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Comparative analysis of various pavement design methods

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TREBALL FINAL DE GRAU

Preface

First of all I would like to thank Warsaw University of Technology and the Faculty of Civil Engineering for giving me the opportunity to study in their university this year and for allowing me to do my thesis, and specially thank my thesis tutor Artur Zbiciak for helping me with my project during this semester in Warszawa. I would also like to thank Rodrigo Miró for taking my project in Barcelona.

Also, thank to the *Escola de Camins, Canals I Ports de Barcelona* of *Universitat Politècnica de Catalunya* for giving me the chance to course my studies of Civil Engineering with them.

Finally, my special gratitude to my family and my friends, particularly to my father and my brother who are present in daily in my life and to my mother who is not here anymore but she will always be with us.

Cristian Rodríguez Rica

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1. Introduction

Every day, almost each person in the world uses any road to move from one place to another. That's why pavement design is very important these days, for the safety and comfort of all the drivers. Therefore, pavement structures have to support the traffic load the entire design life without suffering any failure cracking in their structure in order to behave safely for this period of time. If the road structure doesn't hold the traffic loadings during its design life, there could be some accidents that can risk people's life.

Mechanistic-empirical methods of pavement design play an important role in the analysis of pavement design life. The utilisation of these kind of methods allows us to obtain number of cycles that the structure can support until failure. Then, knowing this number of loadings and the daily average heavy traffic of the road, it is possible to determine if the structure is able to support such quantity of traffic during its design life period.

2. Objectives

The main objective of this project is the analysis and comparison of some mechanistic-empirical design methods for pavement design, with which is possible to calculate the number of repetitions a pavement can support until failure. Our analysis will be done for flexible and semi-rigid pavement structures in order to compare the results for both types of structures.

In order to obtain the parameters for the mechanistic-empirical formulas, an analysis of the strains and stresses for flexible and semi-rigid pavement structures should be carried out. These values will be obtained applying the BISAR program. Then, a comparative analysis will be performed in order to know the changes of strains and stresses from a flexible structure to a semi-rigid one.

3. Asphalt pavement

From some years ago, asphalt has been playing an important role in our daily activities. We don't even think about it, but when we go to any place or when we buy something, asphalt roads are being used.

The European road network consist of about 6.1 million kilometres of paved roads, and about 90% of all these roads are paved with asphalt. The other 10% is made of concrete and pavers (bricks, cobblestones, etc.). Asphalt is also used in railway beds, airport runways, playgrounds, running tracks, tennis courts, bridges, tunnels, etc.

Roads are the most used mode of transport. Over 72% of our inland goods and 83% of passengers travel are done by road, rather than rail, air or water, so here it is show the importance of roads.

3.1 Asphalt pavement composition

Asphalt is a mixture of aggregates, binder and filler. Aggregates used for asphalt could be crushed rock, sand, gravel or slags. In order to get all the aggregates joined into a cohesive mixture, bitumen is used as a binder. The common asphalt pavement design consists on different layers. The bottom layer is the existing soil or sub-grade. The next layer is an aggregate base layer which sometimes is stabilized with asphalt, cement or fly ash. Then, this is followed by one or more layers of asphalt pavement.

The main objective of these layers is to give the pavement the ability to distribute the loads of the traffic, stresses and strains generated, before it arrives at the foundation level. Also, the viscous nature of the bitumen allows the pavement structure to sustain significant plastic deformation, although fatigue from repeated loading is the most common failure mechanism.

3.2 Advantages of asphalt

Asphalt pavement surfaces offer a lot of benefits,

- <u>Smoothness and comfortability:</u> the construction way of multiple layer pavements provides and structure completely smooth, which gives the user that sense of comfort when they use the road.

- <u>Cost-efficient structure:</u> asphalt has low initial costs, lasts long, and due to its recyclability, has greater residual value than other pavements. Porous asphalt pavements are made so that water can drain through the pavement. Also, using asphalt surfaces can significantly reduce the noise inside and outside the vehicle.
- <u>Safety:</u> asphalt structures provides a fast drainage of surface water in order to avoid floods, and consequently aquaplaning, and provide better visibility to drivers in these conditions. Also, it gives more grip to the vehicle wheels for not slipping from the pavement.

- Durability: roads are commonly designed to last about 15-20 years, depending on the traffic it is supposed to suffer. When the wearing course has to be replaced, the old one is reused into a new asphalt layer. Some properly designed and maintained roads may be more time without needing total reconstruction.

- Fast construction: asphalt pavement don't need "cure" time, so construction time is short and there are fewer delays for the traffic during the construction.

- Reusability: asphalt is one of the most recycling construction product in Europe, so less bitumen has to be used in the reconstruction of roads.

- Flexibility: roads can be designed to cope with any traffic load and climate conditions

4. Pavement structural design

4.1 Types of failure

Pavement performance is normally evaluated using fatigue cracking and rutting models. These models are primarily caused by stresses and strains due to repetitions of high traffic loading. Factors such as temperature, moisture, ageing, material mix design, etc. also affect to pavement distress, although we won't talk about them.

4.1.1 Fatigue

Fatigue cracking is the progressive cracking of the asphalt surfacing or stabilised base layers due to cumulative repeated traffic loading. This occurs as a result of tensile stresses and strains in the bottom zone of asphalt layer and propagates upward to the top. On the pavement surface, it finally appears as alligator/crocodile cracks along wheel tracks, as we appreciate in the Figure 1.

Figure 1 *Fatigue cracking on the road surface*

The horizontal tensile stress/strain at the bottom of the bituminous layer is used as the governing parameter for fatigue failure.

Fatigue cracking in asphalt layers is considered a major structural distress and is predominantly caused by traffic loading. Moreover, the effect of rainwater through the cracks can lead to serious structural failure of underlying layers particularly granular and unbound materials including the subgrade.

Logarithmic equations are normally used to obtain number of load repetitions to failure cracking, taking into account tensile stresses or strains and some other parameters depending on the model used.

4.1.2 Rutting

Rutting is defined as the permanent deformation of a pavement due to the accumulation of visco-plastic vertical compressive strains under traffic loading. This is the manifestation of gradual densification of pavement layers, and shear displacement of the subgrade. On the pavement surface, it looks like as longitudinal depressions in the wheel tracks, as we see in the Figure 2. Significant rutting can lead to major structural failures and hydroplaning potentials.

Figure 2 *Rutting on the road surface*

The vertical strain on the top of the subgrade is assumed to be the most governing force for the rutting failure. Rutting is not generally considered for concrete pavement design.

Surface ruts may occur in the asphalt surface due to the action of heavy vehicle loading, and most commonly in areas of high temperatures. The surface rutting in the asphalt is mainly caused by shear deformation coupled with vertical stresses in the top zone of the subgrade. Densification of asphalt mix due to traffic loading is another important factor to take into account. A little uplift on the pavement may also occur along the sides of the rut, as we see in the Figure 2. Surface rutting is very unsafe to motorists. Also, water retained in the ruts may result in hydroplaning, making vehicle steering and braking difficult. Water can also affect to the stiffness of the asphalt due to degradation and stripping. Water infiltration through pores generally weakens the pavement structure, and water ponding on the surface is undesirable.

Figure 3 *Fatigue cracking and rutting on the road surface*

The fatigue and rutting equations are developed from field or laboratory studies, where fatigue/rutting lives are obtained with respect to respective stress/strain for fatigue/rutting. For a given design life, then, allowable fatigue and rutting stress/strains can be estimated using fatigue and rutting equations.

The other types of pavement failures could be shrinkage, thermal fatigue, top down cracking for bituminous pavement, etc.

4.2 Mechanical model of road structure

It is useful to briefly review the fundamental outputs of mechanistic analysis, which can be based on linear elastic, non-linear elastic, viscoelastic or plasticity theory. However, linear elastic theory is the most commonly used in practise and it's the one we will use.

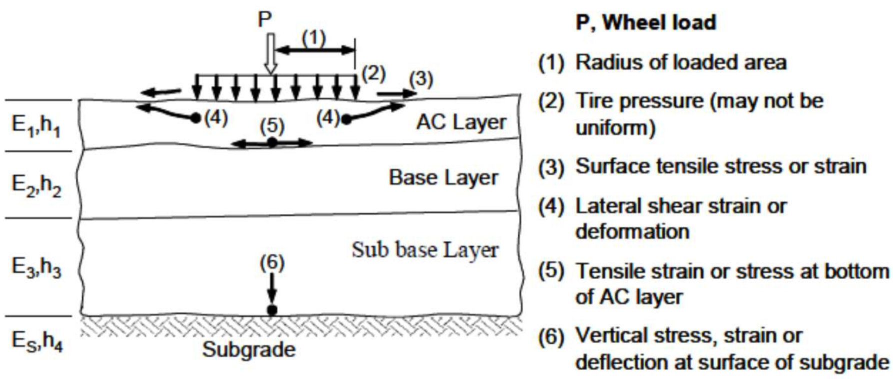


Figure 4 *Structure of the pavement layers*

The model is directed to calculating one or more responses in the pavement structure as a function of material properties, as modulus of elasticity E and Poisson ratio of each layer v. These responses must be related to observed performance of the pavement, such as fatigue cracking or rutting progression.

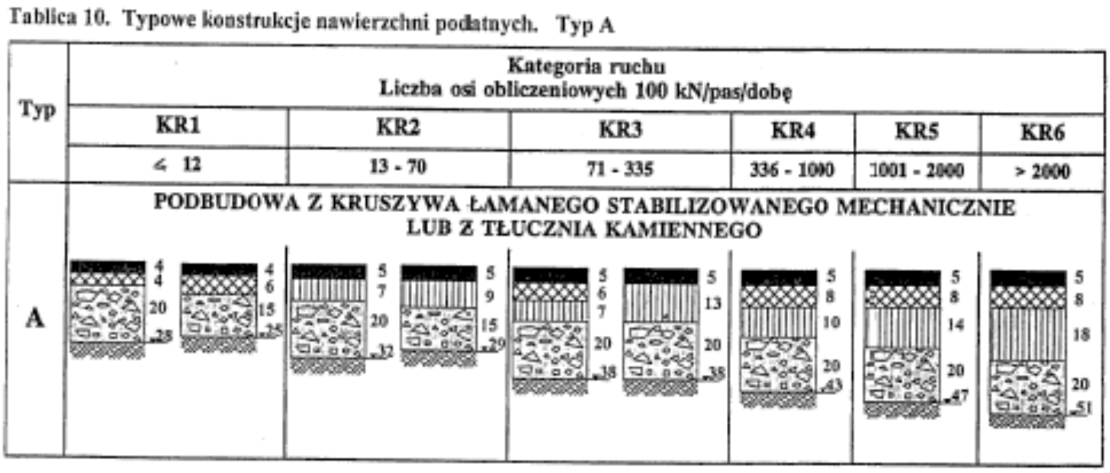
The model we are going to study has the shape of the Figure 4. In our study model, all the layers are considered as homogeneous, linear elastic and isotropic, and the load is considered as static. The applied load is considered as circular shape on the surface.

We only will take into account the stresses and strains produced in the bottom of the asphaltic layer, only horizontals, and forces on the top of the subgrade, vertical strains and stresses.

4.3 Polish pavement structure

As Polish pavement structures will be analysed later, we are going to see the type of flexible and semi-rigid structures that we can find in the Polish catalogue. *"Katalog typowych konstrukcji nawierzchni podatnych i półsztywnych"*

4.3.1 Flexible pavement


Tablica 10. Typowe konstrukcje nawierzchni podatnych. Typ A

Typ	Kategoria ruchu Liczba osi obliczeniowych 100 kN/pas/dobę					
	KR1	KR2	KR3	KR4	KR5	KR6
	≤ 12	13 - 70	71 - 335	336 - 1000	1001 - 2000	> 2000
	PODBUDOWA Z KRUSZYWA ŁAMANEGO STABILIZOWANEGO MECHANICZNIE LUB Z TŁUCZNIA KAMIENNEGO					
A	4, 4, 20, 28; 4, 6, 15, 25	5, 7, 20, 32; 5, 9, 15, 29	5, 6, 7, 20, 38; 5, 13, 20, 38	5, 8, 10, 20, 43	5, 8, 14, 20, 47	5, 8, 18, 20, 51

Figure 5 *Flexible pavement structure of Polish catalogue*

In the figure 5 we can appreciate the different types of pavement structures for flexible pavement structures from the Polish catalogue. In the table we can see the name of each structure and the number of repetitions of heavy traffic in 24 hours. Then, in the row named A, there are drawn the structures, "crushed stone aggregate base mechanically stabilised/threated or crashed stone base", and the layers with each thickness.

The layers for Polish catalogue are commonly designed with layers composed by asphalt wearing course, asphalt binder course (not for KR2), asphaltic concrete foundation (not for KR1), crushed aggregate base and the subgrade.

4.3.2 Semi-rigid pavement

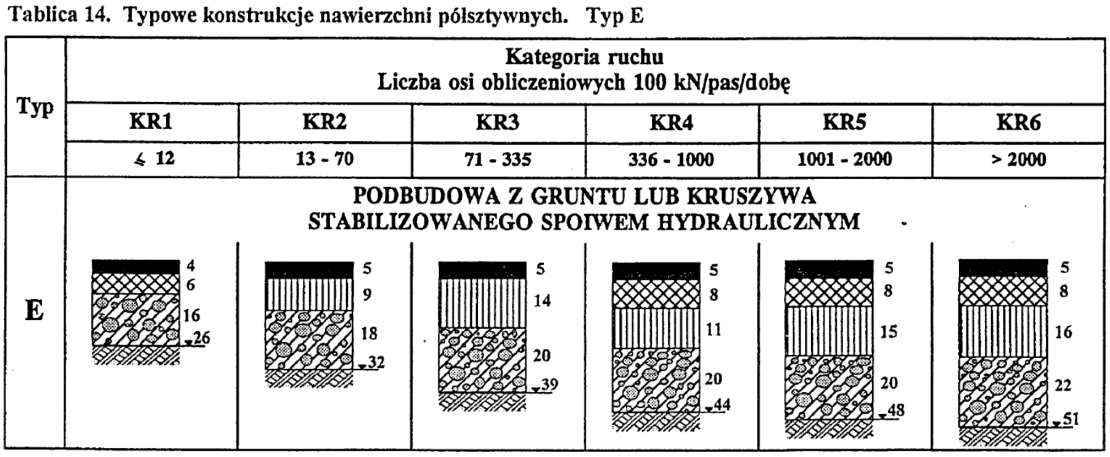


***Figure 6** Semi-rigid pavement structure of Polish catalogue*

The Figure 6 shows the semi-rigid variety of pavement structures the Polish catalogue uses for road construction. In the table we can see the name of the structures (KR1, KR2, etc.) and just below number of heavy traffic repetitions of heavy traffic in 24 hours in order to be designed for this capacity. In the E row, there are draw the different structures, "soil subgrade or cement treated aggregate base", and the layers with their thickness.

The layers of semi-rigid pavement structures are most commonly composed by asphalt concrete with closed structure, asphalt concrete with partial closed structure (not in KR2), asphaltic concrete in the structure of a foundation layer partially closed (not in KR1), cement-stabilized aggregate and the subgrade.

4.4 Design methods

4.4.1 Empirical method

The empirical method is the one based on the results of experiments or experience. This procedure requires a large number of observations in order to obtain the relationship between input variables and outcomes. It is not necessary to firmly establish the scientific basis for the relationships between variables and outcomes as long as the limitations with such an approach are recognized. It is not prudent to use empirically derived relationships to describe phenomena that occur outside the range of the original data used to develop the relationship. Sometimes it is more accurate to rely on experience than to quantify the exact cause and effect of certain phenomena.

Many pavement design procedures use an empirical approach. This means that the relationship between design inputs, such as loads and material properties, and pavement failure were arrived at through experience, experimentation or a combination of both. The simplest approaches of empirical design methods specify pavement structural design based on what happened in the past. More complex approach are the ones based on empirical equations derived from experimentation, which sometimes can be quite elaborate.

The disadvantage of an empirical method is that it can be applied only to a given set of environmental, material and loading conditions. If these conditions are changed, the design is no longer valid, and a new method must be developed through trial and error to be conformant to the new conditions.

4.4.2 Mechanistic-empirical method

The mechanistic-empirical method of design is based on the mechanics of materials that relates an input, such as a wheel load, to an output or pavement response, such as stress or strain. The response values are used to predict distress from laboratory-test and field-performance data. Dependence on observed performance is necessary because theory alone has not proven sufficient to design pavements realistically.

The mechanistic approach seeks to explain phenomena only by reference to physical causes. For pavement design, we might use stresses, strains and deflection within a pavement structure, and the physical causes are the loads and material properties of the pavement layers. The relationship between these phenomena and their physical causes is typically described using a mathematical model. Various mathematical models can be used, the most common is a layered elastic model.

Along this mechanistic approach, empirical elements are used when defining what value of the calculated stresses, strains and deflections result in pavement failure. The relationship between physical phenomena and pavement failure is described by empirically derived equations that compute the number of loading cycles to failure.

The use of vertical compressive strain to control permanent deformation is based on the fact that plastic strains are proportional to elastic strains in paving materials. Thus, by limiting the elastic strains on the subgrade, the elastic strains in other components above the subgrade will also be controlled, hence, the magnitude of permanent deformation on the pavement surface will be controlled in turn.

The advantages of mechanistic methods are the improvement in the reliability of a design, the ability to predict the types of distress, and the feasibility to extrapolate from limited field and laboratory data.

The basic advantages of a mechanistic-empirical pavement design method over the empirical pavement design method are:

- The method can be used for both existing pavement rehabilitation and new pavement construction
- It accommodates changing load types
- Better characterization of materials allowing for:

  - Better utilization of available materials
  - Application of new materials
  - An improved definition of existing layer properties

- Utilisation of material properties that relate better to actual pavement performance

- It provides more reliable performance predictions

- Better definition of the construction role

- It is possible to support environmental and aging effects on materials

5. Mechanistic-empirical design

Between the mechanistic-empirical design methods, we can distinguish two kind of formulas. The first one will be used for the calculation of fatigue cracking, while the second one will be used to calculate of rutting. The rutting formulas for all the methods are very similar, however the coefficients are different for each method.

Present criteria for fatigue cracking can be divided into the following four categories, taking into account the factor which governs the fatigue life: tensile strain at the bottom of asphalt layers, dissipated energy, strain work and fracture mechanics. The tensile strain criteria is still applied in all practically used methods of pavement design.

On the other hand, criteria for structural rutting in all the method are based on a relationship between number of load repetitions and vertical compressive strain developed in the subgrade. Structural rutting is formed not only by deformation of subgrade soil but also by accumulation of permanent deformations occurring in all layers of pavement structure.

We will have to divide the methods for type of pavement because the way of calculation of the number of loadings is different for the flexible and the semi-rigid pavement structure.

5.1 Flexible pavement methods

The methods we will introduce for flexible pavement design are: French method, Asphalt Institute method, and Shell Oil method.

5.1.1 French method

The two criteria used in the French design method are:

- Limitation of the horizontal strain at the bottom of the bituminous layers

- Limitation of the vertical strain at the top of the subgrade

Both limitations are related to the number of cycles (passes of a load) during the considered lifetime of the pavement structure.

For fatigue cracking, the relation between the admissible horizontal strains at the bottom of the bituminous layer $\varepsilon_{t,ad}$and the number of cycles NE is the following:

$$\varepsilon_{t,ad} = \varepsilon(NE,\theta) \cdot k_r \cdot k_c \cdot k_s$$

With,

$$\varepsilon(NE,\theta) = \varepsilon_6(10°C, 25HZ) \cdot \left(\frac{E(10°C)}{E(\theta)}\right)^{0,5} \cdot \left(\frac{NE}{10^6}\right)^{0,2}$$

And finally, number of cycles:

$$NE = \left[\frac{\varepsilon_6(10°C, 25HZ) \cdot k_r \cdot k_c \cdot k_s}{\varepsilon_{t,ad}} \cdot \left(\frac{E(10°C)}{E(\theta)}\right)^{0,5}\right]^{\frac{-1}{0,2}}$$

Where:

$\varepsilon_{t,ad}$: admissible tensile strain in asphalt layer

ε_6: tensile strain at which asphalt specimen is damaged after 10^6 load cycles at the test conditions: temperature 10^o and frequency 25 Hz

NE: number of load repetitions to failure

$E(10°C)$: modulus of stiffness of asphalt mix at temperature of 10^o [MPa]

$E(\theta)$: modulus of stiffness of asphalt mix at temperature of design [MPa]

k_r: risk coefficient adjusting the strain value to the risk chosen according to factors of a confident interval around the thickness of the layers and around the result of the fatigue tests.

k_c: coefficient accounting for type of asphalt mix

k_s: reduction coefficient taking into account a lack of uniformity in the bearing capacity on a soft subgrade

For a defined load, temperature and material, the number of cycles depends only on the strain value at the bottom of the bituminous layer. Thus, with the value of the horizontal strains, we obtain the number of cycles leading to failure.

However, the number of cycles is very sensitive to the coefficients “k” values because they are elevated at a power of 5. This means that the lifetime of pavement structures strongly depends on the value of the three coefficients.

For rutting, the relation between number of load repetitions and vertical compressive strain at top of the subgrade:

$$NE = \left(\frac{k}{\varepsilon_v}\right)^{\frac{1}{m}}$$

where,

ε: vertical compressive strain at the top of the subgrade

NE: number of load repetitions to rutting

m: 0,222

k: coefficient depending of the type of traffic (0,0120 - heavy traffic and 0,0160 - small traffic)

5.1.2 Asphalt Institute

The Asphalt Institute method applies the following formula to relate the strains calculated to the total number of traffic load repetitions to failure. The fatigue cracking will be determined when a 20% of the area is cracked

$$NE = 18{,}4 \cdot 10^{M} \cdot (6{,}167 \cdot 10^{-5} \cdot \varepsilon_h^{-3{,}291} \cdot E^{-0{,}854})$$

Where,

$$M = 4{,}84 \cdot (\frac{V_a}{V_a + V_v} - 0{,}69)$$

ε_h: horizontal tensile strain at the bottom of asphalt layers

NE: number of load repetitions to failure

E: modulus of stiffness of the bottom asphalt layer [MPa]

V_a: volume of asphalt [%]

V_v: volume of voids [%]

For rutting, the relation between number of load repetitions and vertical compressive strain at top of the subgrade:

$$NE = \left(\frac{k}{\varepsilon_v}\right)^{\frac{1}{m}}$$

Where,

ε: vertical compressive strain at the top of the subgrade

NE: number of load repetitions to rutting

m: 0,223

k: $1{,}05 \cdot 10^{-2}$

5.1.3 Shell Oil

The main difference of the Shell Oil method among the French and the Asphalt Institute methods is that the applied load is not applied in the same way. In this case, the applied load is done with two wheels, so the applied forces don't begin just in the symmetric axis and there is an empty space in which there are no applied forces in the surface. That's an important supposition which we have to take into account when using this method.

In the Shell Oil model, the fatigue formula relates the tensile strains on the bottom of the asphalt surface, with number of load repetitions and the properties of the asphaltic layer, as seen in the next formula:

$$NE = (0{,}856 \cdot V_b + 1{,}08)^{5{,}671} \cdot E^{-2{,}042} \cdot \varepsilon_h^{-5{,}671}$$

Where,

ε_h: horizontal tensile strain at the bottom of asphalt layers

NE: number of load repetitions to failure

E: modulus of stiffness of the bottom asphalt layer [MPa]

V_b: percentage of bitumen content [%]

For rutting, the relation between number of load repetitions and vertical compressive strain at top of the subgrade:

$$NE = \left(\frac{k}{\varepsilon_v}\right)^{\frac{1}{m}}$$

Where,

ε: vertical compressive strain at the top of the subgrade

NE: number of load repetitions to rutting

m: 0,25

k: probability of failure (P = 50% - 0,028; P = 85% - 0,021 and P = 95% - 0,0018)

5.2 Semi-rigid pavements design

In the semi-rigid pavement structure we have a cement-stabilized crushed aggregate layer over the subgrade, so for our analysis we will differentiate two stages. The first stage will be based on the calculation of the occurrence of fatigue cracks in the sub-base layer, following the Illinois University criterion. This criterion allows the calculation of the number of loadings the cement-stabilized layer can support before being destroyed, in other words, when it starts transmitting stresses as a flexible layer. We choose the minimum values of loadings because we have to take into account the most restrictive results in order to build safer.

In the second stage, the structure will work as a flexible structure, so number of loadings until failure and rutting can be calculated using the methods we have seen before.

In order to obtain the total number of loadings N_k for the first stage we will use the empirical formula of Illinois University criterion.

$$\log(N_k) = 11{,}784 - 12{,}121 \cdot \left(\frac{\sigma}{R_{zg}}\right)$$

Where,

σ tensile stress of the concrete layer

R_{zg} bending strength of the concrete layer (0,5 MPa typically)

There is also a fatigue reduction factor, that must be applied to the structure.

$$D = \frac{N_k}{N_{zd}}$$

Where,

N_{zd} minimum number of loadings of fatigue or rutting supported by the semi-rigid structure (stage I)

The next step, the second stage, we will obtain the number of loadings in the following way:

$$N^{II} = \min(N_z^{II}, N_d^{II})$$

The number of loadings for the second stage will be the minimum of the loadings for fatigue cracking and for rutting.

Finally, we can calculate the total number of loadings the structure can support.

$$N = N_k + N^{II}(1 - D)$$

6. Stresses and strains

The response of a pavement structure to traffic loading is mechanistically modelled by computing stresses and strains within its layers. If excessive, stresses may cause pavement fatigue cracking and/or surface rutting. This may result in both structural and functional failure, thus causing a safety hazard to motorists. Pavement stress-strain analysis is an ideal tool for analytical modelling of pavement behaviour and thus, constitutes an integral part of pavement design and performance evaluation. It is the fundamental basis for the mechanistic design theory.

In our results, we will present a simplified linear elastic analysis of the stress-strain behaviour of the pavement layers under static traffic loading.

The stresses and strains depend on the variation of the layer thickness, the elastic constants of the layer, as elastic modulus (E) and Poisson ratio (v), and the traffic loading. These parameters are consequently correlated to the pavement service life in terms of the number of load repetitions until failure cracking (relative fatigue life).

To get the results of the strains and stresses of the pavement structure, we have used BISAR program.

In order to run the program with my personal computer, I had to install VirtualBox software to simulate different operative system, because BISAR runs with 32 bit operative system and most of modern computers have difficulties running this kind of programs.

6.1 BISAR program

Bitumen Stress Analysis in Roads (BISAR) computer program was launched by Shell Research in the early 1970s which was used in drawing the design charts of the Shell Pavement Design Manual issued in 1978. The program has been developed, and with BISAR 3.0 the full possibilities of the original program are available to use in Windows software.

In addition to the calculation of stresses and strains, the program allows to calculate deflections and is able to deal with horizontal forces and slip between the pavement layers. This offers the opportunity to calculate comprehensive stress and strain profiles throughout the structure for a variety of loading patterns.

With the BISAR program, following the Boussinesq theory, stresses, strains and displacements can be calculated in an elastic multi-layer system which is defined by the following configuration and material behaviour:

- The system consists of horizontal layers of uniform thickness resting on a semi-infinite base or half space.

- The layers extend infinitely in horizontal directions

- The material of each layer is homogeneous and isotropic
- The materials are elastic and have a linear stress-strain relationship

The system is loaded on top of the structure by one or more circular loads, with a uniform stress distribution over the loaded area. The program offers the possibility to calculate the effect of vertical and horizontal stresses (shear forces at the surface) and includes an option to account for the effect of (partial) slip between the layers, via a shear spring compliance at the interface.

For the BISAR calculations, we have to introduce some data to get our results:

- Number of layers
- Young's modulus for each layer
- Poisson's ratio of the layers
- Thickness of the layers (except for the semi-infinite base layer)
- Interface shear spring compliance at each interface
- Number of loads
- Co-ordinates of the position of the centre of the loads
- One of the following combinations to indicate the vertical normal component of the load
    - Stress and load
    - Load and radius
    - Stress and radius
- Co-ordinates of the positions for which output is required

The centre of the loads and the positions at which stresses, strains and displacements have to be calculated are given as co-ordinates in a fixed Cartesian co-ordinate system. The actual calculations to determine the response of a particular load in terms of stresses, strains and displacements are, however, carried out within a local cylindrical co-ordinate system having the centre of the load as origin. The effect of the simultaneous action of various loads is the sum of effects due to the action of each separate load. This summation is carried out after transformation of the results with respect to the underlying Cartesian co-ordinate system.

The program calculates the eigenvalues and eigenvectors of the stress and strain tensors, the principal stresses and strains and the corresponding principal directions. The maximum and minimum principal values represent the maximum and minimum normal stresses and strains. The principal directions denote the normal of the planes through the point under consideration that are free of shear stresses and strains. The maximum shear stresses and strains, acting in planes bisecting the principal directions are equal to half the difference between these principal values. Since these maximum shear stresses can also be considered in failure studies, they are calculated too, together with the midpoints of the Mohr's stress circles and the total energy density and strain energy density of distortion at the considered position.

The detailed output comprises the following information for each selected position in the structure under consideration for each load (expressed in terms of the cylindrical co-ordinate system for the loading):

- Components of the stress tensor (normal and shear)

- Components of the strain tensor (normal and shear)

- Components of the displacement vector

6.1.1 BISAR calculation procedure

Once knowing what the BISAR program can calculate, we will see the way calculate the strains and stresses of the surface, introducing all the data needed to get the results.

First of all, we have to open BISAR program in a 32 bit operative system, because it is an old software which have some compatibility problems with modern computers. In order to do that, I downloaded a virtual machine, Virtual Box, to simulate the operative system Windows XP 32 bits. In Virtual Box I could run the program and begin with the calculations for our structures.

The first step when you open BISAR program is to set up the data of the chosen pavement structure. We have to give the loads and stresses our pavement is going to suffer. This values are 700 kPa of vertical pressure and 57,5 kN of vertical load, which results to a radius of 16,17 cm. We can see these values in the Figures 7 and 8.

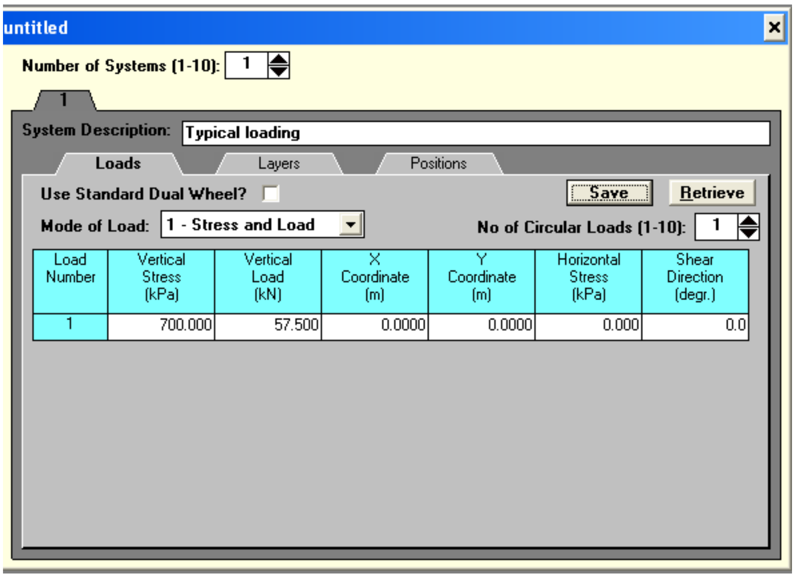


Figure 7 Values of vertical stress and load in BISAR

The values of the coordinates in X and Y axis are 0 m because we are applying the loads and stresses from the beginning of the axis until the distance of the radius. Horizontal load is also 0 kN because we only consider vertical forces and not horizontal ones.

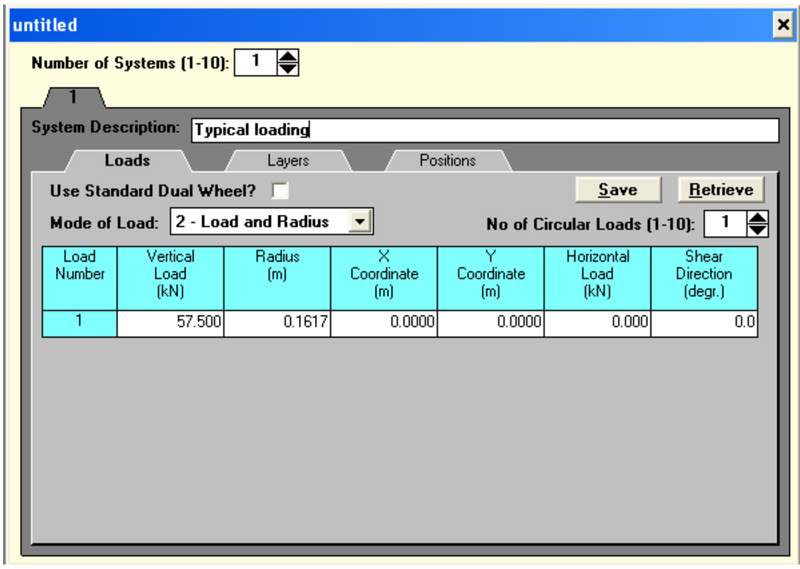


Figure 8 Values of vertical load and radius in BISAR

The second step in BISAR is to stablish the properties of the layers, such as thickness of the layer, modulus of elasticity in MPa and Poisson's ratio. In the Figure 9 we can see all the properties of the KR5 structure from Polish catalogue. The last layer doesn't have thickness because it is the subgrade.

We consider the layers as homogenous and horizontal, so it exists full friction between all the layers of the structure.

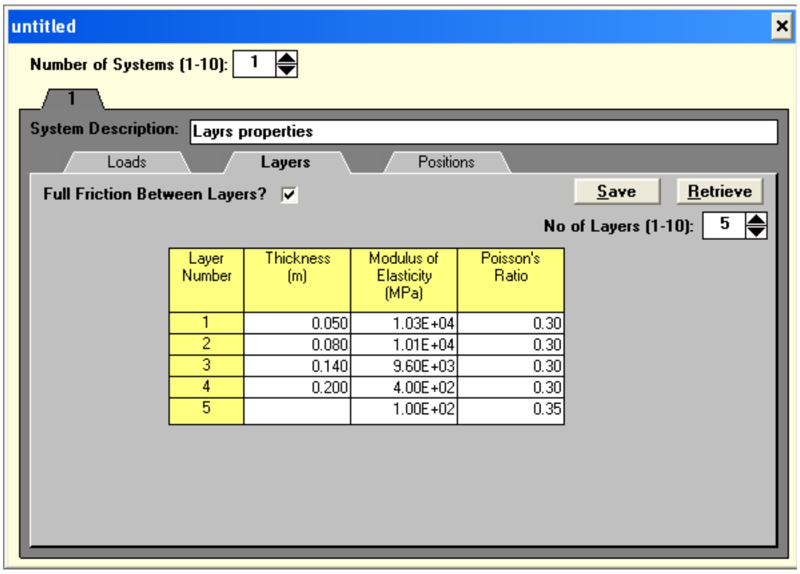


Figure 9 *Layer properties in BISAR of Polish pavement structure KR5*

After setting the loads and properties of the layers, we stablish the positions we want to get the calculations from. In our case, the total thickness of the pavement structure is 47 cm, so we will have to evaluate some points deeper than the structure.

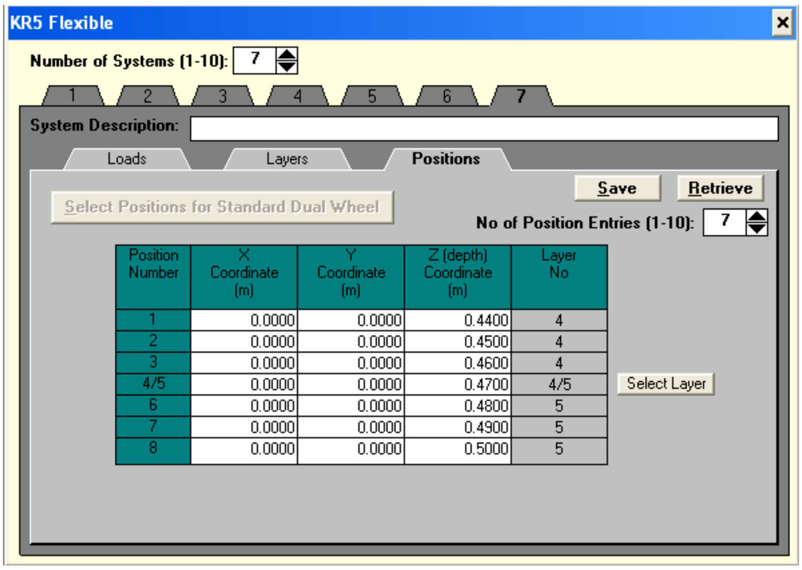


Figure 10 *Z coordinates and number of layer in BISAR*

As we can see in the Figure 10, when there is a change of layers, the program recognises it automatically and makes two calculations, one per each layer. We have to divide the calculations of the total depth because the program doesn't support only 1 calculation fur such quantity of points.

Finally, after stablishing the points where we want to get the stresses, strains and deformations, we just compute the data and BISAR gives us the results we wanted to obtain.

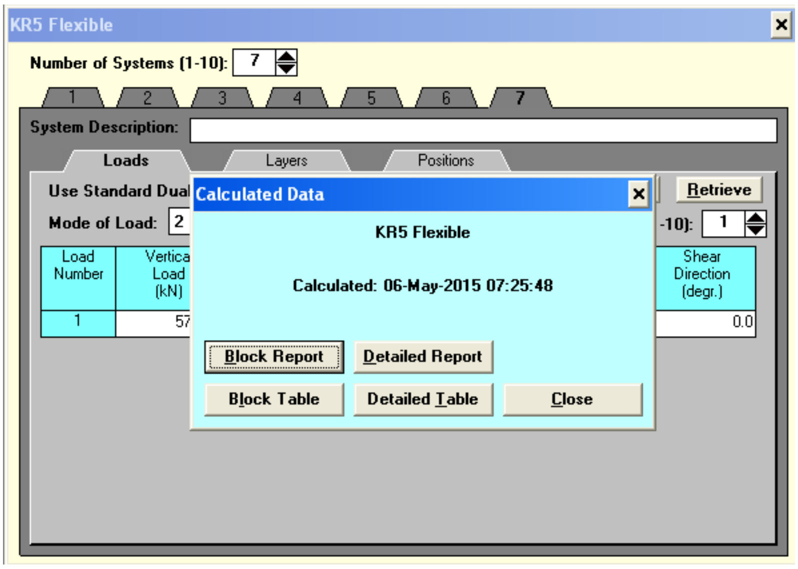


Figure 11 *Result's menu in BISAR*

We can have the results given in two different ways, a detailed report, which shows us the results very detailed per each co-ordinate, or block report, which give us all the strains and stresses divided into different depth co-ordinates. We are going to use the block report because we have all the results together.

6.2 Analysis of stresses and strains

After setting all the data in the program we obtain the results of strains, stresses and displacements in function of the depth of the pavement structure. So, we can create an Excel file in order to get the shape of horizontal and vertical stresses and strains.

In our case, we are going to calculate a flexible and a semi-rigid pavement structure from Polish catalogue.

6.2.1 Flexible pavement structure

For this analysis, we will evaluate a typical flexible pavement structure, as shown in Figure 12, which is Polish KR5 pavement cross section. The layer properties are shown in the table 1.

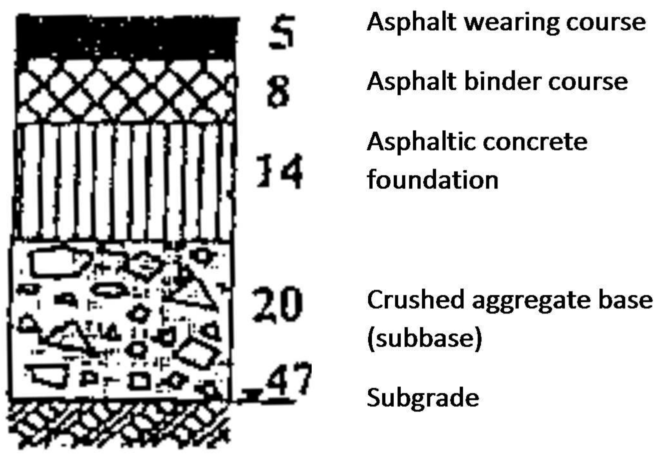


Figure 12 *Polish KR5 flexible pavement structure*

Layer number	Material	E [MPa]	υ (Poisson ratio)
1	Asphalt concrete with closed structure	10300	0.3
2	Asphalt concrete with partial closed structure	10100	0.3
3	Asphaltic concrete in the structure of a foundation layer partially closed	9600	0.3
4	Crushed aggregate stone	400	0.3
5	Soil	100	0.35

Table 1 *Layer properties of KR5 flexible pavement*

Stresses and strains of the structure can be seen in the following graphics.

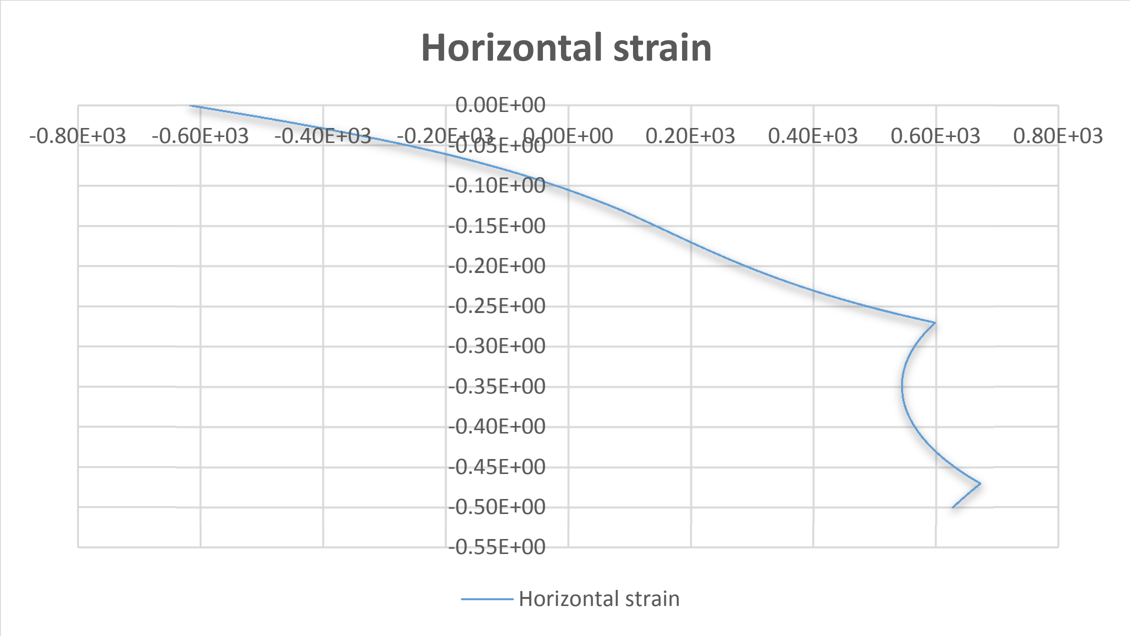


Figure 13 *Horizontal strain for KR5 flexible*

The horizontal strain on the top of the surface is in compression, however, when we go deeper it changes into tension following almost linear relation until there is a huge change in the layers. We change from asphaltic layers into crushed aggregate stone and the shape of the strain changes. We will have into account the horizontal strain in the bottom of asphaltic layers

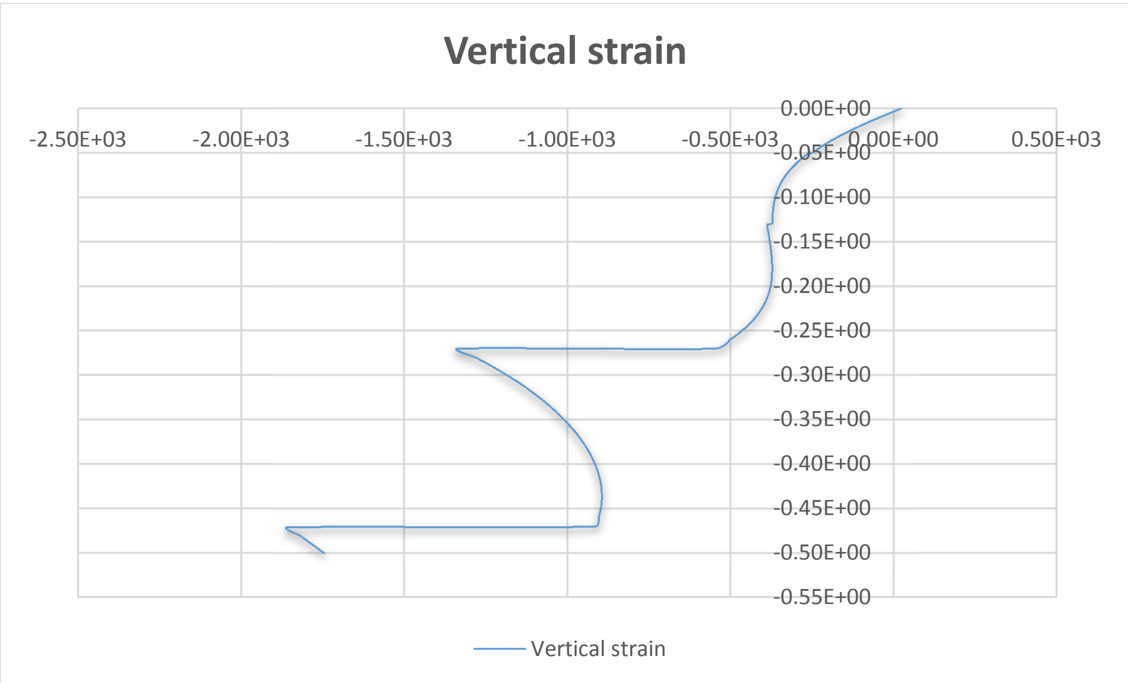


Figure 14 *Vertical strain for KR5 flexible*

The vertical strain is all in compression. It increases a lot when there is a change of layer and decreases with the depth. We will have into account the vertical strain on the top of the subgrade, at 47 cm depth.

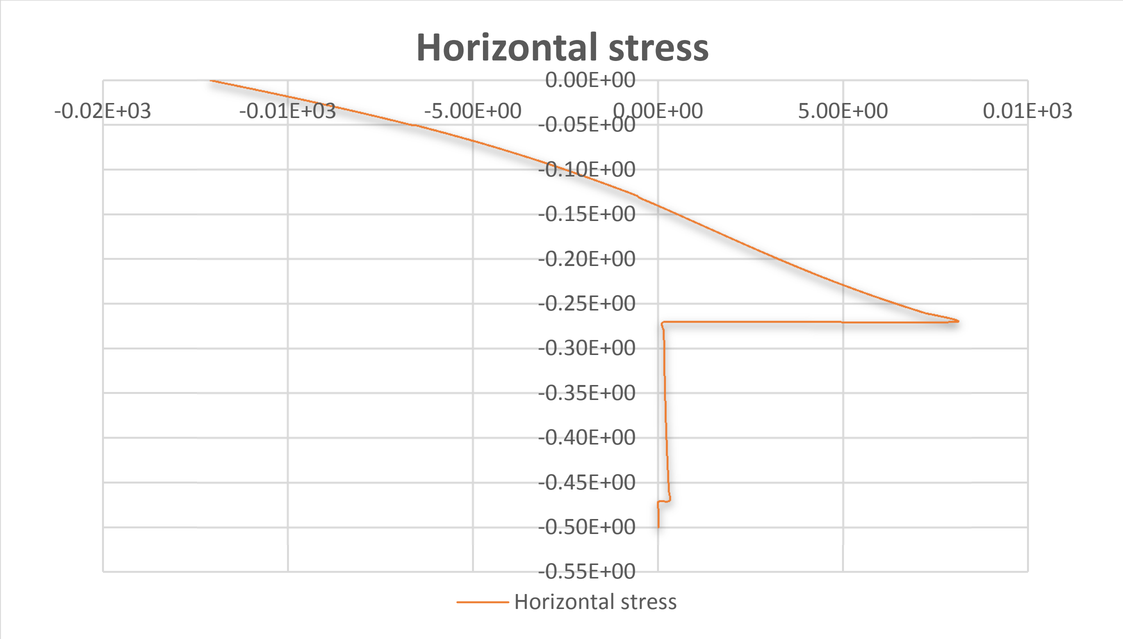


Figure 15 *Horizontal stress for KR5 flexible*

On the surface, the stresses are compressive. This concentration of compressive stresses can cause surface deformation in the asphalt layer. If we get deeper, the stresses become to tension until we reach the bottom of the asphalt layers, where stress become almost 0, and tend to 0 as deep as we move.

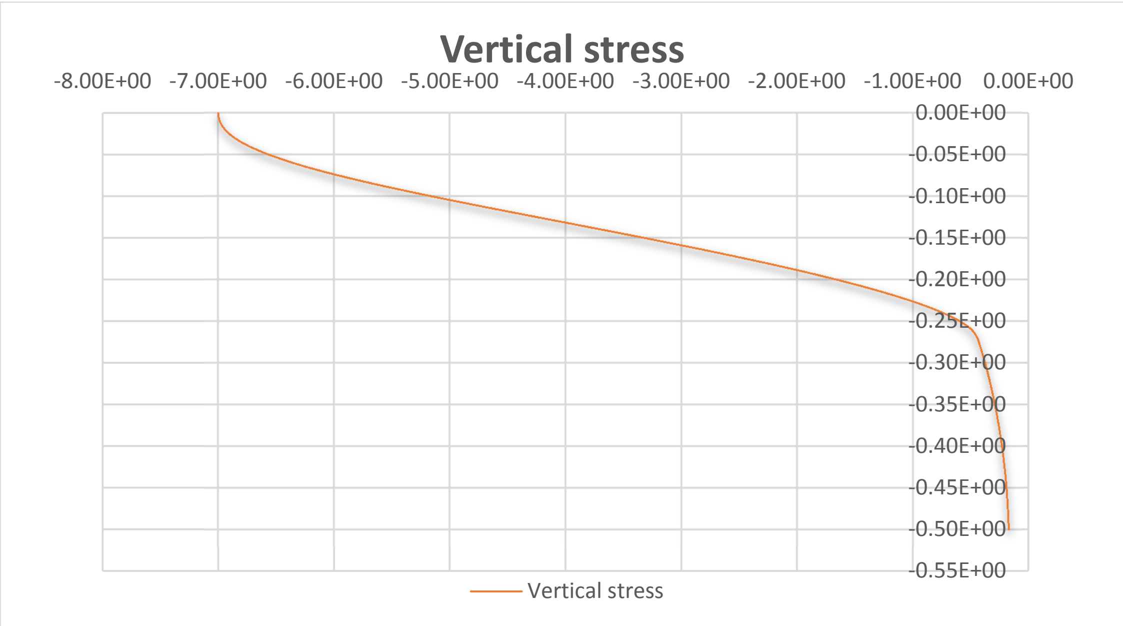


Figure 16 *Vertical stress for KR5 flexible*

Vertical stresses are compressive, it has a significant decrease within the asphalt layer, however when we reach to the crushed aggregate stone vertical stress decreases slowly tending to zero.

6.2.2 Semi-rigid pavement structure

For this analysis, we will evaluate the semi-rigid pavement structure from the structure used previously, so KR5 semi-rigid. The structure is shown in Figure 17. The semi-rigid structure is different from the flexible one, and the way of calculation strains and stresses in order to obtain after the number of cycles of failure is divided into two parts. The first one considering the structure as rigid and the second one taking into account that the structure is flexible. The properties of both stages are shown in Tables 2 and 3.

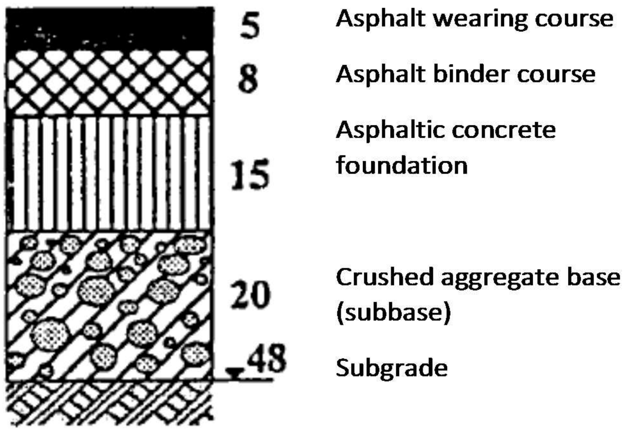


Figure 17 *Polish KR5 semi-rigid pavement structure*

Layer number	Material	E [MPa]	υ (Poisson ratio)
1	Asphalt concrete with closed structure	10300	0.3
2	Asphalt concrete with partial closed structure	10100	0.3
3	Asphaltic concrete in the structure of a foundation layer partially closed	9600	0.3
4	Cement – stabilized aggregate	4500	0.25
5	Soil	100	0.35

Table 2 *Layer properties of KR5 semi-rigid pavement stage I*

The stresses and strains are drawn in the following graphics.

The horizontal strain on the top of the surface is in compression but it changes into tension as we go deeper, just like for the flexible structure. However, when we change from the asphalt layer to the cement stabilized aggregate layer, there is a significant increment of strain compared to the flexible structure.

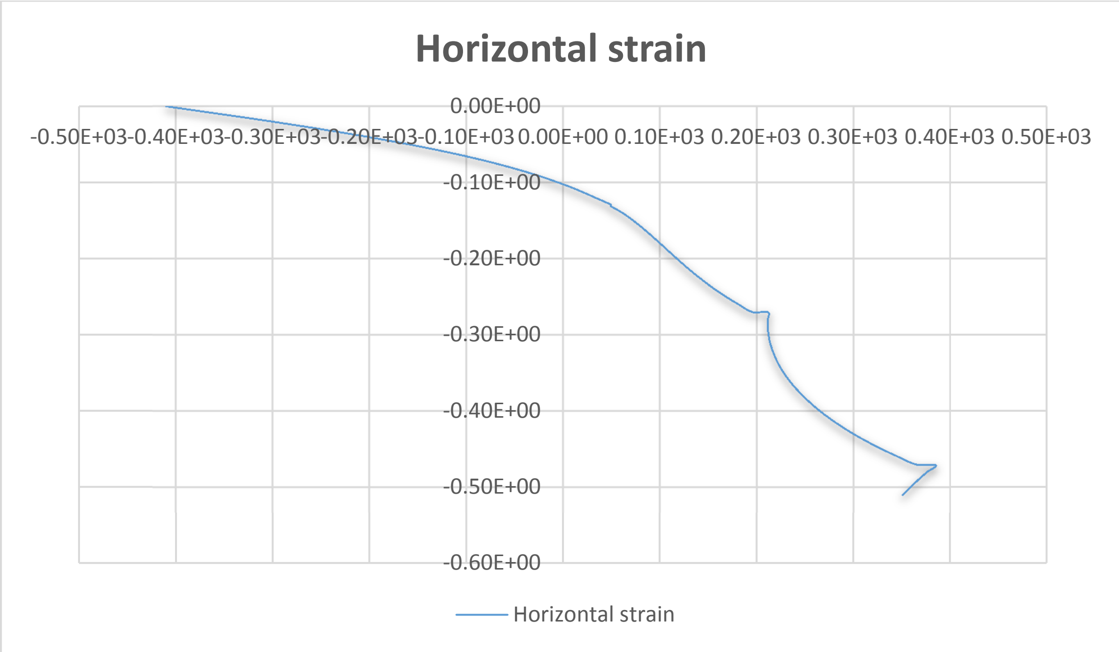


Figure 18 *Horizontal strain for KR5 semi-rigid stage I*

In comparison to the values of flexible pavement horizontal strain values are smaller in the semi-rigid pavement structure because the structure is less flexible. As said before, we will have into account horizontal strain on the bottom of asphalt layer in order to do calculations of number of loadings.

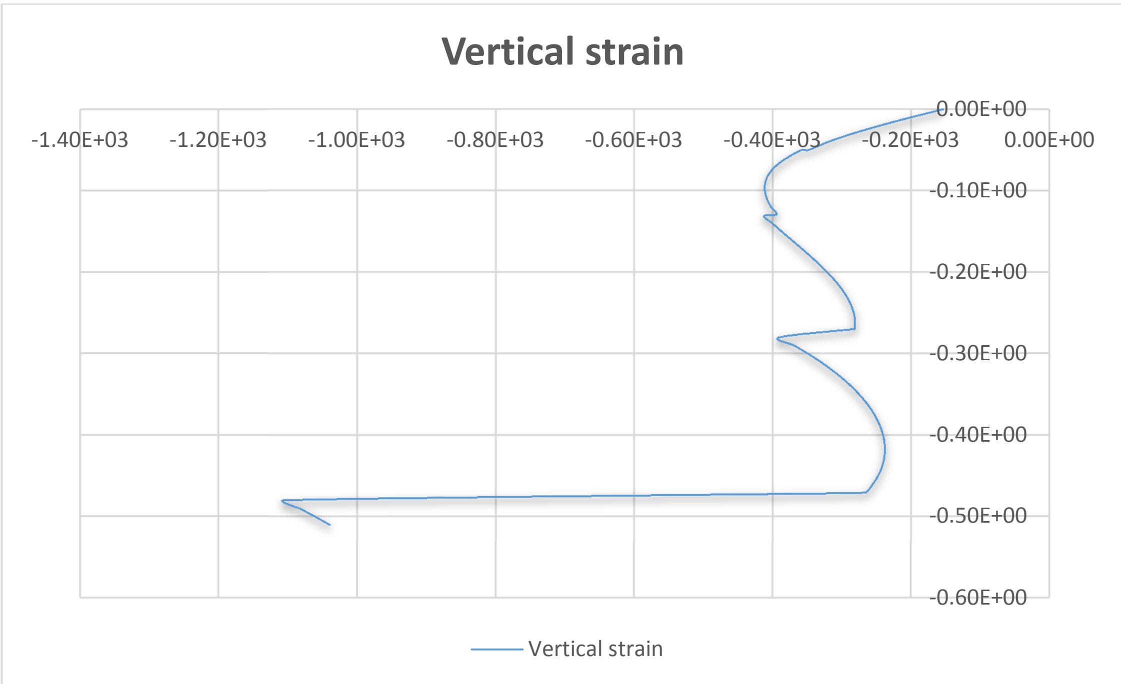


Figure 19 *Vertical strain for KR5 semi-rigid stage I*

Vertical strain is also in compression. It has an "S" shape in the top of the asphalt pavement, and increases again when it changes to the cement-stabilized stone layer.

Then, it decreases until it reaches at the subgrade layer where it gets its bigger value for the vertical strain, which we will use for the calculation of number of loadings for rutting.

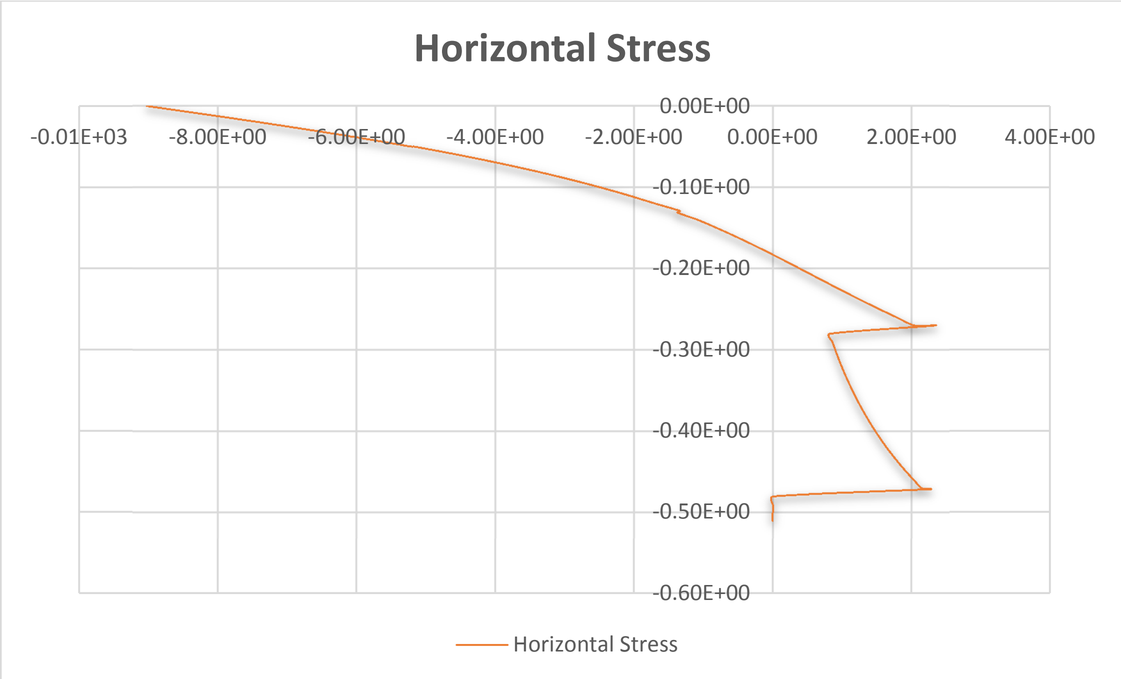


Figure 20 *Horizontal stress for KR5 semi-rigid stage I*

For the semi-rigid structure stresses behave similar as in flexible structure. Also the concentration of compressive stresses can cause surface deformation in the asphalt layer although semi-rigid pavement stresses are smaller than for the flexible pavement, so it is less critical for these deformations. Tension is reached when we move deeper the structure, but also the stresses are lower than for flexible pavement. Lower the asphalt surface, the stresses don't tend to zero as before, they decrease in the top of cement-stabilized layer but increase until the bottom of the layer. In the subgrade, stresses tend to zero as we saw before.

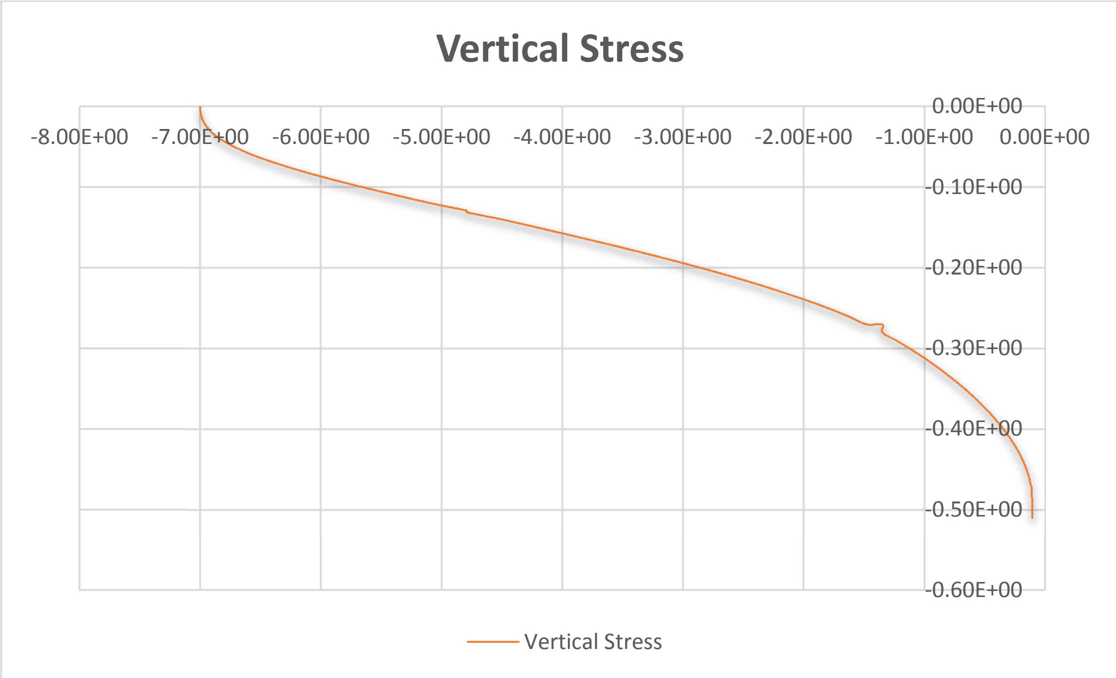


Figure 21 *Vertical stress for KR5 semi-rigid stage I*

Vertical stresses are very similar for flexible than for semi-rigid structure, however, in this case, the stresses decrease slower as deep as we go but also tending to zero in the subgrade.

Now we will analyse strains and stresses for the stage II of the semi-rigid pavement, in which the cement – stabilized aggregate layer takes values of the flexible pavement structure.

Layer number	Material	E [MPa]	υ (Poisson ratio)
1	Asphalt concrete with closed structure	10300	0.3
2	Asphalt concrete with partial closed structure	10100	0.3
3	Asphaltic concrete in the structure of a foundation layer partially closed	9600	0.3
4	Cement – stabilized aggregate	400	0.3
5	Soil	100	0.35

Table 3 *Layer properties of KR5 semi-rigid pavement stage II*

Stresses and strains are drawn in the following graphics.

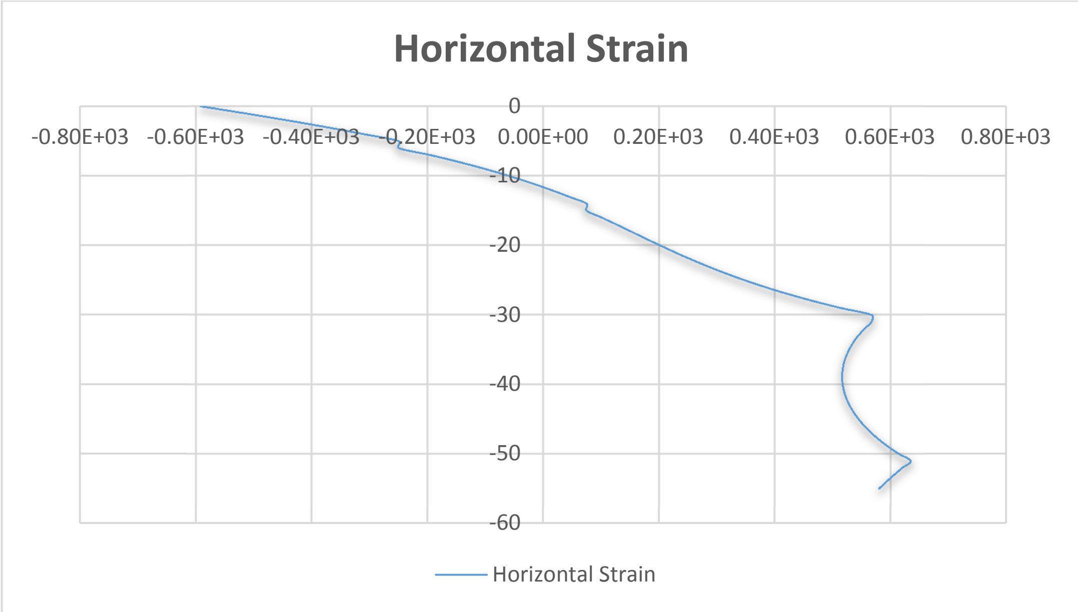


Figure 22 *Horizontal strain for KR5 semi-rigid stage II*

As in the flexible structure, the horizontal strain on the top of the surface is in compression, but it becomes tensile strain when we go deeper the structure. Then we also have into account only the strain in the bottom of asphalt layer.

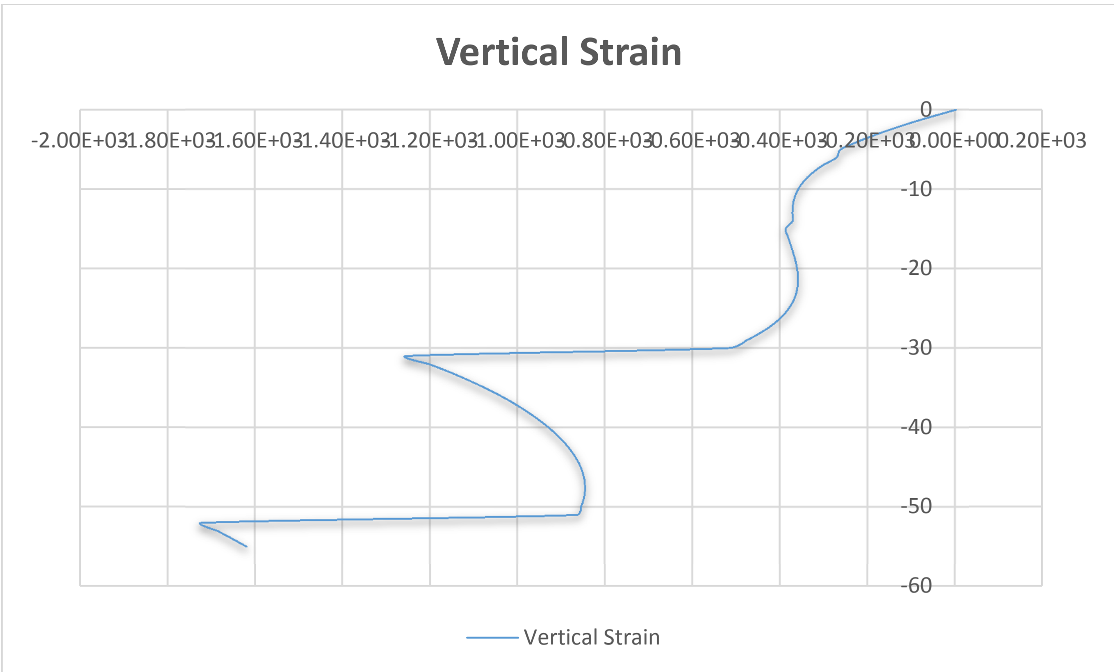


Figure 23 *Vertical strain for KR5 semi-rigid stage II*

Very similar to the flexible structure too with similar values and smaller than for Stage I of semi-rigid structure. It increases when there is a change of layers. We will have into account the vertical strain on the top of the subgrade.

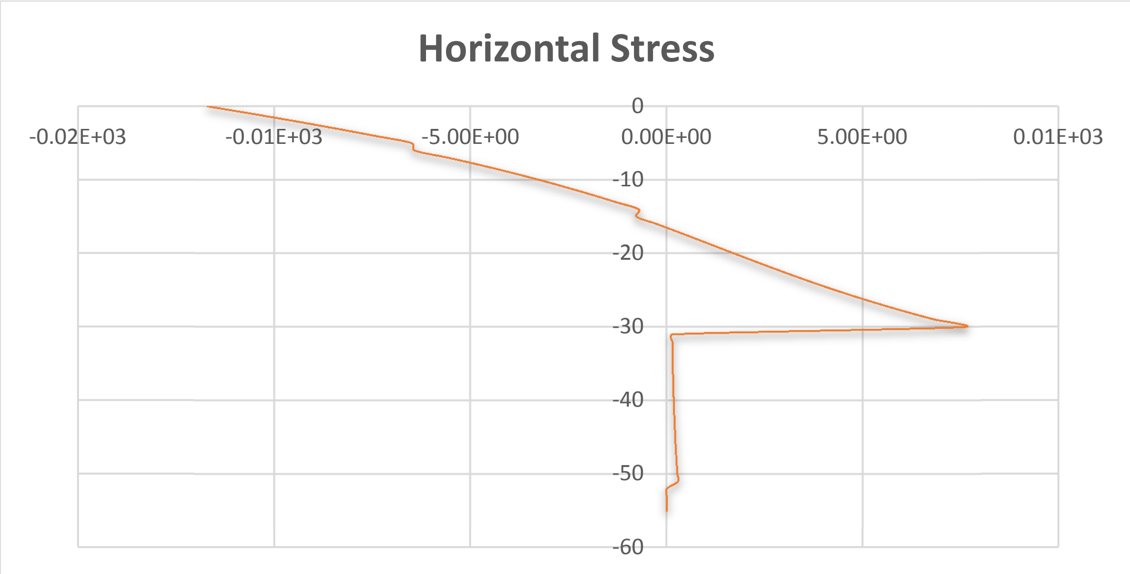


Figure 24 *Horizontal stress for KR5 semi-rigid stage II*

As before, similar to flexible structure, with smaller values than semi-rigid Stage I structure. In this Stage II the compressive stresses can cause more surface deformation in the asphalt layer than in Stage I. Stresses became tensile when we get deeper, and after the asphalt layer stresses tend to zero.

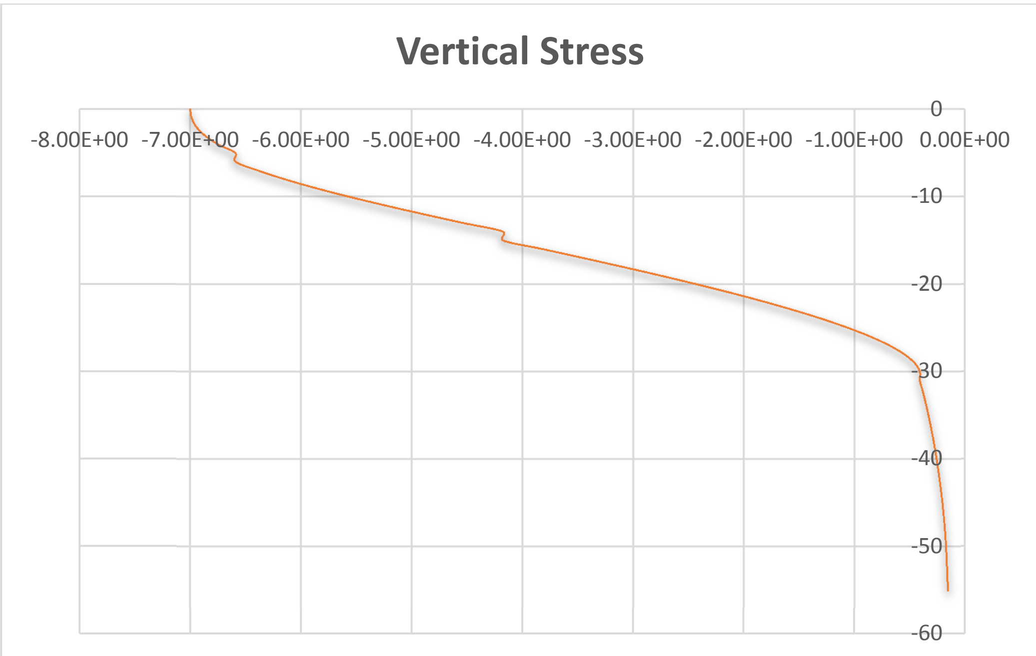


Figure 25 *Vertical stress for KR5 semi-rigid stage II*

Like in flexible and Stage I semi-rigid pavement structure vertical stress is in compression, with high values on the surface but it decreases with the depth. Values of Stage II decrease slower than in Stage I.

7. Comparison between different pavement design methods

For this part of the project we will use the formulas of the French method and the Asphalt Institute to calculate number of loadings until failure and rutting. We won't use the Shell Oil formula because, as it is explained in the Shell Oil method explanation, applied loads are different to the other two methods, they are not applied just in the symmetry axis, they are displaced from the axis because the loads are considered as two wheel system.

Flexible and semi-rigid KR5 pavement structures from Polish catalogue, will be analysed. To carry out with this analysis, the horizontal strain on the bottom of the asphalt layers will be used to determine the number of loadings for fatigue cracking, whereas the vertical strain on the top of the subgrade will be used to calculate the cycles until rutting.

The results of strains and stresses obtained with BISAAR program will be attached in the appendices.

7.1 Flexible pavement

From the analysis of stresses and strains, we have that horizontal and vertical strains are:

$$\varepsilon_H = 59{,}8 \cdot 10^{-6}$$
$$\varepsilon_V = 185{,}8 \cdot 10^{-6}$$

7.1.1 French method

- Fatigue cracking

$$NE = \left[\frac{\varepsilon_6(10°C, 25HZ) \cdot k_r \cdot k_c \cdot k_s}{\varepsilon_H} \cdot \left(\frac{E(10°C)}{E(\theta)}\right)^{0,5}\right]^{\frac{-1}{0,2}}$$

Where:

ε_6: $115 \cdot 10^{-6}$

k_r: 0,75 value for high traffic category

k_c: 1,3 value for high traffic category

k_s: 1 value for high traffic category

$\frac{E(10°C)}{E(\theta)}$ 1 temperature of design is supposed to be $10°C$

Applying the empirical equation, we obtain:

$$\mathbf{NE = 23\ 174\ 286\ number\ of\ loadings}$$

- Rutting

$$NE = \left(\frac{k}{\varepsilon_v}\right)^{\frac{1}{m}}$$

Where:

m: 0,222

k: 0,0120 - heavy traffic

Applying the empirical equation, we obtain:

$$\boldsymbol{NE = 142\ 483\ 206\ \text{number of loadings}}$$

We will consider the minimum result from fatigue cracking and rutting because it will be the safest for the construction of the pavement.

$$\boxed{\boldsymbol{NE = 23\ 174\ 286\ \text{number of loadings}}}$$

7.1.2 Asphalt Institute

- Fatigue cracking

$$NE = 18{,}4 \cdot 10^{M} \cdot (6{,}167 \cdot 10^{-5} \cdot \varepsilon_h^{-3{,}291} \cdot E^{-0{,}854})$$

Where,

$$M = 4{,}84 \cdot \left(\frac{V_a}{V_a + V_v} - 0{,}69\right)$$

E: 9600 MPa

V_a: 10%

V_v: 8%

Applying the empirical equation, we obtain:

$$\boldsymbol{NE = 7\ 983\ 576\ \text{number of loadings}}$$

- Rutting

$$NE = \left(\frac{k}{\varepsilon_v}\right)^{\frac{1}{m}}$$

Where:

m: 0,223

k: $1{,}05 \cdot 10^{-2}$

Applying the empirical equation, we obtain:

$$\boldsymbol{NE = 71\ 969\ 112\ \text{number of loadings}}$$

We will consider the minimum result from fatigue cracking and rutting because it will be the safest for the construction of the pavement.

$$\boxed{\boldsymbol{NE = 7\ 983\ 576\ \text{number of loadings}}}$$

7.2 Semi-rigid pavement

Now we have to analyse the semi-rigid pavement structure. We will have to analyse the structure in two parts, the first one considering the structure as semi-rigid whereas in the second one we will consider it as flexible.

The strains for the semi-rigid pavement stage I are:

$$\varepsilon_H = 21{,}13 \cdot 10^{-6}$$
$$\varepsilon_V = 112{,}8 \cdot 10^{-6}$$

The strains for the semi-rigid pavement stage II are:

$$\varepsilon_H = 56{,}67 \cdot 10^{-6}$$
$$\varepsilon_V = 175{,}6 \cdot 10^{-6}$$

Firstly, using Illinois University formula, we will calculate number of loadings using tensile stress in the concrete layer.

$$\sigma = 2{,}271 \cdot 10^{-1} MPa$$

$$\log(N_k) = 11{,}784 - 12{,}121 \cdot \left(\frac{\sigma}{R_{zg}}\right)$$

Where

R_{zg} 0,5 MPa

$$\boldsymbol{N_k = 1\ 899\ 510\ \mathit{number\ of\ loadings}}$$

Now we have to apply the equations of Asphalt Institute and French method to calculate the number of loadings for fatigue and rutting and consequently, the fatigue factor D for each method: $D = \frac{N_k}{N_{zd}}$:

- French method
  - Fatigue cracking

    $$\boldsymbol{NE = 4\ 207\ 409\ 614\ \text{number of loadings}}$$
  - Rutting

    $$\boldsymbol{NE = 1\ 349\ 132\ 839\ \text{number of loadings}}$$

$$D = \frac{1\,899\,510}{4\,207\,409\,614} = 4{,}515 \cdot 10^{-4}$$

Now we will evaluate stage II of the semi-rigid structure in order to get the number of loadings for the second stage N^{II}

- Fatigue cracking

$$\boldsymbol{NE = 30\,321\,189}\ \textbf{number of loadings}$$

- Rutting

$$\boldsymbol{NE = 183\,746\,690}\ \textbf{number of loadings}$$

$$\boldsymbol{N^{II} = 30\,321\,189\ number\ of\ loadings}$$

Finally, we can calculate the maximum number of loads the semi-rigid pavement structure can support with the French method:

$$N = N_k + N^{II}(1 - D)$$

$$\boxed{\boldsymbol{N = 32\,207\,000\ number\ of\ loadings}}$$

- Asphalt Institute
  - Fatigue cracking

$$\boldsymbol{NE = 244\,949\,627}\ \textbf{number of loadings}$$

  - Rutting

$$\boldsymbol{NE = 674\,619\,966}\ \textbf{number of loadings}$$

$$D = \frac{1\,899\,510}{244\,949\,627} = 7{,}755 \cdot 10^{-3}$$

Now we will evaluate stage II of the semi-rigid structure in order to get the number of loadings for the second stage N^{II}

- Fatigue cracking

$$\boldsymbol{NE = 9\,528\,743}\ \textbf{number of loadings}$$

- Rutting

$$\boldsymbol{NE = 92\,705\,750}\ \textbf{number of loadings}$$

$$\boldsymbol{N^{II} = 9\,528\,743\ number\ of\ loadings}$$

Finally, we can calculate the maximum number of loads the semi-rigid pavement structure can support with the Asphalt Institute method:

$$N = N_k + N^{II}(1 - D)$$

$$\boxed{\boldsymbol{N = 11\,354\,400\ number\ of\ loadings}}$$

Nº of loadings	French method	Asphalt Institute
Flexible KR5	**23 174 286**	**7 983 576**
Semi-rigid KR5	**32 207 000**	**11 354 400**

Table 4 *Number of loadings calculated with French method and Asphalt institute for different type of pavement*

In the Table 4 there are show the values we have obtained calculating the numbers of loadings repetitions until failure using strains and stresses from the pavement structure KR5 of the Polish catalogue.

We have done the calculation of number of cycles until failure for fatigue cracking and rutting. However, for the final result, we have chosen the smaller value between the two of them, because it is more restrictive for the construction of the read, therefore it is safer.

Analysing the values of the table 4 and as it was expected, the number of cycles until failure is bigger for semi-rigid pavement than for flexible. That is caused by the more rigid structure of the semi-rigid pavement, where the stresses and strains are lower than for flexible structure, so it exposed to less efforts and holds more cycles until failure.

If we compare now the two methods we have used to do the calculations, we can appreciate that the values obtained with the French method are about 3 times bigger than the ones we have calculated with the Asphalt Institute formula.

To see the relationship between the two formulas, French method and Asphalt Institute, we have drawn a graphic for fatigue cracking and for rutting, where we can see how they change, depending on the strain and on the number of cycles.

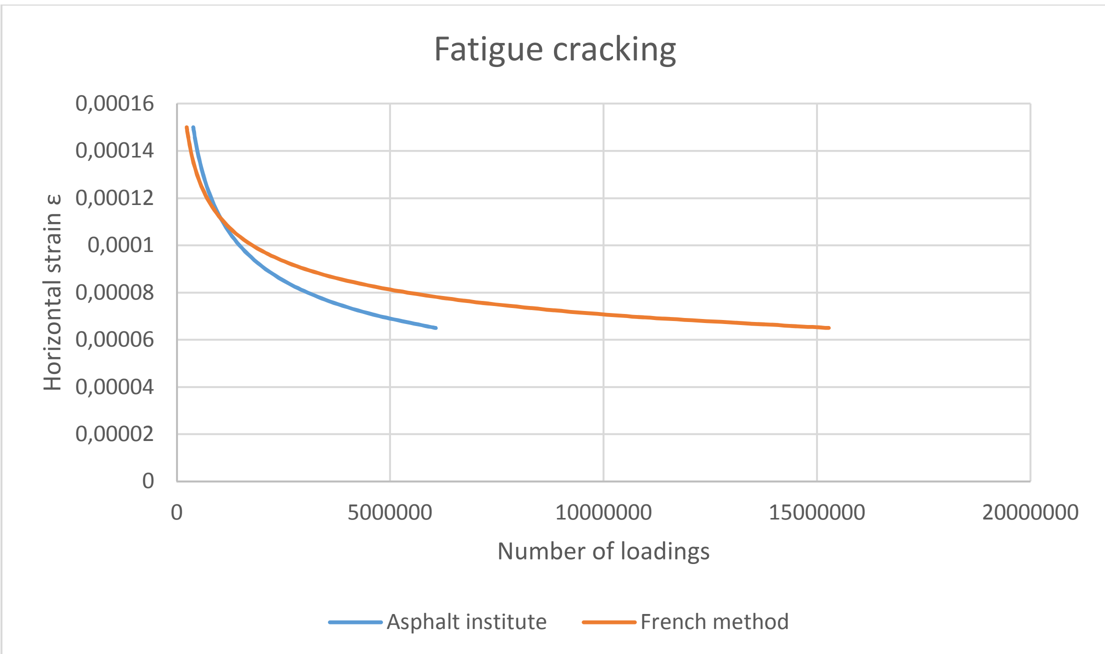


Figure 26 *Relation of French method and asphalt institute formulas in fatigue cracking depending on horizontal strain and number of loadings*

From the Figure 26 we can observe that the two methods cross in a certain point, so depending on the horizontal strains, there is one method one restrictive than the other. The crossing point is more or less for the value of $\varepsilon = 100 \cdot 10^{-6}$, so for smaller values of strain, Asphalt Institute results will be more restrictive, whereas for bigger values, French method should be used in order to obtain safer values.

In the structures we have studied, all the values of the horizontal strains have been smaller than $\varepsilon = 100 \cdot 10^{-6}$. These structures are for heavy traffic and have a wide bituminous layers. However, for smaller traffic categories which have smaller thickness of bituminous layers, we could reach strain values bigger than $\varepsilon = 100 \cdot 10^{-6}$.

Therefore, for heavy categories of traffic and roads with more demand, as highways or primary roads, it would be worth it to use the Asphalt Institute formula in order to get safer values of loading repetitions. On the other hand, for smaller categories of traffic with less demand, as secondary roads, French method should give more restrictive number of loading repetitions.

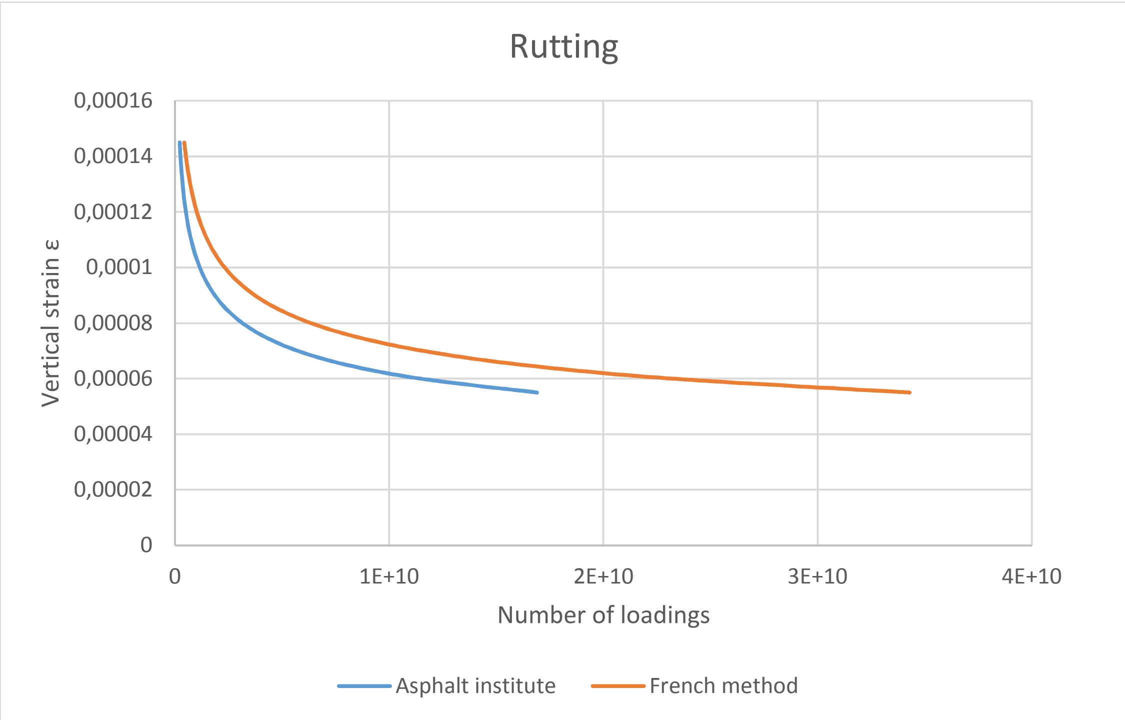


Figure 27 *Relation of French method and Asphalt Institute formulas in rutting depending on vertical strain and number of loadings*

We have also analysed values of formulas for rutting, which can be seen in Figure 27. In this case, the two formulas don't concur at any point, so for every value of number loadings will be smaller for Asphalt Institute than for French method. Though, we will always have to take into account both values from fatigue cracking and for rutting to choose the most restrictive number of cyclic loadings. So if the smaller value from the two methods is from rutting calculation, Asphalt Institute formula should be used for a safer design of the pavement structure.

8. Conclusions

The main objective of this project was to compare some mechanistic-empirical pavement design methods. In order to perform this comparison, we have done an introduction to pavement structural design and some mechanistic-empirical methods. Furthermore, we have done an analysis of stresses and strains for flexible and semi-rigid pavement structures, which has been very useful in order to obtain the results for mechanistic-empirical formulas.

After calculating number of load repetitions from French method and Asphalt Institute method we have seen that for heavy traffic categories, Asphalt Institute method would be more restrictive whereas for small traffic categories, French method would be safer because number of cyclic loadings would be smaller than for Asphalt institute method. We have to take into account that our analysis has been carried out with Polish structures, so we have taken Polish conditions for the formulas. It can be possible that for other types of countries with different conditions and parameters, we obtain different results that for our analysis. Therefore, that's why it is very important the utilisation of various type of mechanistic-empirical methods to analyse the design life of the structure, because not always the same method can give the safest value of design, which is the one we should choose.

As we have seen in the analysis of strains and stresses for flexible and semi-rigid pavement structures, the values are very different depending the type of structure. In the flexible pavement, values of horizontal and vertical strains are bigger than for semi-rigid structure. Thus, using mechanistic-empirical formulas for flexible and semi-flexible pavement structures, we get bigger values for semi-rigid structures as expected, so it can last more time than the flexible pavement due to its rigidity.

Roads are designed for a certain period of time. However, there has to be a maintenance of them in order to extend the serviceability life time and to keep the road in the best conditions as possible all the time. Also mention that depending on the country we are situated, there are some points to take into account while designing and maintaining the pavement structure, such as temperature or rainfall. So in some countries roads should have more maintenance or cost much more money when constructing them in order to build a high quality road.

9. Literature

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[17] Pavement Interactive Articles “Flexible and Semi-rigid pavements”

10. Appendices

FATIGUE CRACKING		
Horizontal strain (µstrain)	Asphalt institute	French method
	Number of loading	
5	28119703886	5,67103E+12
10	2872903427	1,7722E+11
15	756492616,8	23337588882
20	293515683,2	5538119237
25	140831712	1814730911
30	77288517,68	729299652,6
35	46536433,18	337420961,4
40	29987592,17	173066226,1
45	20351604,04	96039460,42
50	14388341,7	56710340,98
55	10514470,73	35212659,95
60	7896329,498	22790614,14
65	6067687,012	15273743,64
70	4754483,862	10544405,04
75	3788736,566	7468028,442
80	3063739,812	5408319,567
85	2509593,28	3994088,206
90	2079260,622	3001233,138
95	1740334,15	2290309,918
100	1470012,499	1772198,156
105	1251950,172	1388563,627
110	1074231,048	1100395,624
115	928035,1691	881095,6934
120	806743,633	712206,692
125	705326,4567	580713,8917
130	619916,8697	477304,4888
135	547510,6801	395224,117
140	485750,9536	329512,6576
145	432771,7782	276485,4421
150	387083,5307	233375,8888
155	347487,6777	198086,0033
160	313012,8482	169009,9865
165	282866,4024	144908,0657
170	256397,406	124815,2564
175	233068,0857	107974,7076
180	212431,6454	93788,53557
185	194114,8985	81781,23003

190	177804,573	71572,18495
195	163236,4425	62854,91211
200	150186,6436	55381,19237
205	138464,7005	48948,90433
210	127907,8881	43392,61335
215	118376,6528	38576,24761
220	109750,8733	34387,36324
225	101926,7931	30732,62733
230	94814,49123	27534,24042
235	88335,78903	24727,08769
240	82422,50904	22256,45912
245	77015,02197	20076,21595
250	72061,0289	18147,30911
255	67514,53697	16436,57698

Table 5 *Number of loadings for fatigue cracking of French method and Asphalt institute method in function of horizontal strain*

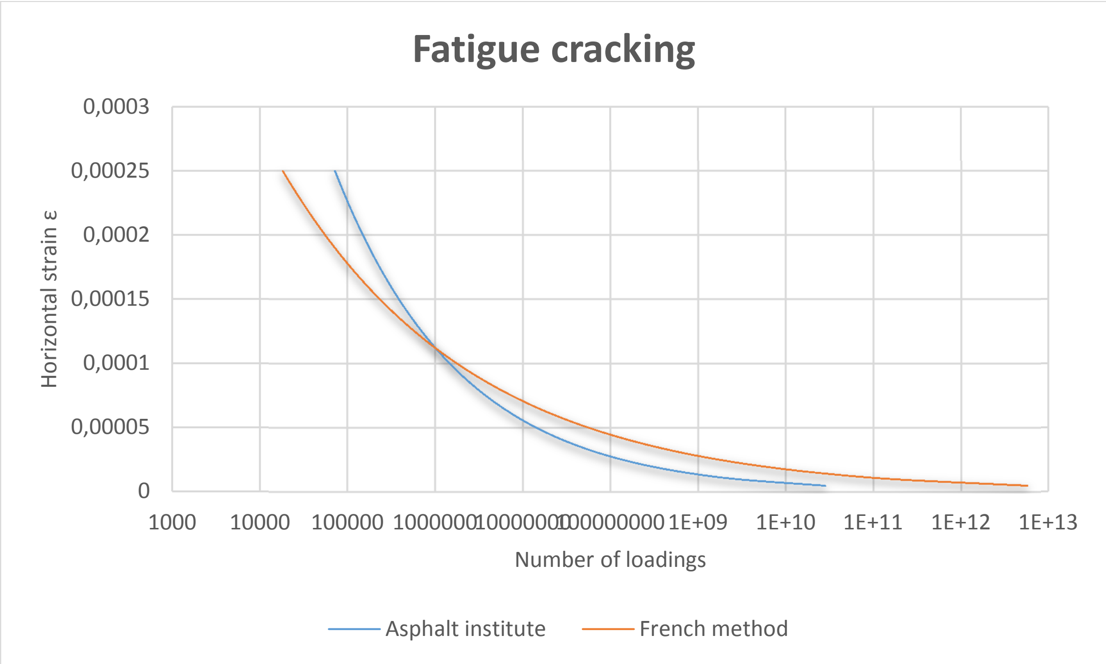

Figure 28 Relation of French method and asphalt institute formulas in fatigue cracking depending on horizontal strain and number of loadings (logarithmic scale)

RUTTING		
Vertical strain (µstrain)	Asphalt institute	French method
	Number of loading	
5	7,90395E+14	1,68336E+15
10	3,5313E+13	7,41627E+13
15	5,73175E+12	1,19394E+13
20	1,5777E+12	3,26734E+12
25	5,80029E+11	1,19581E+12
30	2,56081E+11	5,26006E+11
35	1,28282E+11	2,62681E+11
40	70487723985	1,43947E+11
45	41565209987	84681215329
50	25914297383	52683213785
55	16901374153	34294045776
60	11441068506	23173945457
65	7990660911	16158978989
70	5731347842	11572784472
75	4206225352	8481416491
80	3149221394	6341804921
85	2399585359	4826297129
90	1857033270	3730749684
95	1457213851	2924323463
100	1157788266	2321032857
105	930271820,1	1863090689
110	755112607,8	1510872275
115	618645016,6	1236709205
120	511159329,2	1020960662
125	425652407,8	849473232,3
130	357003445	711906477,9
135	301420497,9	600609560,8
140	256062789,7	509855247,6
145	218779091,9	435309751
150	187923997,5	373660696,4
155	162227236,8	322352688,5
160	140699611,6	279397108,4
165	122564534,5	243233776,1
170	107207682,7	212629287,6
175	94139616,17	186601574,3
180	82967764,78	164363408,7
185	73375258,5	145279733,5
190	65104798,04	128835170,7
195	57946272,63	114609092,9
200	51727185,56	102256357,1

205	46305200,27	91492315,11
210	41562299,83	82081072,78
215	37400182,22	73826239,69
220	33736608,95	66563596,65
225	30502493,32	60155251,83
230	27639566,32	54484958,16
235	25098496,06	49454342,41
240	22837365,21	44979853,6
245	20820432,75	40990282,22
250	19017122,32	37424734,4
255	17401192,34	34230970,68

Table 6 *Number of loadings for rutting of French method and Asphalt institute method in function of vertical strain*

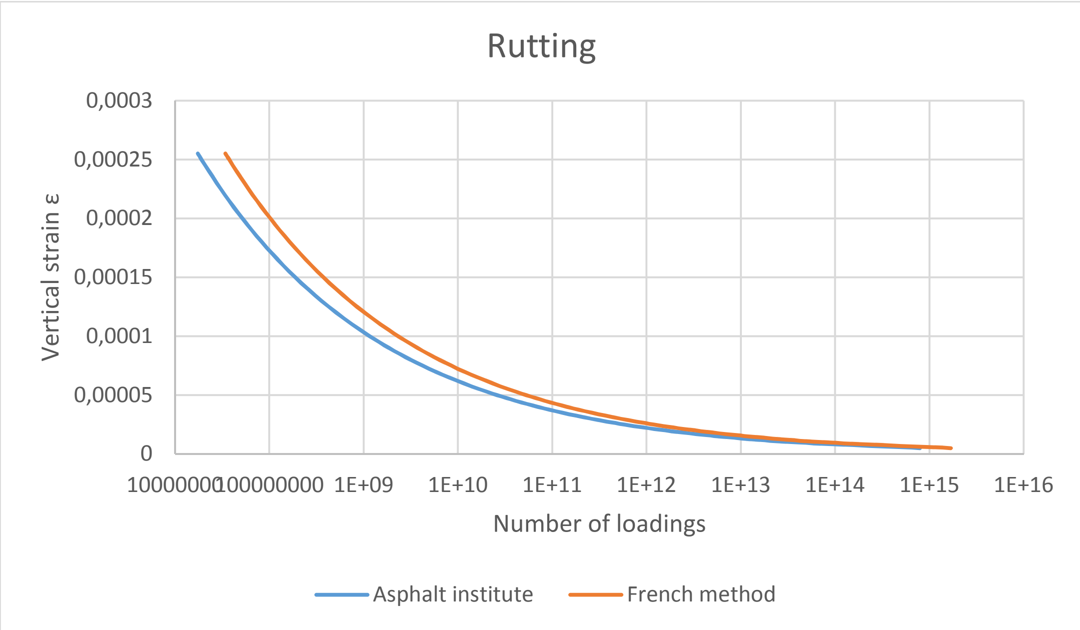

Figure 29 *Relation of French method and asphalt institute formulas in rutting depending on vertical strain and number of loadings (logarithmic scale)*