varepsilon_{\text{r}} = K_{\text{flex}}K_{\text{safety}}\varepsilon_6(\frac{N}{10^6})^{-0.24} \tag{23}$$

For K_{flex},this factor depends upon the design stiffness (E) of the asphalt base, as defined in Eq. (24). The use of this criterion ensures that pavement with stiff asphalt bases does not bend as much as pavement with a less stiff asphalt base. For K_{safety},this factor can be used to control the inherent risk in pavement design. The value could be adjusted for roads with very heavy traffic or for roads constructed in sensitive areas or to give additional strength to designs using new materials or new construction practices. The default value will be 1.0.

$$K_{\text{flex}} = 1.089E^{-0.172} \tag{24}$$

More practical is the fatigue law developed by LCPC for French design manual, which has its format presented in Eq.(25). The ε_6 and b are dependent on the asphalt mixes, according to Table 4.

$$\frac{\varepsilon}{\varepsilon_6} = (\frac{N}{10^6})^b \tag{25}$$

Table 4 Specifications for fatigue resistance.

	Class	ε_6	-1/b
Asphalt concrete	1	70	5
	2	80	5
	3	90	5
High modulus asphalt concrete	1	100	5
	2	130	5

Over a fairly broad range of positive temperatures, an approximate value for the interdependency of the stiffness modulus E and of the strain ε_6 can be obtained with the Eq.(26). In the absence of results of fatigue tests for a given material at different temperatures, a mean value of 0.5 can be selected for n.

$$\varepsilon_6(t)E^n(t) = \text{constant} \tag{26}$$

The design of pavements in the French method is associated to a degree of risk that is introduced in the admissible strain for the asphalt layers, as expressed in Eq. (27).

$$\varepsilon_{\text{t,ad}} = \varepsilon(N, T_{\text{eq}}, f)k_{\text{r}}k_{\text{c}}k_{\text{s}} \tag{27}$$

where $\varepsilon_{\text{t,ad}}$ is the admissible tensile strain at the bottom of the asphalt layer, ε is the tensile strain at the bottom of the asphalt layer, obtained in laboratory tests for a given equivalent temperature (T_{eq}) and a given frequency (f). $\varepsilon(N, T_{\text{eq}}, f)$ is the strain for which conventional failure on a test sample, being obtained after N cycles with 50% probability of failure, for the equivalent temperature T_{eq} and at the frequency f. Eq.(28) defines the coefficient for the adjustment of the laboratory fatigue results to a given temperature. In terms of frequency, no adjustment is need for frequencies between 10 and 25 Hz for average temperatures around 15 ℃.k_{r} is a coefficient which adjusts the strain value to the calculated risk, chosen according to factors of a confidence interval around the thickness (standard deviation Sh), and the results of the fatigue test (standard deviation SN). The k_{r} is calculated according to Eq.(28).

$$k_{\text{r}} = 10^{-ub\delta} \tag{28}$$

where u is a reduced centered variable associated with the risk r, b is the slope of the material fatigue law (bi-logarithmic law), δ is the standard deviation of the distribution of log(N) at failure, given by Eq.(29), c is the coefficient linking the variation in strain to the random variation of the pavement thickness, Δh. For usual structures, c is approximately 0.02 cm^{-1}.

$$\delta = \sqrt{\mathrm{SN}^2 + (\frac{c}{b})^2 \Delta h^2} \quad (29)$$

k_c is a coefficient allowing adjustment of the fatigue model to the behaviour observed on pavements in service of the same type. For asphalt pavements, the values chosen for the coefficient of adjustment according to the nature of the asphalt material are specified in Table 5.

Table 5 Values of the coefficient k_c.

Material	k_c
Road base asphalt concrete, BG	1.3
Asphalt concrete, BB	1.1
High modulus asphalt concrete, EME	1.0

k_s is a coefficient of reduction to take into account the effect of a lack of uniformity in the bearing capacity of the subgrade, as defined in Table 6.

Table 6 Values of the coefficient k_s.

Modulus	E< 50 MPa	50 MPa ≤ E< 120 MPa	120 MPa ≤ E
k_s	1/1.2	1/1.1	1

Mixes design could also be studied with an accelerated loading facility (ALF), in field or at laboratory. With an ALF, a controlled application of a prototype wheel loading, at or above legal load limit, allows for an assessment of pavement response and performance. The acceleration of damage in the pavement is obtained by increasing the number of loading repetitions, modified loading conditions or by the use of thinner pavement (Metcaft, 1996).

Many agencies operate accelerated pavement testing facilities to evaluate construction materials and pavement design and other aspects related to pavement technology. Of primary concern in accelerated pavement testing is the application of a certain traffic volume, in a reasonable length of time and at an acceptable cost to produce a measurable response or deterioration (Saeed and Hall, 2003).

Hugo and Epps-Martin (2004) stated that accelerated pavement testing has served as a means of improving performance and economics of pavements and improving the understanding of the factors that affect pavement performance through the ability to

- explore a wide variety of pavement compositions;
- simulate deterioration mechanisms and conditions of loading and environment;
- test and characterize materials;

- analyze and understand the response and performance of pavement.

In Europe there are 15 accelerated loading facilities (Table 7), supporting researches in pavement materials and pavement design. The largest are the CEDEX and LCPC facilities, which are presented in Fig. 9.

Table 7 Accelerated loading facilities in Europe.

#	Place/name, Country	Type of installation	Length (m)	Speed (km/h)
1	Lyngby, Denmark	Linear	12	24
2	Oulu, Finland	Linear		
3	LINTRACK, Netherlands	Linear	4	20
4	LAVOC, Switzerland	Linear	2	12
5	MSL-EMPA-ETH, Switzerland	Linear	4.2	22
6	TRL, UK	Linear	7	20
7	Bergich Gladback, Germany	Linear	4	22
8	Nottingham, UK	Linear	4	12
9	Lisbon, Portugal	Linear	12	20
10	Sweden/Finland	Linear (movable)	6	12
11	CEDEX, Spain	Linear/Circular	288	60
12	LCPC, France	Circular	110	100
13	IASI, Romania	Circular	47	40
14	Bratislava, Slovakia	Circular		
15	Dresden, Germany	Pulse loading	--	--

(a) (b)

Fig. 9 LCPC and CEDEX accelerated loading facilities. (a) LCPC. (b) CEDEX.

The review of design methods carried out by Nunn and Merrill (1997) has shown that 60% of European countries surveyed have developed analytical designs methods, which are similar in concept. These methods deal only with 2 forms of deterioration, fatigue, and structural deformation, in a fairly simplistic manner, with many assumptions inherent in the methods and factors that need to be calibrated. The pavement design methods presented, namely from LCPC (France), Shell, TRL (UK) are included in the group of mechanistic-empirical methods that use the same methodology for the design, presenting small differences. The more relevant differences are observed in the definition of materials and its models for the mechanical characterization inherent to the material specifications for each country.

This conclusion means that the mechanistic-empirical pavement design methods as previously defined can be applied to any country by changing the material properties due to the climatic conditions and types of material used in that country. These properties are related to the stiffness of the asphalt mixes as well as its fatigue response. For the granular layer of the subgrade, its properties for pavement design are more stable and, in general, its adaptation for every country is not necessary.

4 Pavement design challenges

Previous sections have shown the present situation in the field of pavement design in Europe, which is not too much different from other developed countries around the world. Hereafter, the future challenges for road infrastructures and the present challenges for pavement design will be discussed. At the end, present research developments on pavement design and an implementable methodology from deep research will also be discussed.

4.1 Future challenges for road infrastructures

The ultimate challenge of road infrastructures must be to provide a reliable service to people and goods, and the main focus is the reliability of the road network, in terms of time, safety and comfort.

After a period without any significant changes, the future will be much different due to the exponential increase in the technology that leads to different types of transportation which require suitable infrastructures.

In order to anticipate future needs, a dialogue with decision makers, as well as with the vehicle industry, will need to be established as it continues to be decades ahead in the development of vehicles for future transportation.

Thus, research and technology in the field of road infrastructure must be in line with the vehicle industry, since during the next decades, transportation modes will be more challenging, mainly due to the appearance of electrical and autonomous vehicles, supported by ITS technology for data communication and electronics, also with vehicles producing and sharing energy.

In this context, with the incorporation of more and more high value materials and technologies inside road infrastructure, therefore this must be perpetual, mainly through perpetual pavements, only requiring surface rehabilitation, where the key word is that of long term planning within the life cycle assessment of infrastructure, which supports the process of asset management and provide not only the technical solution but also the economical solution in terms of cost/benefit analysis in a multidisciplinary approach.

To achieve this global challenge, another mandatory word is that of integration of core components: i) transport modes and infrastructures, ii) users and society's expectations and demands, iii) economic challenges, iv) environmental protection. All these challenges would only be possible through multidisciplinary and cooperative research efforts, supporting the vision of "S4 roads: sustainable, smart, safe and smiling roads". Under this vision, in Europe, FEHRL (2008) analyzed new road construction concepts for a reliable, green, safe, smart and human infrastructure, proposing the consideration of the following expectations.

- Reliable infrastructure, standing for optimizing the availability of infrastructure;
- Green (environmentally-friendly) infrastructure, standing for reducing the environmental impact of traffic and infrastructure on the sustainable society;
- Safe and smart infrastructure, standing for optimizing flows of traffic of all categories of road users and safe road construction working;
- Human infrastructure, standing for harmonizing infrastructure with the human dimensions.

4.2 Present challenges for pavement design

When analyzing the current pavement design methods in Europe, it was concluded that the two structural pavement design criteria are: i) fatigue cracking, at bottom of the asphalt layers, ii) permanent deformation, at the top of the subgrade.

However, at present, and particularly for pavement structures intended for heavy traffic, these distress mechanisms are no longer the most frequently used ones. In fact, frequently observed deterioration mechanisms in field, such as rutting originating in the asphalt layers and cracking initiated in the pavement surface, are not directly taken into account in current pavement design methods. In addition, functional distresses appearing in the pavement surface, such as roughness, loss of surface skid resistance and raveling must be included, although, these last ones are closely related with the properties of wearing course, whose design should prevent its occurrence.

Thus, it can be concluded that when reviewing the requirements of the main pavement components and deterioration mechanisms, together with the review of current pavement design methods, some discrepancies can be observed between present modes of pavement deterioration and the modes of pavement deterioration on which current pavement design methods are based. This situation, in addition to the variability of materials characteristics and consequent behavior along a road, could explain the majority of cases when real pavement performance does not match the expected one at pavement design phase.

The behavior of a pavement is extremely complex with cyclic effects and systematic changes observed during its service life. The material properties can change for different reasons and some of the causes of change could act in the opposite sense, which makes the prediction of pavement life problematic. For instance, the stiffness of asphalt can increase due to age related hardening, further aggravated by traffic, falling temperature or healing. However, stiffness could be reduced due to traffic fatigue, thermal fatigue and rising temperature. In addition, there are interactions between all layers of the road structure. Present design methods do not recognize this interdependence, as well as changes in properties of the layers with time, consequently assuming a modest representation of reality.

Another relevant issue in pavement design quality is related to the consideration of variability, which would lead to the adoption of the probabilistic approach. In the process of pavement design structures (new or rehabilitated), several factors intervene, presenting a variable or uncertain nature with the traffic prediction, along with the pavement life period being the most relevant. In addition to these uncertainties, variability is also associated with the wander effect of traffic, which is related to the speed and transversal geometry of the road. Climatic conditions will also result in variations on their characteristics along its life span. Subgrade, as well as the materials of the different layers and their construction processes quality will impose a significant additional variability in the structural behavior of the pavement, with a direct impact on the performance of the pavement and on its life span.

In the complexity of pavement behavior, another source is found regarding the interactions between different forms of deterioration, occurring with different degrees according to the condition of pavement along its life span. As a conclusion, in an ideal situation, prediction of a pavement distress should not be considered without taking into account the evolution of other types of distress, along the same period of time.

To deal with the present situation and the complexity pavement behavior, the European Commission (EC, 1999, 2000) has stressed the needs for development of a new, coherent, cost-effective and harmonized pavement design method that can be applied throughout Europe.

The new method should therefore incorporate advanced models and should also be able to make a better prediction of pavement performance, taking into consideration of changes over the entire life cycle, from the main components intervening in the design process.

Despite the needs for the development of present pavement design methods, implementation should assume the balance between efficiency and complexity that must be applied to a pavement design method. A design method is only efficient and reliable if it can predict pavement performance using a small number of variables with an acceptable cost. Otherwise, given the dependence between the variables involved in the pavement design, the prediction of the pavement performance would be of less accuracy.

4.3 Present research developments on pavement design

In the USA, a mechanistic-empirical approach was carried out to improve pavement design and the result is the NCHRP 1-37A Project (NCHRP, 2004) which implements the Mechanistic-Empirical Pavement Design Guide. This included calibrated models to predict distinct distresses induced by traffic loads and environmental conditions, as well as the evolution from ESAL to vehicle class and a load distribution approach. Also, the incremental analysis during pavement life time was implemented in order to predict a continuous pavement performance evolution not only for structural distresses, but also for functional distresses. Despite the innovation offered by the MEPDG, the basis of the method is still the simple mechanistic-empirical approach developed by Dormon and Metcalf (1965) and implemented in some design methods, both in the USA and Europe. The main innovation obtained in the MEPDG is related to the characterization of the traffic, climatic conditions, materials and response and performance models.

In Europe some brainstorms were carried out to analyze the existing pavement design methods and to define improvements to adapt the existing ones. COST Action 333 recommended that a number of improvements or new developments could be applied to pavement design while the AMADEUS project showed that some of the design elements already incorporated in existing software tools might be used as a starting point for such improvements.

Hereafter, the main components involved in an innovative pavement design method, geometry, traffic, climatic conditions, materials and pavement design methodology, have been discussed, considering present researches and the expected future evolution of their accuracy.

4.3.1 Geometry

In pavement geometry, it is not expected that the traditional configuration will experience relevant changes in the next decades during which the pavements will continue to have several layers, from granular to bound layers, apart from the constitution of layers materials.

Meanwhile, new developments in the vehicles will lead to different structures, probably stiffer, with only one structural layer and one wearing course submitted to different distresses. In this case, the maintenance and rehabilitation of the pavement will be dedicated to the wearing course regeneration or recycling without interventions in the structural base layer.

However, during its life, road pavement is subjected to some variations in its geometry, mainly in the layer thickness that can be included in sophisticated design methods. The effect of this variation has no significance in static analysis, as it has been demonstrated in the current pavement performance. However, it is important when performing dynamic analysis. This is highlighted in the Fig. 10 where Xia et al. (2015) studied the effect of the pavement roughness on the dynamic response of pavements and concluded that the pavement response increased with increased suspension stiffness and tire stiffness and decreased with increased suspension damping and tire damping. Similar studies were carried out by Graczyk et al. (2016), Khavassefat et al. (2012, 2013, 2015) and Lak et al. (2011), emphasizing the importance of the dynamic load in pavement analysis.

(a)

(b)

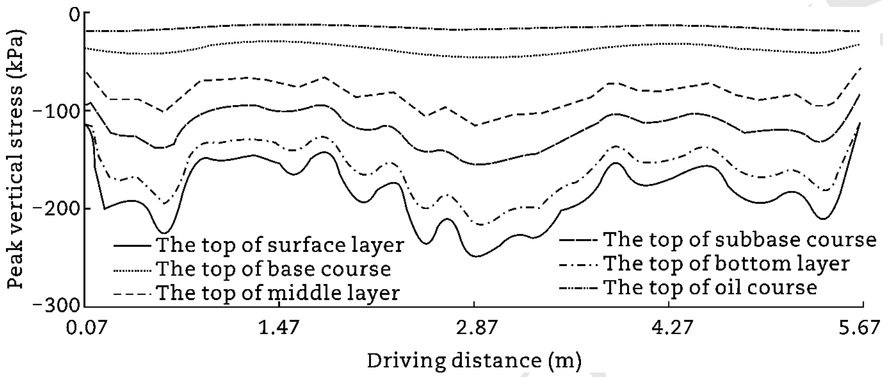

Fig. 10 Effect of the pavement roughness on the dynamic response of pavements due to the pavement roughness. (a) Pavement roughness. (b) Effect of the pavement roughness on the dynamic response of pavement (Xia et al., 2015).

Apart from the variation in layer thickness inherent to the construction process, the variation in layer thickness is the result of the transverse unevenness (rutting) due to permanent deformation of all pavement layers, with a relevant contribution of the subgrade and wearing course. Rutting must be considered when lateral wander of vehicles in the wheel path is taken into consideration. This deviation could decrease when the transverse unevenness increases and thus result in a change in the loading conditions.

The longitudinal unevenness resulting from construction variability, due to spreading and compaction of the asphalt mix (and granular layers), causes a dynamic load effect and changes in the loading conditions as well. Unevenness influences the ride comfort, with possible damage to goods, vehicle wear, safety and environmental noise, but also has consequences on pavement damage due to the dynamic effects of the vehicles along the road.

Thus, pavement geometry, evolving with time, can be one of the challenges in the future development of new pavement design methods by considering the evolution of the layer thickness during pavement life and consequent dynamic loading.

The use of the Burmister model, where pavement layers are considered with a finite and constant thickness, except the subgrade, constitutes an approach that cannot be used to implement the thickness variation. Considering the effects of the thickness variation, a finite element or a discrete element method must be used in the pavement analysis and design.

Associated with the reflective cracking, also considered as a main distress mode in rehabilitated pavements (Sousa et al., 2002), the presence of interlayers in the pavement will be a subject for further development in the geometry of pavement, mainly due to the inclusion of geocomposites and geogrids. In this case, the model of the pavement structure must allow for large movements in the vicinity of the cracks and horizontal displacements between the interlayer material and the adjacent layers to model the real behaviour of the pavement as presented in Fig. 11.

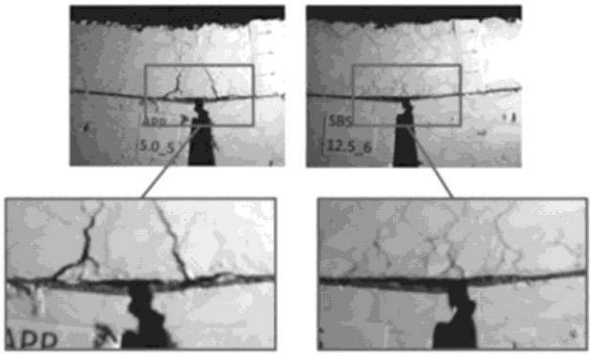

Fig. 11 Crack pattern resulting from the debonding between membranes and asphalt layers (Pasquini et al., 2015).

4.3.2 Traffic

Traffic constitutes the most relevant component of any pavement design, mainly because it is the factor that represents the characteristics of the vehicles in pavement modelling, namely axle and wheel configuration where the different pressure configurations applied by wheels represent the main challenge for the adequate characterization of the traffic (Amorim et al., 2015; Pais et al., 2013). Also, the axle suspension, presenting interaction with the unevenness of the pavement, constitutes a huge challenge for pavement modelling.

The development of a future pavement design methodology must answer to these challenges and not remain in simple analysis based on the load equivalence factors that are implemented worldwide and at present, constitutes a simplified tool to characterize road traffic.

Thus, the future methodology for pavement design must be supported by numerical modelling, for example, finite elements offering powerful possibilities in the modelling of complex problems, namely simulating non-circular and non-uniform loading areas, representative of the contact wheel-pavement.

However, for a more realistic pavement modelling, the load, actually considered by circular areas in the Burmister approach or by rectangular/squared areas in finite elements models, must consider the tire-pavement interaction in terms of elastic deformation of the tire against inelastic deformation of the pavement. Also, the tire structure, load, internal pressure, velocity, braking, free rolling and acceleration must be considered. This can be accomplished by using the numerical model, such as finite elements, where recently Wollny et al. (2016) and Wang and Al-Qadi (2011) modelled the load as a real tire (Fig. 12), allowing to obtain a more realistic representation of the applied stress by the traffic, as represented in Fig. 13, obtained by Wang (2011) under static loading conditions.

(a) (b)

Fig. 12 FE-tire model. (a) 2D cross-section model. (b) 3D model (Wollny et al., 2016).

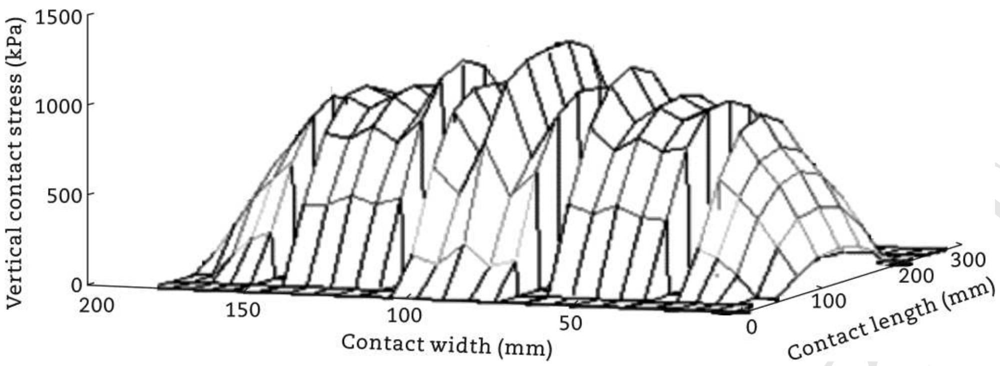

Fig. 13 Vertical contact stress obtained by the real modelling of tire-pavement interaction (Wang, 2011).

Of relevant importance for advanced characterization of the pavement performance, together with advanced models for materials and pavements, is the modelling of moving wheel loads, which requires a complex characterization of the loads applied by the traffic including the behavior of the tires. This modelling is essential for a dynamic analysis of integrating pavement irregularity, vehicle suspension system and tire deformation.

One possibility for this type of dynamic modelling can follow the Lak et al. (2011) work where the vehicle was modelled by its body as a rigid frame with three degrees of freedom (bounce, pitch and roll). Axles are modelled as rigid bars with two degrees of freedom (hop and roll) and the suspension system and tires are modelled as linear spring-dashpot systems as illustrated in Fig. 14.

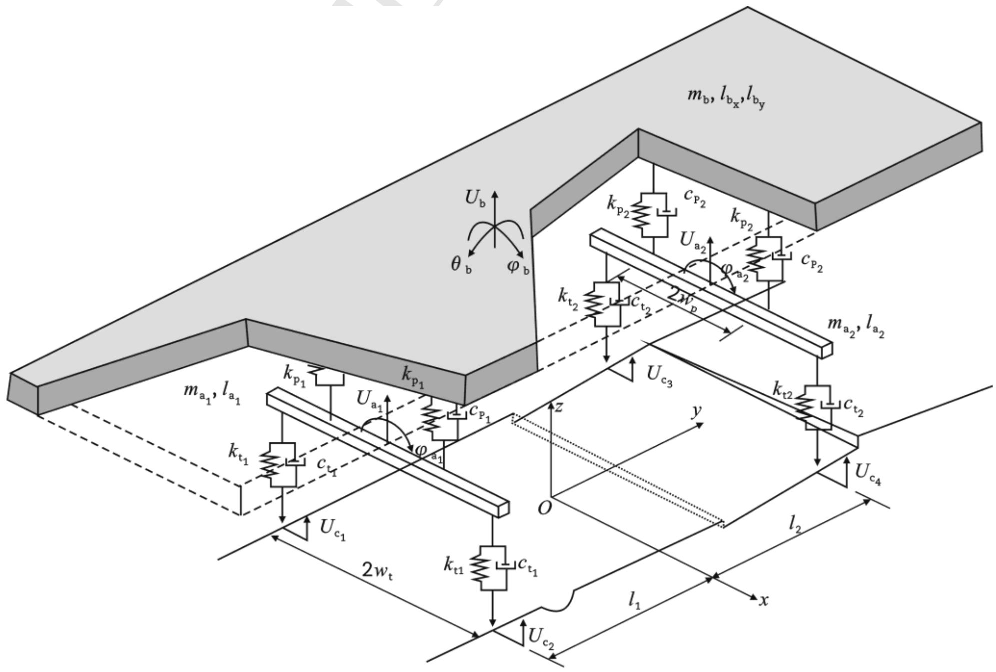

Fig. 14 3D model of a two-axle vehicle used by Lak et al. (2011) to model the relation between road unevenness and the dynamic vehicle response.

4.3.3 Climatic condition

Climatic conditions play an important role in the performance of pavement. The current pavement design methods limit the effect of climatic conditions to the study of the influence of the temperature in the asphalt mixes, where the stiffness modulus is the function of temperature, with the behavior the subgrade being influenced by moisture. Temperature is considered as a weighted average temperature that has an influence on the annual behavior of the pavement, equivalent to the individual temperatures during the year.

Temperature variations are also important in the mechanical behavior of asphalt layers as mechanical behavior of asphalt layers differs with temperatures. Fig. 15 presents an example of the hourly temperature observed in a pavement during a year, at 0.125 m below the pavement surface (Minhoto et al., 2008). The daily variations are also useful to optimize the choice of binders, which will be able to withstand large and sudden deformations due to temperature variations, with an influence on the thermal cracking. The temperature variation produces stresses and strains in the pavement that can be of equal magnitude of the one from axle load as represented in Figs. 16 and 17, respectively for the Von Mises strain in a pavement overlay due to the 80 kN axle load and temperature variations. The seasonal variations of temperature is also relevant in the prediction of the pavement performance during the year (Minhoto et al., 2005). Depending on the season, the response of the pavement is completely different.

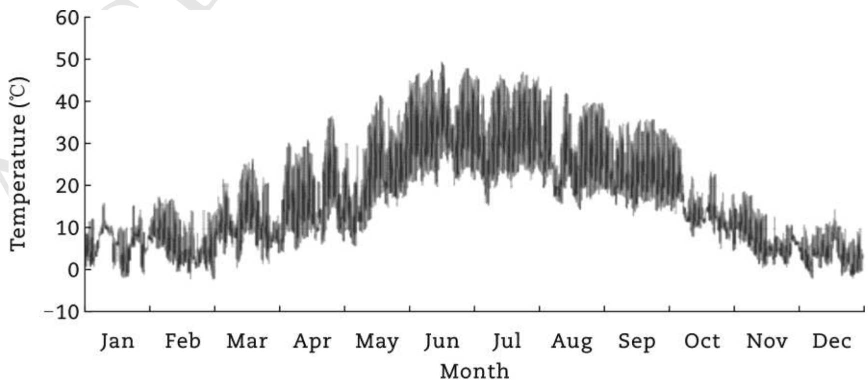

Fig. 15 Observed temperatures in a pavement 0.125 m below the pavement surface (Minhoto et al., 2008).

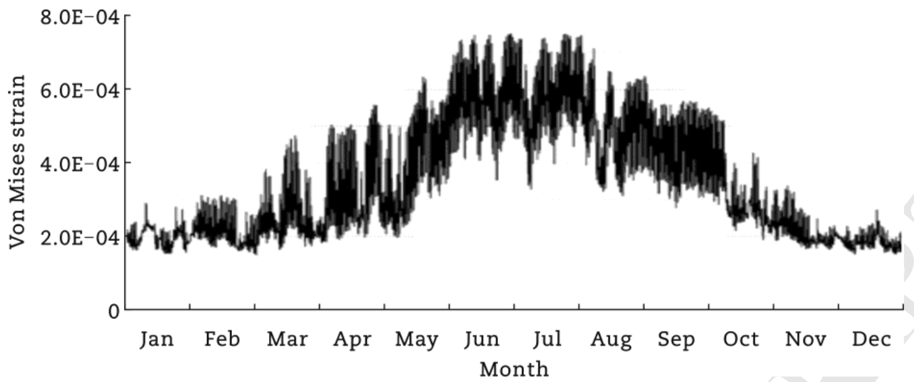

Fig. 16 Von Mises strain due to 80 kN axle load (Minhoto et al., 2008).

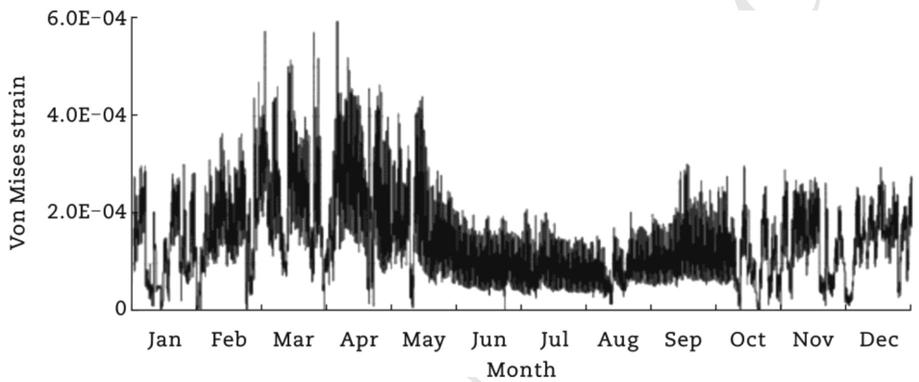

Fig. 17 Von Mises strain due to temperature variation (Minhoto et al., 2008).

Freezing and thawing behaviors of the asphalt mixes are considered only during the asphalt mix design which is valid for the moment of the design and does not provide information for the entire pavement life. Therefore, it is important that deterioration mechanisms associated with freezing and thawing should be examined in detail with long-term predictive models being developed for freezing/thawing related deterioration, associated with seasonal variations of climatic conditions.

Water in subgrade and granular layers is only considered for the application and compaction of these layers and its consideration in pavement design is assumed when evaluating with the subgrade bearing capacity. The water in the asphalt mixture is studied during its design, by the evaluation of the retained strength.

In order to contribute to a sustainable pavement performance over the entire life period and to contribute to an incremental pavement design approach, a climatic data bank would be obtained and maintained in a long-term approach, including not only temperature and water content, but also all other related climatic factors such as sunshine, precipitation, seasonal variations, with the aim of capturing climate change and evaluating its impact on pavement performance over the entire pavement life cycle as well.

Bearing in mind the relevance of climatic conditions for road pavement, the University of New Hampshire, USA decided to establish the Center for Infrastructure Resilience to Climate dedicated to accelerating and advancing the development of new methods and approaches to planning, design, and the operation and maintenance of climate and weather resilient transportation and building infrastructure systems (Daniel et al., 2013). This importance is emphasized when analyzing Fig. 18 from the UN Intergovernmental Panel on Climate Change (Pachauri and Meyer, 2014), showing an average global air temperature increase of 1 ℃ over the last 130 years. In Fig.18, linetypes indicate different data sets. In addition to this, significant changes in global climate are expected in the coming decades, with an increase in severe weather phenomena such as extreme temperatures, heavy rainfall (Wistuba and Walther, 2013).

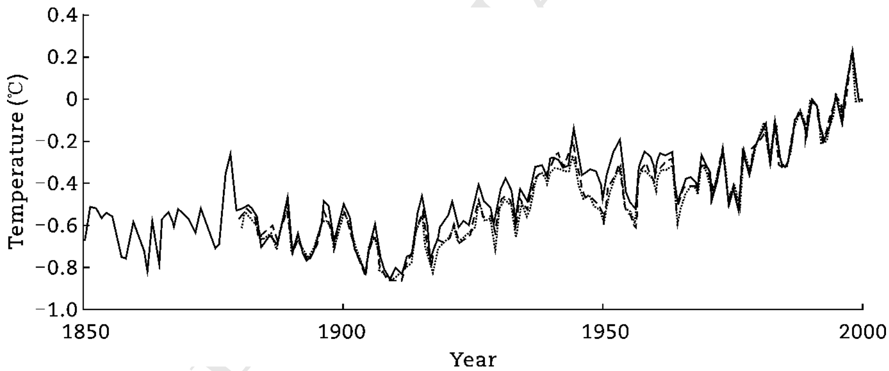

Fig. 18 Development of the average global air temperature from 1850 to 2000. (Pachauri and Meyer, 2014).

The other problem associated with the climatic conditions is the urban heat island in the urban areas as a result of a relatively greater proportion of incident solar energy that is absorbed and stored by man-made materials where the pavements play an important role as they absorb the solar radiation during the day and transform it into heat which is released during the day, affecting the social life in the urban areas as well as material behaviour. The increase in temperature deteriorates air and water quality. Asphalt mix designs can contribute to the solution of urban heat by modifying the thermal properties and emissivity of paved surfaces.

4.3.4 Material

In relation to current pavement structures, within the vision of new environmental-friendly road infrastructures, a new concept should be considered where alternative eco-friend materials would be adopted for all layers of the pavement, replacing traditional materials. At surface layer and asphalt base layers, bio-binders, as well as recycled rejuvenated binders with high rate of reclaimed asphalt, would be adopted, while at granular layers aggregates from construction and demolition wastes should replace virgin aggregates.

Road materials science has been the area where researchers and road agencies have invested the most part of the available resources, for the development of new materials and new testing techniques. This focus on road materials has also been supported because it is the component of the pavement system where it is easy to obtain rapid results compared to the other components that need much more intensive researches.

However, the contribution of research results for the improvement of pavement design has been reduced with the granular materials continuing being characterized as linear elastic materials based on a simple parameter, such as the CBR value, instead of complex characterization through triaxial tests. For asphalt materials, its characterization for pavement design has been based on linear elastic behaviour instead of a non-linear viscoelastoplastic behaviour, incorporating the effect of loading history including the temperature and rest periods.

Complex characterization of materials for current pavement design is being limited by the existing models for pavement analysis and design, which are based on existing theories such as linear elastic behaviour, multi-layers systems and the Burmister model. This fact can only be solved by the development of new approaches for pavement analysis, by using advanced modelling techniques such as finite, discrete or distinct elements.

New developments in terms of the characterization of road materials, including new innovative eco-friend alternative materials, must include more realistic models dealing with the real elements of material behaviour, containing viscous and/or plastic elements, capable of predicting deformation, as well as stress and strain response of the pavement under moving wheel loads. This requires more sophisticated laboratory tests, necessary to measure the material properties required by these models, supporting the evaluation of mechanical characteristics.

Related to the durability of asphalt mixes, moisture induced damage has been evaluated by several phenomenological methods (indirect tension strength ratio, Hamburg Wheel Track Test or Duriez test) which include the loss of adhesion between the asphalt and the aggregate and the loss of cohesion within the mix. These methods do not allow for the understanding of the underlying processes and mechanisms of moisture damage. They only evaluate the behavior of the asphalt mix to a given process of damage. Lytton et al. (2005) developed an approach based on surface free energy to evaluate the susceptibility of aggregates and asphalts to moisture damage by understanding the micro-mechanisms that influence the adhesive bond between aggregates and asphalt and the cohesive strength and durability of the asphalt. This approach was also used by Grenfell et al. (2014) in conjugation with the characterization of the mineralogical composition of the aggregates determined using a mineral liberation analyzer to explain different performances of the mixes (Fig. 19).

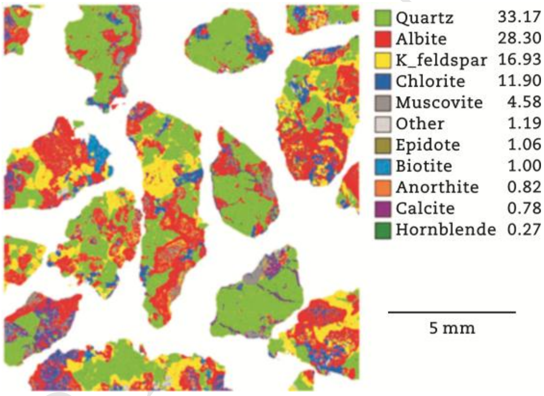

Fig. 19 Mineral liberation analysis of a granite aggregate (Grenfell et al., 2014).

Among the various methods for advanced characterization of asphalt materials, the atomic force microscopy (AFM) seems to be one with promising techniques due to its non-destructive imaging tool, which is capable of qualitative and quantitative surface analysis with sub-nanometer resolution. Simultaneously with the topology at the micro-scale, AFM is capable of acquiring micro-mechanical information such as relative stiffness/Young's modulus, stickiness/adhesion, hardness, and energy loss and sample deformation quantitatively. Using AFM is now widely accepted that the asphalt binder is neither a homogeneous nor a single phase system, but contains micro-structures with a size of several microns to tenth of microns with different micro-mechanical properties, as observed in Fig. 20 (Das et al., 2016).

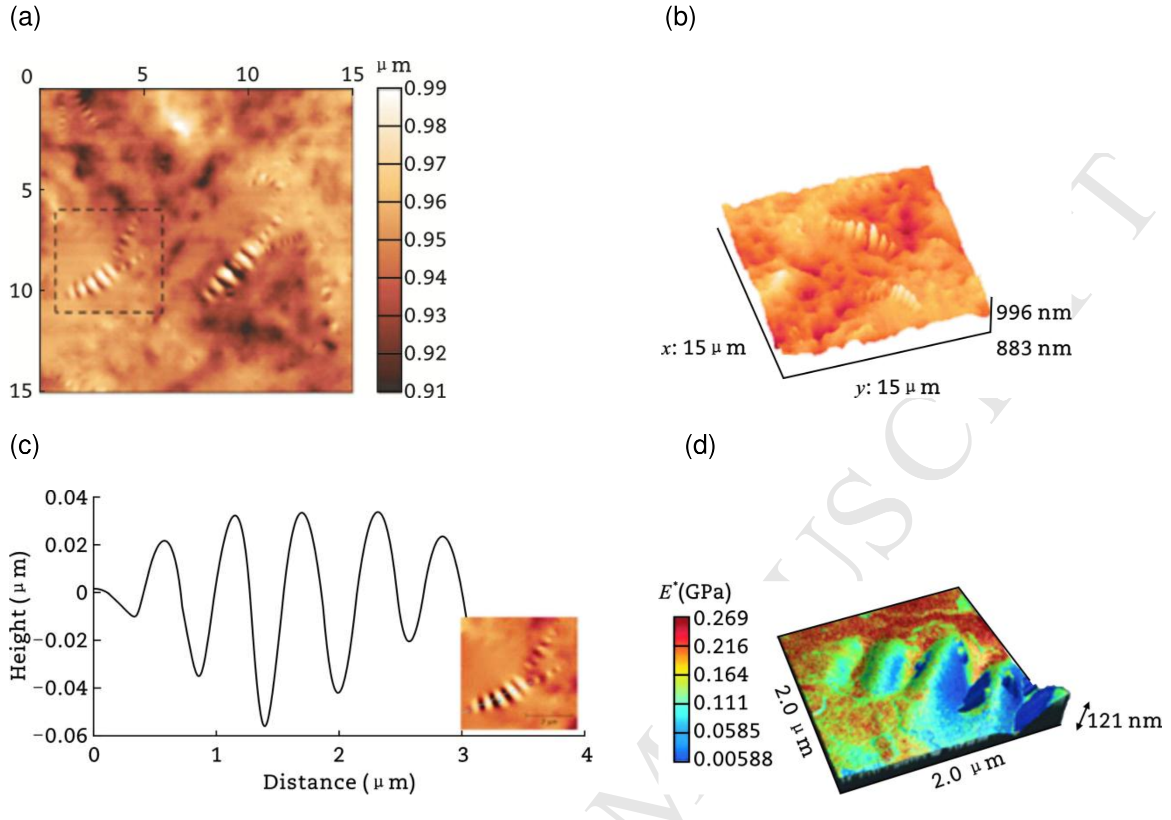

Fig. 20 Typical AFM images of asphalt binder. (a) Topographic 2D. (b) Topographic 3D. (c) Line profile along 'bee-shaped' micro-structure. (d) Relative stiffness, which indicates evidence of micro-structures (Das et al., 2016).

New developments in pavement design should therefore consider performance properties, namely those related to fatigue, permanent deformation, cracking propagation, ageing, healing and moisture.

Moisture in the asphalt mixes should be controlled in order to prevent the separation of the aggregates from the mix, inducing weakening and mechanical damage due to the traffic loads, responsible for a progressive dislodgement of the aggregates. And in some cases, this damage pattern becomes a dominant mode of failure and a cause for diminished road safety. This damage phenomenon is known as stripping or raveling of the asphalt wearing surface and contributes to a combined weakening of the mastic and a weakening of the aggregate–mastic bond (Kringos and Scarpas, 2008). These authors have proposed an approach to study the moisture effect in asphalt mixes. This approach considers the weakening of the mastic and of the aggregate-mastic bond due to molecular diffusion of moisture. Also, a weakening of the mastic from an erosion process caused by water flow, with the occurrence of intense water pressure fields inside the mix caused by traffic loads is considered (Fig.

21(a)). Fig. 21(b) presents geometry and setup of the finite element mesh used to combine the physical and mechanical moisture model based on a micro-scale representation of the asphalt pavement, demonstrating the importance of each of these moisture induced damage processes on the eventual developed damage pattern.

(a) (b)

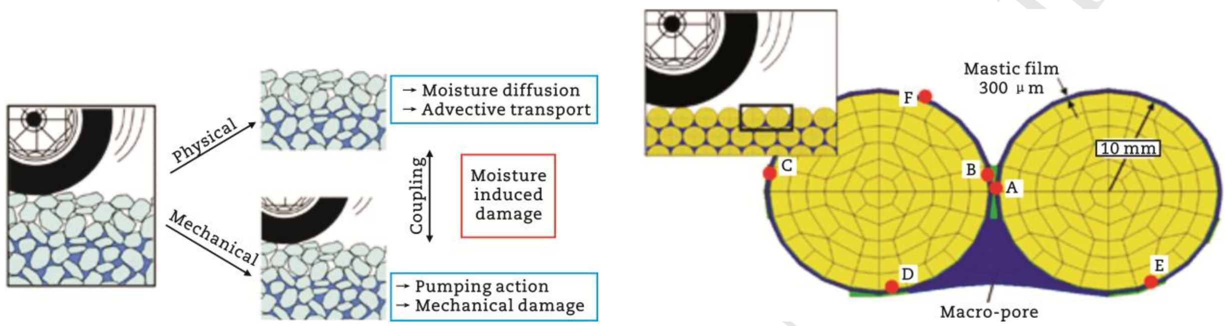

Fig. 21 Schematic and finite element mesh. (a) Schematic of the new approach towards moisture induced damage. (b) Finite element mesh for the micro-scale analyses (Kringos and Scarpas, 2008).

Recently, nanomaterials have been used to modify and improve the properties of asphalt mixes with moisture being one of the focus for these materials as studied by Hamedi and Nejad (2016), applying the nanocoating on the surface of aggregates in order to reduce the moisture damage of asphalt mixes. This study was developed through the application of thermodynamic and mechanical methods. In this work, the authors have concluded that the obtained surface free energy indicates that the coating of aggregates with nanoparticles reduces the differences between the free energy of adhesion in wet and dry conditions, which reduces the stripping tendency of asphalt mixtures.

The modelling of crack initiation and propagation has been done by several methods and, probably, the most developed and successful approach for modelling damage evolution in bituminous materials is the continuum damage mechanics approach, whose implementation started with Kim and Little (1990). Currently, this approach is implemented in the layered viscoelastic pavement analysis for critical distresses (LVECD) program that simulates damage growth using a moving vehicle and pavement temperature data (Fig. 22). The program simulates various types of axle loads as well as climate changes (Choi and Kim, 2014).

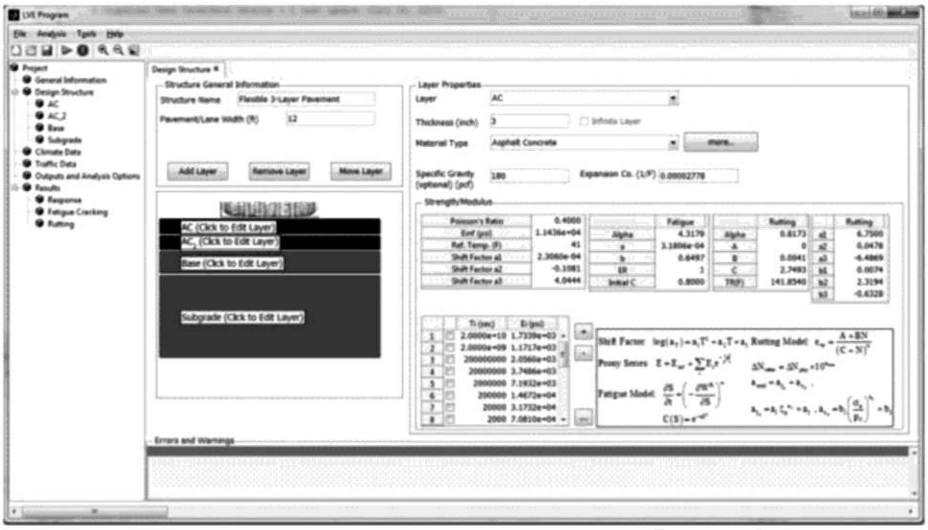

Fig. 22 Screen shot of LVECD program input window (Choi and Kim, 2014).

In spite of significant versatility and simplicity in characterizing structural degradation and damage evolution of asphalt materials, the continuum damage mechanical approach does not account for individual and interrelating effects of mixture constituents and directly measured or measurable physical damage phenomena such as micro and macrocracks. Various types of damage, including cracks in the asphalt sample were considered by a stiffness reduction in the asphalt sample as a function of damage parameters (Kim, 2011).

One of the most powerful methods to study crack initiation and propagation uses the fracture mechanics principles through the cohesive zone model. As stated by Park (2009), the cohesive zone model has four stages as shown in Fig. 23. The first stage (Stage Ⅰ) represents general material behavior without damage. The next stage (Stage Ⅱ), is the initiation of a crack when a certain criterion is met. The third stage (Stage Ⅲ) describes the nonlinear material softening that characterizes damage evolution and the final stage (Stage Ⅳ), defines failure with a critical crack opening width representing the new surfaces created by the fracture process, which have no traction (no loadbearing capacity) (Kim, 2011).

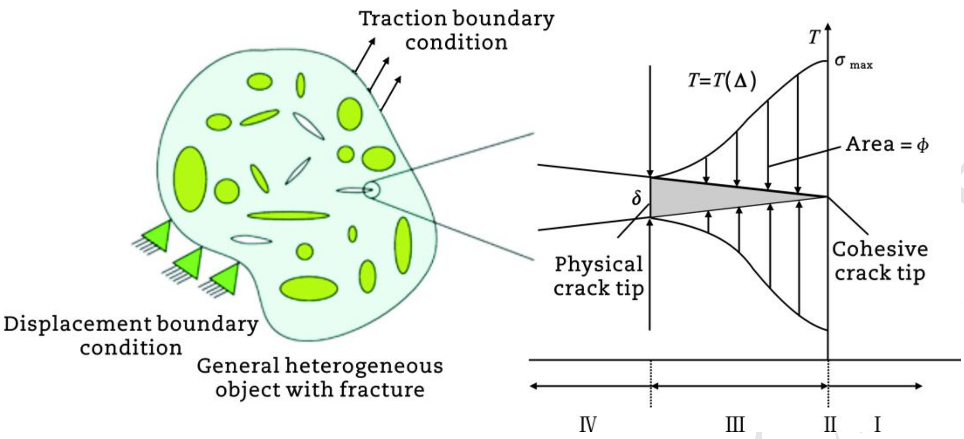

Fig. 23 Stages of the cohesive zone model (Kim, 2011).

One of the main applications of the cohesive zone analysis is the modelling of the micros-tructure of the asphalt mixes by separately considering the behaviour of the aggregates and mastic as indicates in Fig. 24.

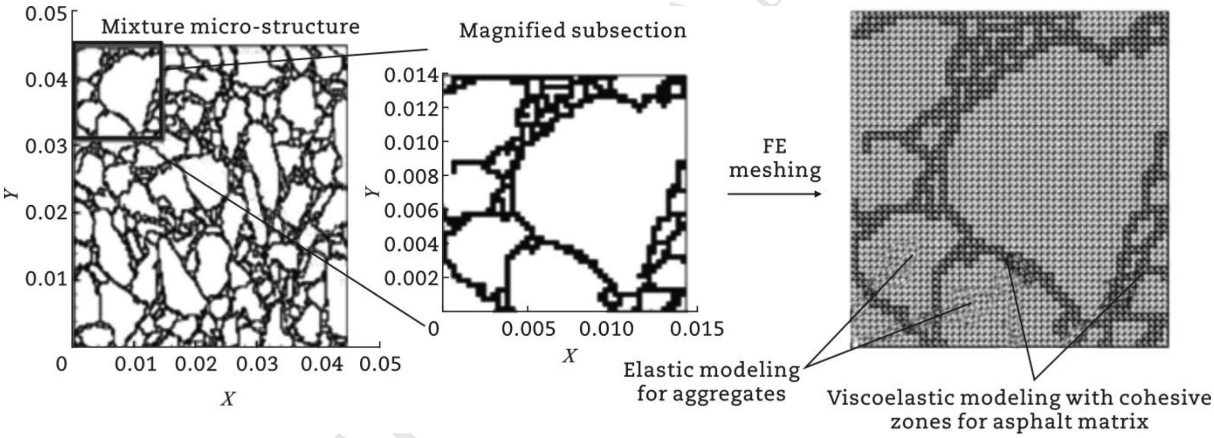

Fig. 24 Micro-structure finite element modelling with intrinsic cohesive zone elements (Kim, 2011).

For soils and granular materials, extensive material testing is necessary to obtain non-linear and plastic parameters models. Furthermore, standardized test procedures of a more fundamental nature need to be adopted more widely to accumulate knowledge of the behaviour of these materials.

In parallel with the structural characterization of asphalt mixes, particular attention will also be needed for the functional characteristics of the wearing course, bearing in mind its particular demands in terms of safety and comfort. Friction and noise are the relevant parameters in this study, which are influenced by texture, porosity and aggregate gradation, type of asphalt and stiffness of the asphalt mix. Also, the changes in pavement surface characteristics that occur with time due to traffic wearing and weather exposition, which change the friction and noise characteristics, needed to be taken into consideration.

4.3.5 Pavement design methodology

Current pavement design methods in Europe use the mechanistic-empirical methodology, considering only two forms of deterioration, fatigue and permanent deformation, with a simplistic manner inherent to the methodology and in calibrations to predict bottom-up cracking and permanent deformation due to the subgrade. This is the methodology developed in 1965 by Dormon and Metcalf and represents a huge simplification of pavement behaviour. However, it is important to emphasize that during the last 50 years, road pavements have been designed with this methodology and have presented a reasonable behaviour, which can be predicted by the existing models. However, it is recognized that this methodology must be improved.

One of the main criticisms of the current methods is the fact that they use the initials properties of the materials to predict the performance for the entire life period of pavements. The NCHRP (2004) has implemented an incremental procedure where pavement analysis is made on a periodic basis and the properties of the materials are also defined on the same basis, considering the evolution of traffic and climatic conditions over time. This procedure is being implemented in several states in the USA.

The failure mechanisms considered in the present pavement design methods must be updated, taking into account the current failure modes of the pavements, mainly those related to the top-down cracking, reflective cracking, thermal cracking and functional distresses.

In terms of top-down cracking, the crack initiation mechanism is primordial for the behaviour analysis of pavements as well as the crack initiation time which can be used to optimize the asphalt mixes, mainly their morphology. A framework for this analysis must include an input module, a material property sub-model, a pavement response sub-model, a damage accumulation and recovery sub-model and a crack initiation prediction sub-model interconnected as implemented by Dinegdae et al. (2015).

However, pavement design needs to look forward to the focus on an integration of design components, considering interactions among the different deterioration models, based on an understanding of the physical processes involved and namely loading characteristics, climatic conditions, material properties and its dependency with time and traffic. This implies the improvement of the present models and the development of new ones.

In terms of pavement modelling, based on the asphalt and granular material mechanical properties and distresses models, the use of advanced numerical models must be adopted instead of the Burmister theory based on linear elastic analysis. Candidates for such improvement are, for example, the finite elements method and the discrete elements method that allow for the definition of any type of load configurations, the modelling of pavement discontinuities and the use of advanced models for material characterization.

Another issue for pavement analysis is related to the accumulation of damage which implies the use of a model that will be able to predict, in a quantitative way, how the different forms of damage are building up in function of time during the whole service life of a pavement and how they interact with each other, instead of using the Miner’s law.

In this context, the probabilistic analysis must be one of the goals of pavement design, considering the interactions between different forms of deterioration and variability of physical and mechanical properties of the materials and changes in layer thickness, during the life of the pavement (Retherford, 2012; Sharma and Swamy, 2016; Sun and Hudson, 2005).

Additionally, it is vital for an innovative pavement design procedure to incorporate reliability principles. By incorporating probabilistic-based reliability analysis techniques, the design procedures could address systematically design parameters-associated uncertainty and variability effects on performance prediction. However, probabilistic-based pavement design involves the repeated application of reliability analysis tools such as the first-order reliability method to evaluate and assess the reliability of trial designs until estimated reliability converges to the target reliability (Dinegdae and Birgisson, 2016).

Asphalt pavements are inherently graded viscoelastic structures, mainly because the oxidative aging of the asphalt binder and temperature cycling due to climatic conditions that represent the major cause of this non-homogeneity (Dave, 2009). This grading is expressed by a continuous variation of pavement layer properties that cannot be rigorously simulated in the numerical analysis unless the use of smoothly-graded approaches as illustrated in Fig. 25, where it can be seen the sub-division of body into three layers with each one modelled using average properties (using the traditional numerical analysis) and a smoothly-graded modelling approach where the material variation is accounted for through spatial dependence of material property.

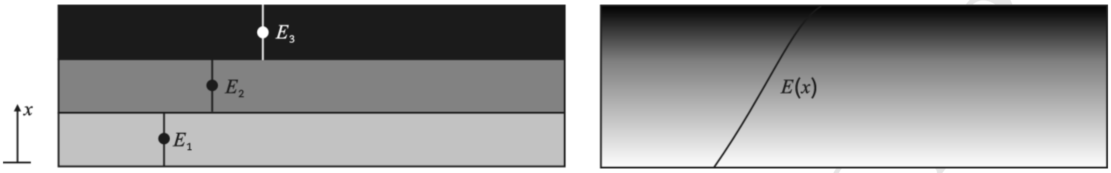

Fig. 25 Different modelling approach. (a) Layered approach. (b) Smoothly graded approach (Dave, 2009).

The first application of this methodology was done by Paulino and Kim (2007) where it presented a series of weak patch tests for the graded elements. The work demonstrated the existence of two length scales, namely a length scale associated with element size and a length scale associated with material non-homogeneity. The example in Fig. 26 illustrates the use of generalized isoparametric graded finite elements with property variation in both x and y directions and where the results show that stress evaluation can capture the non-homogeneity of the material.

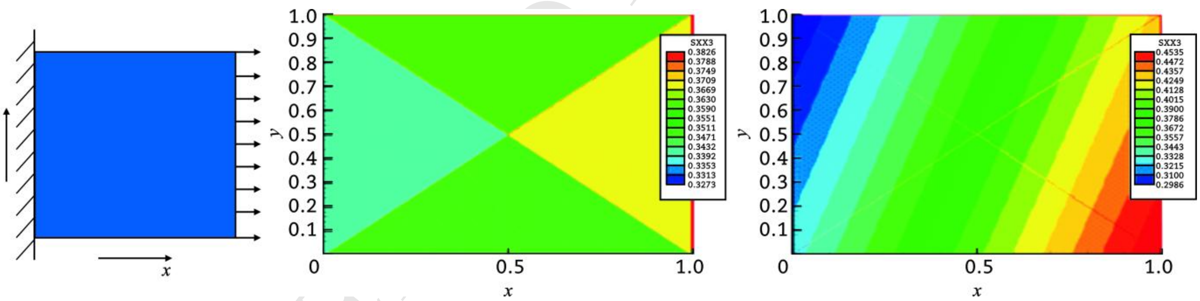

Fig. 26 Comparison of standard (uniform) element with graded element (Dave, 2009).

The application of this methodology for pavement analysis shows big benefits for both the characterization of asphalt layers, where, due to temperature variation, the stiffness of the asphalt mix changes throughout the depth of the layer, but also for granular layers, where the modulus is dependent on the state of stress installed in the material.

4.4 Pavement design: from a deep research to an implementable methodology

The new developments for a European pavement design method should be supported by the current state of the art, both with the knowledge achieved in Europe and the recent AASHTO

Mechanistic-Empirical Pavement Design Guide although bearing in mind the reduced acceptance by the US Departments of Transportation (DOT), due to its complexity and the amount of data required for a suitable application.

Based on the analysis of literature review, a pavement design method for application in all of Europe should be as follows.

- A modular framework, enabling the pavement design methodology to be updated as new deterioration mechanisms are included and as improved deterioration models are developed.
- An incremental procedure to predict pavement deterioration, integrating changes in the pavement structure and in material properties (variation of the behaviour of materials, ageing, unevenness) occurring during pavement life, as well as the evolution of traffic characteristics and climatic conditions (seasonal and long-term).

One of the requirements of this new pavement design method will be addressing separately its main components: geometry, traffic, climate conditions, materials, design system, including response and performance models.

In terms of pavement structure, as stated in the previous sections, a new pavement design method will follow the traditional conception used to model road pavements, where a set of layers rest over the subgrade. However, critical aspects that can be considered for the pavement geometry, namely distresses like cracks in the old pavement, for pavement rehabilitation design, and the unevenness to consider the dynamic effect of the traffic, are difficult to implement in a current design methodology. Its inclusion could be made indirectly through shift factors allowing for the transfer of laboratory results to expected ones in situ.

Considering that a new pavement design method should take into account the category of the road and distresses and unevenness are related to the level of pavement maintenance, when dealing with the incremental approach. These factors could be indirectly considered in the calibration process and confidence level of the distress laws. Thus, researches on cracking propagation and unevenness are necessary to better understand the mechanisms for both cracking propagation and for the effect of dynamic loads.

Regarding traffic characterizations, a European pavement design method can adopt either a linear elastic analysis or a viscoelastic analysis. The first one has been used in current pavement design methods and has the advantage of being faster than the one using viscoelastic analysis. In terms of input data, the linear elastic analysis requires less and easier data compared to that for viscoelastic analysis. The definition of the type of analysis also has other consequences, including the way how traffic is considered, i.e., ESAL and vehicle spectra. The first one is well known also having the advantage of using only one parameter for traffic definition, while the second one requires the knowledge of the number of vehicles for each traffic class. However, the latter would be adopted, allowing for a more robust analysis, compatible with the new models for material characterization.

Considering an incremental analysis approach, climatic conditions should consider temperature value variations during the day and during the year. For this analysis, a daily sample analysis is required to consider the climatic conditions during the day and night. The first one is related to traffic intensity, while the second one should be considered for thermal analysis. This thermal analysis could also be assessed during the asphalt mix design instead of being included in the pavement design, which reduces the computation time and the complexity of the problem.

Another issue in the definition of a pavement design methodology is the way how the design parameters are considered. Two possibilities could be considered: i) only considering the initial properties and models of the behaviour of materials; ii) considering an incremental approach where the properties and models assume their evolution with time as well. This last approach is more precise because the properties of the materials evolve with time and this approach also allows for the assessment of the evolution of distresses during the pavement life time. The main concern of this analysis is the computing time necessary for the analyses of all data required for the design that depends on the sample interval considered.

In terms of materials, and the associated models for their characterization, a new pavement design method should be based on easy models, both for the characterization of mechanical properties as well as for the evolution of the distress modes during pavement life time. These models should therefore, consider both the ones related to the structural as well as the functional distresses. The latter are of crucial importance in pavement engineering, related with safety and comfort of driving.

Despite the possibility of the assessment of the evolution of the distresses with time, the dispersion of the data used for that analysis is, in general, extremely large, which could compromise the accuracy of the final results. An example of this situation that can be observed in Fig. 27 where the laboratory fatigue results of 50 similar asphalt mixes are presented, with a scattering of around 100 times. This dispersion is greater when the laboratory results are converted to an in situ expected performance, resulting in a poor reliability of the overall design process.

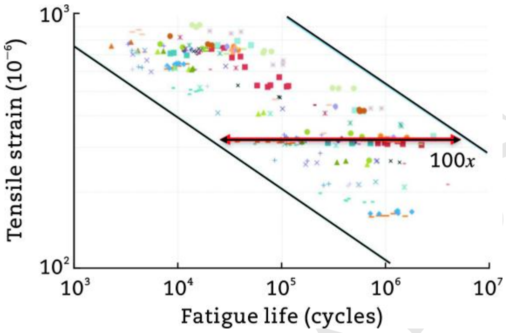

Fig. 27 Fatigue test results of asphalt mixes (Pais et al., 2009).

Concerning the behavior models of materials, and assuring a successful pavement design method, particular attention would be required for the required data, which would be easily obtained by all users. The incorporation of extremely sophisticated models with a huge number of parameters could lead to rising concerns in the acquisition and reliability of that data (time and costs) for a current application of the method. One mandatory rule when moving to a very demanding pavement design input data is that of the homogeneity of its quality as if, for instance, considering 32 variables with 95% accuracy, the final result could be 81% wrong (Visser and Hudson, 2016). Bearing in mind the huge amount of performance pavement related data available, artificial intelligence techniques should also be used, both for data quality evaluation and material and pavement behaviour modellings.

Finally, in terms of the pavement design methodology, in spite of all advances in the characterization of all components involved in the design process and in the modelling techniques, the mechanistic-empirical methodology seems to be the one that will be used as a basis for any improvement in the science of pavement design.

5 Final considerations

This article embraces the challenges of sharing the present situation of pavement and mix design in Europe, highlighting future research efforts worthy to be assumed by the academia, institutions and companies, towards a more efficient road infrastructure.

Over the last five decades, significant investment and research progress in the field of pavement design was reached, contributing to a sound road network in Europe.

However, there is still a wide space for the improvement of the present knowledge and particularly to respond to future challenges coming from transportation evolution characteristics, including vehicles, users, society and environment, under the vision of “S4 roads: sustainable, smart, safe and smiling roads”. In this context, in the field of pavement design, one crucial challenge will be providing reliable and green structures, using innovative environmental-friendly materials, under the mandatory goal of contributing to a sustainable energy reduction policy, with relevant impact on environment protection and the life quality of citizens.

In order to achieve these goals, researchers and practitioners should take advantage of powerful numerical and experimental tools, however always making adequate use of the huge data and information accumulated over the last decades, which possess enormous potentials for the evolution of knowledge within all pavement engineering fields, including pavement design methods with the support of powerful tools from the artificial intelligent field.

Finally, all progress should consider that in order to contribute to the evolution of pavement design, the main message should be: “keep it simple to be effective”, where the high complexity of pavement design research will bolster the development of practical pavement design methods. But the more important thing is to find a pilot that guide all the actors in the same direction toward the main goal: to have a European pavement design method.

Acknowledgments

The second author would like to express the support of Portuguese National Funding Agency for Science, Research and Technology (FCT) through scholarship SFRH/BSAB/114415/2016.

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

References

American Association of State Highway and Transportation Officials (AASHTO), 1961. AASHTO Guide for Design of Pavement Structures. AASHTO, Washington DC.

AASHTO, 1972. AASHTO Guide for Design of Pavement Structures. AASHTO, Washington DC.

AASHTO, 1986. AASHTO Guide for Design of Pavement Structures. AASHTO, Washington DC.

AASHTO, 2003. AASHTO Standard Specifications for Transportation Materials and Methods of Sampling and Testing, twenty-third ed. AASHTO, Washington DC.

Adesiyun, A., Amaud, L., Bueche, N., 2008. New Road Construction Concepts. Towards Reliable, Green, Safe & Smart and Human Infrastructure in Europe. Forum of European National Highway Research Laboratories (FEHRL), Brussels.

Amorim, S.I.R., Pais, J.C., Vale, A.C., et al., 2015. A model for equivalent axle load factors. International Journal of Pavement Engineering 16(1), 881-893.

Araya, A.A., 2011. Characterization of Unbound Granular Materials for Pavements (Master thesis). Delft University of Technology, Delft.

Artamendi, I., Khalid, H., 2004. Different approaches to depict fatigue of bituminous materials. In: The 15th European Conference of Fracture, Stockholm, 1983.

Asphalt Institute, 1970. Thickness Design: Full Depth Asphalt Pavement Structures for Highways and Streets. MS-1. Asphalt Institute, Lexington.

ASTM, 2010. Standard Test Method for Determining Fatigue Failure of Compacted Asphalt Concrete Subjected to Repeated Flexural Bending. ASTM D7460-08. ASTM International, West Conshohocken.

Bonnaure, F., Gest, G., Gravois, A., et al., 1977. A New Method of Predicting the Stiffness of Asphalt Paving Mixtures. In: Association of Asphalt Paving Technologists, San Antonio, 1977.

Brovelli, C., Crispino, M., Pais, J.C., et al ., 2015. Using polymers to improve the rutting resistance of asphalt concrete. Construction and Building Materials 77, 117–123.

Brown, S.F., Brunton, J., Stock, A., et al.,1985. The analytical design of bituminous pavements. Proceedings of Institution of Civil Engineers 79(2), 293-295.

Comité Européen de Normalisation (CEN), 2004a. Bituminous Mixtures-test Methods for Hot Mix Asphalt–Part 26: Stiffness. CEN, Brussels.

CEN, 2004b. Bituminous Mixtures-Test Methods for Hot Mix Asphalt-Part 24: Resistance to Fatigue. Comité Européen de Normalisation, Brussels.

CEN, 2004c. Bituminous Mixtures-Test Methods for Hot Mix Asphalt-Part 22: Wheel Tracking. Comité Européen de Normalisation, Brussels.

Choi, Y.T., Kim, Y.R., 2014. Implementation and verification of a mechanistic permanent deformation model (shift model) to predict rut depths of asphalt pavement. Road Materials and Pavement Design 15(1), 195-218.

Claussen, A.I.M., Edwards, J.M., Sommer, P., et al., 1977. Asphalt pavement design-the shell method. In: The 4th International Conference on the Structural Design of Asphalt Pavements, Ann Arbor, 1977.

Daniel, J.S., Jacobs, J.M., Douglas, E., et al., 2013. Impact of climate change on pavement performance: preliminary lessons learned through the infrastructure and climate network (ICNet). In: International Symposium of Climatic Effects on Pavement and Geotechnical Infrastructure, Fairbanks, 2013.

Das, P.K., Baaj, H., Tighe, S., et al., 2016. Atomic force microscopy to investigate asphalt binders: a state-of-the-art review. Road Materials and Pavement Design 17(3), 693-718.

Dave, E.V., 2009. Asphalt Aging and Temperature Dproperties Using Functionally Graded Viscoelastic Model (PhD thesis). University of Illinois at Urbana-Champaign, Urbana-Champaign.

Dinegdae, Y.H., Birgisson, B., 2016. Reliability-based calibration for a mechanics-based fatigue cracking design procedure. Road Materials and Pavement Design 17(3), 529-546.

Dinegdae, Y.H., Onifade, I., Jelagin, D., et al., 2015. Mechanics-based top-down fatigue cracking initiation prediction framework for asphalt pavements. Road Materials and Pavement Design 16(4), 907-927.

Dormon, G.M., Metcalf, C.T., 1965. Design Curves for Flexible Pavements Based on Layered System Theory. Highway Record 71. Highway Research Board, Washington DC.

European Commission (EC), 1999. Development of New Bituminous Pavement Design Method. Cost Action 333. European Commission, Luxembourg.

European Commission (EC), 2000. Advanced Models for Analytical Design of European Pavement Structures. European Commission, Luxembourg.

European Commission (EC), 2015. Statistical Pocketbook 2015. EC, Luxembourg.

European Union Road Federation (EURF), 2015. Yearbook 2014-2015. EURF, Brussels.

Graczyk, M., Rafa, J., Zofka, A., 2016. The selected problems of multi-layer pavements—influence of composite impacts vehicles and climatic factors on the behavior of roads pavements. Transportation Research Proceedia 14, 2487–2496.

Grenfell, J., Ahmad, N., Liu, Y., et al., 2014. Assessing asphalt mixture moisture susceptibility through intrinsic adhesion, bitumen stripping and mechanical damage. Road Materials and Pavement Design 15(1), 131-152.

Guler, M., 2008. Effects of mix design variables on mechanical properties of hot mix asphalt. Journal of Transportation Engineering 134(3), 128-136.

Hamedi, G.H., Nejad, F.M., 2016. Use of aggregate nanocoating to decrease moisture damage of hot mix asphalt. Road Materials and Pavement Design 17(1), 32-51.

Highway Research Board (HRB), 1952. Final Report on Road Test One Maryland. Special Report 4. HRB, Washington DC.

Highway Research Board (HRB), 1954. The WASHO Road Test, Part 1: Design, Construction and Testing Procedures. Special Report 18. HRB, Washington DC.

Highway Research Board (HRB), 1955. The WASHO Road Test, Part 2: Test Data, Analyses Findings. Special Report 22. HRB, Washington DC.

Highway Research Board (HRB), 1962. The AASHO Road Test, Report 7. Special Report 61-G. HRB, Washington DC.

Hugo, F., Epps-Martin, A.L., 2004. Significant Findings from Full-scale Accelerated Pavement Testing. NCHRP Synthesis of Highway Practice 325. Transportation Research Board, Washington DC.

Kerkhoven, R.E., Dormon, G.M., 1953. Some Considerations on the Californian Bearing Ratio Method for the Design of Flexible Pavement. Shell International Petroleum Company, London.

Khavassefat, P., Jelagin, D., Birgisson, B., 2012. A computational framework for viscoelastic analysis of flexible pavements under moving loads. Materials and Structures 45(11), 1655–1671.

Khavassefat, P., Jelagin, D., Birgisson, B., 2013, Impact of long and heavy vehicles on pavement damage. In: The 92nd Transportation Research Board Annual Meeting, Washington DC, 2013.

Khavassefat, P., Jelagin, D., Birgisson, B., 2015. Dynamic response of flexible pavements at vehicle-road interaction. Road Material and Pavement Design 16(2), 256-276.

Kim, Y.R., 2011. Cohesive zone model to predict fracture in bituminous materials and asphaltic pavements: state-of-the-art review. International Journal of Pavement Engineering 12(4), 343-356.

Kim, Y.R., Little, D.N., 1990. One-dimensional constitutive modeling of asphalt concrete. Journal of Engineering Mechanics 116(4), 751–772.

Kringos, N., Scarpas, A., 2008. Physical and mechanical moisture susceptibility of asphaltic mixtures. International Journal of Solids and Structures 45(9), 2671–2685.

Lak, M.A., Degrande, G., Lombaert, G., 2011. The effect of road unevenness on the dynamic vehicle response and ground-borne vibrations due to road traffic. Soil Dynamics & Earthquake Engineering 31, 1357–1377.

Laboratoire Central des Ponts et Chaussées (LCPC), 1981. Conception et Dimensionnement des Structures de Chaussée—Guide Technique. Laboratoire Central des Ponts et Chaussées, Paris.

LCPC, 1992. Réalisation des Remblais et des Couches de Forme. Laboratoire Central des Ponts et Chaussées, Paris.

LCPC, 1994. French Design Manual for Pavement Structures—Guide Technique. Laboratoire Central des Ponts et Chaussées, Paris.

LCPC, 2003. Practical Manual for the Use of Soils and Rocky Materials in Embankment Construction. Laboratoire Central des Ponts et Chaussées, Paris.

LCPC, 2007. LPC Bituminous Mixtures Design Guide. Laboratoire Central des Ponts et Chaussées, Paris.

Lee, A.R., Croney, D., 1962. British full-scale pavement design experiments. In: The International Conference on the Structural Design of Asphalt Pavements, Ann Arbor, 1962.

Lytton, R.L., Masad, E.A., Zollinger, C., et al., 2005. Measurements of Surface Energy and Its Relationship to Moisture Damage. Texas Transportation Institute, Texas A&M University, College Station.

Metcaft, J.B., 1996. Application for Full-scale Accelerated Pavement Testing. NCRRP Synthesis of Highway Practice 235. Transportation Research Board, Washington DC.

Minhoto, M.J.C., Pais, J.C., Pereira, P.A.A., 2008. The temperature effect on the reflective cracking of asphalt overlays. Road Materials and Pavement Design 9(4), 615-632.

Minhoto, M.J.C., Pais, J.C., Pereira, P.A.A., et al., 2005. The influence of temperature variation in the prediction of the pavement overlay life. Road Materials and Pavement Design 6(3), 365-384.

Monismith, C.L., 2004. Evolution of long-lasting asphalt pavement design. methodology: a perspective. In: International Symposium on Design and Construction of Long Lasting Asphalt Pavements, Alabama, 2004.

Monismith, C.L., Epps, J.A., Kasianchuk, D.A., et al., 1971. Asphalt Mix Behaviour in Repeated Flexure. Report TE 70-5. University of California, Berkeley, Berkeley.

Monismith, C.L., Epps, J.A., Finn, F.N., 1985. Improved asphalt mix design. In: Association of Asphalt Paving Technologists, St Paul, 1985.

National Cooperative Highway Research Program (NCHRP), 2004. Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures. NCHRP Project 1-37A. National Research Council, Washington DC.

Newcomb, D.E., Buncher, M., Huddleston, I.J., 2001. Concepts of Perpetual Pavements. Transportation Research Circular, Number 503. Transportation Research Board, Washington DC.

Nunn, M.E., Merrill, D.B., 1997. Review of Flexible and Composite Pavement Design Methods. TRL Paper PA/3298/97. Transport Research Laboratory, Crowthorne.

Nunn, M., 2004. Development of a More Versatile Approach to Flexible and Flexible Composite Pavement Design. TRL Report 615. Transportation Research Laboratory, Crowthorne.

Pachauri, R.K., Meyer, L.A., 2014. Intergovernmental Panel on Climate Change (IPCC), 2014: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva.

Pais, J.C., Amorim, S.I.R., Minhoto, M.J.C., 2013. Impact of traffic overloads on road pavements performance. Journal of Transportation Engineering 139(9), 873-879.

Pais, J.C., Pereira, P.A.A., Minhoto, M.J.C., et al., 2009. The prediction of fatigue life using the k1-k2 relationship. In: The 2nd Workshop on Four-point Bending, Guimarães, 2009.

Park, K., 2009. Potential-based Fracture Mechanics Using Cohesive Zone and Virtual Internal Bond Modeling (PhD thesis). University of Illinois at Urbana-Champaign, Urbana-Champaign.

Pasquini, E., Pasetto, M., Canestrari, F., 2015. Geocomposites against reflective cracking in asphalt pavements: laboratory simulation of a field application. Road Materials and Pavement Design 16(4), 815-835.

Paulino, G.H., Kim, J.H., 2007. The weak patch test for nonhomogeneous materials modeled with graded finite elements. Journal of the Brazilian Society of Mechanical Sciences and Engineering 29(1), 63-81.

Potter, J.F., Currer, E.W.H., 1981. The Effect of Fabric Membrane on the Structural Behavior of a Granular Road Pavement. LR 996. Transport and Road Research Laboratory, Crowthorne.

Powell, W.D., Potter, J.F., Mayhew, H.C., et al., 1984. The Structural Design of Bituminous Roads. LR 1132. Transport and Road Research Laboratory, Crowthorne.

Retherford, J.Q., 2012. Management of Uncertainty for Flexible Pavement Design Utilizing Analytical and Probabilistic Methods (PhD thesis). Vanderbilt University, Nashville.

Saal, R.N.J., Pell, P.S., 1960. Fatigue of bituminous road mixes. Kolloid-Zeitschrift 171(1), 61-71.

Saeed, A., Hall, J.W., 2003. Accelerated Pavement Testing: Data Guidelines. NCRRP Report 512. Transportation Research Board, Washington DC.

Sharma, H., Swamy, A.K., 2016. Development of probabilistic fatigue curve for asphalt concrete based on viscoelastic continuum damage mechanics. International Journal of Pavement Research and Technology 9(4), 270–279.

Shell International Petroleum Company, Ltd, 1978. Shell Pavement Design Manual: Asphalt Pavements and Overlays for Road Traffic. Shell International Petroleum Company, Ltd, London.

Shook, J.F., Finn, F.N., Witczak, M.W., et al., 1982. Thickness design of asphalt pavements-the asphalt institute method. In: The 5th International Conference on the Structural Design of Asphalt Pavements, Delft, 1982.

Sousa, J.B., Pais, J.C., Saim, R., et al., 2002. Mechanistic-empirical overlay design method for reflective cracking. Transportation Research Board 1809, 209-217.

Stock, A.F., 1979. Flexible Pavement Design (PhD thesis). University of Nottingham, Nottingham.

Sun, L., Hudson, W.R., 2005. Probabilistic approaches for pavement fatigue cracking prediction based on cumulative damage using miner's law. Journal of Engineering Mechanics 131(5), 546-549.

Tayebali, A.A., Deacon, J.A., Coplantz, J.S., et al., 1994. Fatigue Response of Asphalt-Aggregate Mixtures. SHRP-A-404. National Research Council, Washington DC.

Timm, D.H., Newcomb, D.E., Birgisson, B., et al., 1999. Incorporation of Reliability into the Minnesota Mechanistic－Empirical Pavement Design Method. MN/RC-1999-35. University of Minnesota, Minneapolis.

U.S. Army Corps of Engineers, 1945. The California Bearing Ratio Test as Applied to the Design of Flexible Pavements for Airports. Technical Memory. Number 213-1. Waterways Experiment Station, Vicksburg.

Ullidtz, P., Peattie, K.R., 1982. Programmable calculators in the assessment of overlays and maintenance strategies. In: The 5th International Conference on Structural Design of Asphalt Pavements, Delft, 1982.

Van der Poel, C.A., 1954. A general system describing the visco-elastic properties of bitumen and its relation to routine test data. Journal of Chemical Technology and Biotechnology 4(5), 221-236.

Visser, P., Hudson, R., 2016. Pavement performance depends on integration of design and management. In: The 4th Chinese European Workshop, Delft, 2016.

Wang, H., Al-Qadi, I., 2011. Impact quantification of wide-base tire loading on secondary road flexible pavements. Journal of Transportation Engineering 137(9), 630-639.

Wang, H., 2011. Analysis of Tire-Pavement Interaction and Pavement Responses Using a Decoupled Modeling Approach (PhD thesis). University of Illinois at Urbana-Champaign, Urbana — Champaign.

Wistuba, W.P., Walther, A., 2013. Consideration of climate change in the mechanistic pavement design. Road Materials and Pavement Design 14(S1), 227-241.

Wollny, I., Behnke, R., Villaret, K., et al., 2016. Numerical modelling of tyre–pavement interaction phenomena: coupled structural investigations. Road Materials and Pavement Design 17(3), 563-578.

Xia, R., Li, J., He, J., et al., 2015. Effect analysis of vehicle system parameters on dynamic response of pavement. Mathematical Problems in Engineering 2015, 561478.

Paulo Pereira is a professor of transportation at the Department of Civil Engineering, University of Minho, the head of the Centre for Territory, Environment and Construction, a researcher on highway engineering, road pavements, road management systems, asphalt pavement materials, road surface characteristics, road safety and urban mobility.

He is responsible of several funded research projects, at national and international level. He is the project coordinator of the Portuguese Pavement Management System, the author of more than two hundred and forty papers in international and national journals and in international conferences, the chair of international and national conferences on pavements and transport infrastructures, and a member of editorial board of four international journals.

Jorge Pais is an associate professor of the Department of Civil Engineering at the University of Minho in Portugal. He received his PhD degree from the University of Minho in 1999 with a thesis on reflective cracking in flexible pavements. Jorge Pais teaching areas include road pavement design and railways design for undergraduate and post-graduate courses.

His research areas include pavement materials design and characterization, advanced laboratory testing, field performance evaluation and maintenance, and rehabilitation techniques. In the materials area, he has been involved in fatigue and reflective cracking characterization of asphalt mixes and in the numerical modelling of road pavements.