Prediction of Flexible Pavement Degradation: Application to Rutting in Cameroonian Highways

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ABSTRACT
The present paper is a pushover for preventive maintenance activities performed on flexible pavements. It is undertaken to enhance their performance and to limit the life-cycle costs of highway facilities. Theoretical degradation models are based on the superposition method in each pavement layer and on its elasto-visco-plastic behavior resulting from the wheel-pavement mechanical interaction. Flexible pavement degradation level is measured through the rut depth formulated in the transformed field domain using experimental data of in-situ conditions with specific parameters. The rutting depth is developed in a finite element program to allow the user in a simplistic manner to investigate and control effects of various parameters on the rutting process, and to better understand flexible pavements behavior. Obtained results on permanent stresses and deformations, and on their direct correlation with the accumulation of rutting and degradations in various directions, have triggered local highway authorities to contextualize modern preventive maintenance strategies in Cameroon.

KEYWORDS: Rutting, flexible pavement, elasto-visco-plastic behaviour, stress, deformation, deterioration, preventive maintenance.
INTRODUCTION

The implementation of the Sub-regional Central African Economic and Monetary Community has boosted Trade Agreements between Cameroon, Chad and Central African Republic. Since the last two countries do not have direct maritime access, surface transport through Cameroon became the focal point of local authorities in order to understand the impact of transit heavier axle loads and new axle configurations on their highway networks. For example national roads designed to carry maximal vehicle axle loads of 130 kN could be trafficked with gross vehicle axle loads over 300 kN, which might have major impact on the performance of the Cameroon highway network. This situation, in the present process of fund decentralization in the country, had put regional highway agencies under constant public pressure to provide optimal road infrastructures maintenance with limited resources. To ensure the effectiveness of their infrastructures management system, it is important for those agencies to be able to predict the remaining life of a pavement or any corresponding structure with reasonable accuracy.

Cameroonian highway construction and rehabilitation companies have mainly focused on corrective maintenance activities. However, with the constant demand on highway networks and the extensive cost required for rehabilitation, these companies with the control of LABOGENIE (National Civil Engineering Laboratory) have started to adopt preventive maintenance strategies into their programs. Preventive maintenance is a set of activities performed while the pavement is still in a good or fair condition to inhibit progressive failure and therefore extend the service life of the pavement, thus potentially enhance pavement performance and reduce the life-cycle cost of highway facilities (Bekheet, 2005; Tseng, 1989; Bassem, 2006; Madjadoumbaye, 2008). This can be achieved by determining feasible maintenance activities for each pavement section based on a number of factors, which include: existing pavement surface layer, condition, age, traffic, and prediction tools. Flexible pavement deterioration is broadly a function of the original design, material types, construction quality, traffic volume, axle load characteristics, road geometry, environmental conditions, age of pavement, and the maintenance policy applied.

![Figure 1: Physical state of Cameroonian Highways: (a) mixed Rut-crack degradation; (b) extensive rutting and gullies on earth roads; (c) Rut development on a flexible pavement](image)

Theoretical and mechanical design methods (Sambo, 2009; Iancu-Bogdan, 2010; Chehab, 2003; Lytton, 2002; Sousa, 1994; Perret, 2003) of flexible pavements are part of an emerging technology, which contains a number of distress models, mainly fatigue cracking and rutting. Strains due to cracking and rutting are considered as the most critical for the design of asphalt pavements. In general the horizontal tensile strain at the bottom of the asphalt layer causes fatigue cracking, and the vertical compressive strain on the surface of the subgrade causes permanent...
deformation or rutting. Although mechanical pavement failures due to cracking (Figure 1.a) are very important in the Cameroon highway network, the present investigation focuses only on rutting (Figure 1.c) distress models since its initiation and its progression allow rehabilitation companies to take appropriate measures before the occurrence of other related distress models leading to failure as seen in Figures 1.a and 1.b. Thus, theoretically distress models can be used to predict the behavior of new constructed flexible pavements assuming that the pavement configuration is not changed, and if the reliability for a certain distress is less than the minimum level required, the assumed pavement configuration should be changed (Huang 2004). Pavements usually do not serve for the design period efficiently, safely, comfortably, and economically due to early deteriorations, and the proper time to apply maintenance is before the need is apparent to the casual observer (Okafor, 2010; Chehab, 2005).

The primary objective of the work conducted under this research study was to develop a predictive tool with the capacity to calculate flexible pavements rutting under any type of traffic load with various pavement parameters. The pavement theoretical model is based on the superposition method in each layer of the pavement and it consists of the elasto-visco-plastic model of the surfacing course, and of the elasto-plastic model of the roadbase and foundation layers. The shape of the tire-pavement contact area was assumed to be rectangular, and any change in the shape during load variation was neglected while the load pressure within the contact area was assumed to be uniformly distributed. The rutting evaluation tool consists of two main modules: the problem definition module and the resolution and the analysis module. The problem definition module develops formulations in the transformed field domain using experimental data to represent in-situ conditions with specific parameters such as the road geometry, material characteristics, boundary conditions and input loadings. The resolution and analysis module contains: the rutting calculations for all pavement layers as a function of traffic load; the graphical user interface that functions as a pre- and a post-processor for the developed finite element program. This last module allows the user in a simplistic manner to investigate and control effects of various parameters on the rutting process such as stresses and deformations on the wheel running surface, their variation away from the interface wheel-pavement, the vehicle running speed, the tire inflated pressure, the material Elasticity Modulus, and the maintenance level. All these results allow the determination and the understanding of flexible pavements behavior in order to better characterize the rutting process in flexible pavements and to advance the state-of-the-art in various local highway agencies. With these findings the LABOGENIE Laboratory, in collaboration with laboratories of University 1, has lunched numerous experimental programs to assess local pavement materials and to establish lasting highways technical codes and standards that are easy to apply by local engineers in remote areas.

THEORETICAL RUTTING MODELS

The deformation response of flexible pavements under traffic loading is characterized by recoverable deformations and permanent deformations. The permanent deformation is much smaller than the recoverable deformation and, as the number of load repetitions increases, the plastic strain due to each load repetition decreases. The deformation of materials is the result of three mechanisms: the consolidation mechanism (the change in the shape and compressibility of particle assemblies); the distortion mechanism characterized by bending, sliding, and rolling of the particles; and the crushing and the breaking of the particles occur when the applied load exceeds the strength of particles. Rutting models are related to functions, which are the measure of distress due to the magnitude of loads, the number of load repetitions, the pavement
composition and its thickness, and the subgrade moisture. These functions should be able to predict the change in flexible pavement condition over a given period of time.

**Description of Pavement layers**

A highway pavement, depicted in Figure 2, is composed of a system of overlaid strata of chosen processed materials that are positioned on the in-situ soil, termed the subgrade. Its basic requirement is the provision of a uniform skid-resistant running surface with adequate life and requiring minimum maintenance. There are three basic components of the highway pavement: the foundation consisting of the native subgrade soil and the layer of graded stone (subbase) immediately overlaying it; the roadbase is the main structural layer whose main function is to withstand the applied wheel stress and strain incident on it and to distribute them to materials beneath it; and the surfacing, normally applied in the base course and the wearing course, combines good riding quality with adequate skidding resistance, while minimizing the probability of water infiltrating the pavement with consequent surface cracks.

**Figure 2:** Layers within a typical flexible highway pavement and rutting characteristics

**Rutting Characteristics**

Experience has indicated that deterioration in the form of cracking/deformation is most likely to be found in the surface of the pavement rather than deeper down within the structure. A well-constructed pavement will have an extended life span on condition that distress, seen in the form of surface cracks and ruts, is taken care of before it starts to affect the structural integrity of the highway. Permanent deformation, as one of the most important distresses occurring in the flexible pavement, is associated with rutting in the wheel path and develops gradually as the number of load repetitions increase. Tseng and Lytton (1989) predicted the permanent deformation in the course, the roadbase and the foundation layers. Their model describes the relationship between the permanent strains and the number of load repetitions through three experimental parameters or estimated material properties from laboratory tests. These three parameters in the course layer are sensitive to the resilient modulus, the deviatoric stress, the asphalt content and the temperature, while in granular base materials they are functions of the resilient modulus, the confining pressure and the water content.

In practice rutting stems from a permanent deformation in any of the pavement layers usually caused by consolidated or lateral movement of materials due to traffic load. Pavement uplift may occur along the sides of the rut, but in many cases, rutting is noticeable only after a rainfall when
the paths are filled with water. On the site rutting is measured in square meters of surface area and its severity is determined by the mean depth of the rut, calculated by laying a straight edge across the rut, measuring depths at discrete points along the rut length and then computing the mean depth in millimeters. The mean rut depth as a damage factor is calculated from the ratio of the number of load repetitions of a truck to achieve a given amount of rutting, to the number necessary for the standard truck to reach that given amount of rutting. Thus the rut depth is defined as the permanent traffic-associated deformation within all pavement layers which, if channelized into wheel paths, accumulates over time and becomes manifested as a rut (Paterson, 1987). Rut depth modeling is based on four components of rutting: initial densification; structural deformation; plastic deformation; and wear from studded tires.

Theoretical Models

The prediction of the failure of a pavement system has been empirically developed by the correlation between the multilayered elastic theory and field tests such as the AASHO road test (1962). For pavement rutting models, most studies employ the correlations between strains and load repetitions. Correlations between the vertical strain on top of the subgrade and the number \( N \) of equivalent single axle load repetitions are widely used. These types of models assume that rutting can be minimized by limiting the amount of vertical compressive strains on top of the subgrade (Dachyoeun, 2005). In the study of Tseng and Lytton (1989), the vertical resilient strains were calculated at the middle of each layer (or sublayer) using the finite element program and the permanent deformation is taken as the summation of the permanent deformations in all sublayers. For a single axle load, the permanent deformation, \( \delta_a \), is given by

\[
\delta_a = \sum_{i=1}^{n} \left( \frac{\varepsilon_{ai}}{\varepsilon_{ri}} \right) e^{-\left( \frac{\varepsilon_{ri}}{\varepsilon_r} \right)^{\beta_i}} \int_{h_{i-1}}^{h_i} \varepsilon_v(Z) dz
\]  

where

- \( \delta_a \) = permanent deformation for layer/sublayer,
- \( \varepsilon_r \) = average vertical resilient strain in the layer/sublayer as obtained from the primary response model,
- \( h \) = thickness of the layer/sublayer,
- \( \varepsilon_v \) = resilient strain imposed in laboratory test to obtain material properties \( \varepsilon_o, \beta, \) and \( \rho \), depending on the water content, the deviatoric stress and the bulk stress.

The form of the Tseng and Lytton Model was modified in the AASHTO (2002) to include a calibration factor \( \beta_1 \):

\[
\delta_a(N) = \beta_1 \left( \frac{\varepsilon_o}{\varepsilon_v} \right) e^{-\left( \frac{\varepsilon_v}{\varepsilon_r} \right)^{\beta_f}} \varepsilon_v h
\]  

The calibration factor for the unbound granular and subgrade materials being equal to 2 for the base layer, and to 8.0 for the subgrade soil.

Claussen (1977) utilized the experimental results of an AASHTO research and proposed a simpler expression relating the maximum number of equivalent loading cycle \( N_f \) and the allowable permanent deformation on the top layer \( \delta_v \):
Total Deformation Model

Present experimental tests have given way to display the influence of different factors affecting flexible pavements performance. Thus it is possible to accelerate the rutting process in the laboratory setting by increasing the number of loading cycle and/or the load intensity, by choosing an appropriate configuration of the contact area of the load, by changing climatic conditions, or by varying the form, the strength, the size and the distribution of voids (or sand-gravel aggregates and the bitumen content) of the surfacing and the roadbase layers. Studies done by many researchers (Chehab, 2003; Lytton, 2002; Sousa, 1994; Elsa, 2010) show that the total deformation of the bituminous surfacing layers depicted in Figure 3 can be expressed as:

$$\delta = \delta^e + \delta^p + \delta^{ve} + \delta^{vp}$$

where: $\delta^e$ is the elastic deformation; $\delta^p$ is the plastic deformation; $\delta^{ve}$ is the visco-elastic deformation; $\delta^{vp}$ is the visco-plastic deformation.

The elastic deformation $\delta^e$ of all layers depends on the temperature $T$, the stress $\sigma$ and the loading frequency $f$. The elasto-plastic component of a layer can be associated to a creep model that is derived from the Von-Mises model and from experimental parameters of creep testing.

![Figure 3: Components of the total deformation (adapted from Chehab (2003)).](image)

Surfacing Model

According to Uzan J. (1986) the elasto-plastic component depends on the permanent deformation or on the visco-plastic component. Rutting thus depends mainly on visco-plastic deformation $\delta^p$ and the visco-elastic response defines the response of anisotropic materials at different temperatures and at high deformation rates. We can therefore analyze the rutting behavior of a typical flexible highway pavement with an elasto-visco-plastic model taking into consideration the temperature influence (Bassem, 2006) by the following expression:
\[
\delta^{pp} = A_T \sigma^n \xi^{m+1}
\]  \hspace{1cm} (6)

where: \( \sigma \) = the considered state stress
\( A_T = A'(a_T)^{m+1} \);
\( \xi \) = reduced time defined as \( \xi = t/(a_T)_{vp} \);
\( (a_T)_{vp} \) = factor of temperature change considering visco-plastic effects;
\( n, m, A' \) = creep experimental parameters.

The temperature influence on the Elasticity Modulus is computed using the Ullidtz (1999) model given by the following expression:
\[
E_T = E_{ref} e^{a_E(T - T_{ref})}
\]  \hspace{1cm} (7)

where \( E_T \) = the elasticity modulus at temperature \( T \) (°C);
\( E_{ref} \) = the elasticity modulus at reference temperature \( T_{ref} \) (\( T_{ref} = 25^\circ\text{C} \));
\( a_E \) = the temperature change viscous factor in elasticity from experimentation.

**Foundation model**

Layers of the pavement foundation also display complex behavior since they are constituted of different soils subjected to the state of stress, the degree of saturation, the humidity and the size and form of grains. To obtain an appropriate mechanical behavior we use in analysis linear elastic and elasto-plastic models. The Hooke’s law is used for the linear elastic model, while the Mohr-Coulomb creep formulation is used for the elasto-plastic model in the following form:
\[
F = R_{mc}q - ptan\phi - c
\]  \hspace{1cm} (8)

where \( R_{mc}(\theta, \phi) = \frac{1}{\sqrt{3}cos\phi} \sin \left( \theta + \frac{\pi}{3} \right) + \frac{1}{3} \cos \left( \theta + \frac{\pi}{3} \right) tan\phi \);
\( c \) = material cohesion coefficient;
\( \phi \) = friction angle;
\( s = \sigma_{pl} \) = deviatoric stress;
\( q = \sqrt{3/2 (s:s)} \);
\( p = tr(\sigma)/3 \) = average stress;
\( r = (9/2, s:s)^{1/3} \);
\( \theta \) = the Lode angle defined by \( \cos(3\theta) = (r/q)^3 \).

**Loading model**

The contact surface is an important parameter to consider in analysis of pavement behavior. A study done by Sousa (1999) compared the effect of circular and rectangular forms of the contact surface and has shown that corresponding photo-print shapes are rectangular for simple tires and oval for super single tires. There is however a difference between the gross contact surface and the reel contact surface when we take into account the effects of running strips (Figure 4). Simplifications have been made by Daehyeon (2005) and Huang (2004) to find an equivalent contact surface area as \( A_c = \pi (0.3L)^2 +(0.4L)(0.6L) \) where \( L \) is the exact length of the area in the running direction, and an equivalent interface contact pressure of tires strips equal to the air pressure in the tire. It is evident to understand that the equivalent contact surface area and the equivalent interface contact pressure will depend on the vehicle axle load and on the tire
inflating pressure. Based on these assumptions, for double and suppler single tire models, we consider in our analysis: maximal tire inflating pressures of 900 kPa; two vehicle axle loads of 11.5 and 8 tons (Michelin, 2008); two tire systems pictured in Figure 4; ambient temperature 30° and 50° C.

Figure 4: Configuration of a heavy truck: Single and Dual tire model systems.

ANALYTICAL MODELS

The development of analytical models with the use of Finite Element (FE) analysis at first in three-dimension model and then in two-dimension has been adopted in accordance with theoretical models developed above. Models of the geometry, materials and loadings are described in subsequent sections. In the previous sections, the described material properties of the pavement were given from an experimental background in order to give a clear representation of flexible pavements mechanical behavior when subjected to various loadings and surrounding conditions. The pavement theoretical model is based on the superposition method in each layer and it consists of the elasto-visco-plastic model of the surfacing course taking into consideration the temperature influence, and of the elasto-plastic model of the roadbase and foundation layers using the Mohr-Coulomb creep formulation. Thus if $j$ is the $j^{th}$ subdivision of the $i^{th}$ layer (or division) of the flexible pavement with height $h_{ij}$ and corresponding permanent deformation $\delta_{ij}$, then the considered rutting depth is given as:

$$d = \sum_{i}^{m} \sum_{j}^{n} \delta_{ij} h_{ij}.$$  \hspace{1cm} (9)

Pavement Cross Section

Meshing procedure is critical in a flexible pavement model in which the subgrade is considered as semi-infinite elastic solid. Inappropriate mesh size may result in either poor accuracy or enormous demand for computer resources. In the study proposed by Sambo (2009) and Patil (2010), infinite elastic solids were replaced by finite elastic solids in accordance with expected responses of the underlain soils layers. This replacement was also helpful in reducing the analytical depth of the foundation under the pavement and in reducing the number of elements in the subgrade model to improve the efficiency of analysis. Since great attention should be paid
to determine the appropriate boundary conditions to assure a realistic modeling, transverse displacements are not restricted in other to get transverse resultants moments and forces on a finite element (Cheng-Ming, 2004), but the infinite depth of the foundation is replaced by a 20 cm of a concrete layer allowing us to clearly understand the building up of permanent deformations in considered layers. The discretization of one tire-pavement interface (considering only a 400 cm pavement width (Y-Y) perpendicular to the motion direction (X-X) with varying length) into 8-node brick FEs of the pavement cross section given in Figure 2 is done over each layer as shown in Figure 5 with element sizes varying with the distance to the tire/pavement interface. The thickness of each layer, adopted from the work done by Bassem (2006), is: 3 cm for the wearing course; 17 cm for the base course; 40 cm for the roadbase; 122 cm for the support foundation and 20 cm of a concrete layer representing the effect of an infinite natural sol layer.

Material Properties

Based on experimental studies done in LAVOC (Laboratoire des Voies et Communications de Lausanne) by Peret (2003) to illustrate permanent deformations on flexible pavements the base course given in figure 2 is composed of 3 cm of bituminous running course (MR11, Micro Roughness 11) and of a 14 cm bituminous base course (HMT22s, Hot Treated Materials for the base course with corresponding serial number) with design parameters provided in Table 1.

<table>
<thead>
<tr>
<th></th>
<th>HMT22s</th>
<th>MR11</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apparent mass density (g/cm³)</td>
<td>2.387</td>
<td>2.319</td>
</tr>
<tr>
<td>Empty voids content HM (%)</td>
<td>6.6</td>
<td>6.6</td>
</tr>
<tr>
<td>Filled voids content HR (%)</td>
<td>60.9</td>
<td>66.4</td>
</tr>
<tr>
<td>Stability Limit SM (kN)</td>
<td>9.8</td>
<td>6.0</td>
</tr>
<tr>
<td>Creep FM (mm)</td>
<td>2.3</td>
<td>3.1</td>
</tr>
<tr>
<td>SM/FM (kN/mm)</td>
<td>4.2</td>
<td>2.0</td>
</tr>
<tr>
<td>Binder content (%)</td>
<td>4.31</td>
<td>4.10</td>
</tr>
</tbody>
</table>

The main feature of flexible pavement model is to characterize the behavior of bituminous materials. As they act as an elastic solid and obey the Hooke’s law at low temperature, they
deform and recover instantly upon loading and unloading. Yet, they soften as temperature rises and behaves as a viscous fluid, which obeys the Newton’s law of viscosity with constant creep rate at high temperature (Huang, 2004). At ambient temperature, the behavior of asphalt material is between pure elastic and viscous model. Since values of the elasto-visco-plastic permanent deformation (Equation 6) and the elastic modulus (Equation 7) during the motion are temperature-dependent we use in the present numerical model experimental results obtained in the LAVOC laboratory, in which the factor of temperature change $a(E)$ and the parameter $A_T$ as function of temperature for bituminous base course materials MR11 and HMT22s.

The roadbase (of grain size less than 60 mm) is made up of two layers of 20 cm thickness each with appropriate grain size contents, and has the Elasticity Modulus $E=270$ MPa. The support foundation made of clean fine sand (grain size less than 2 mm) of thickness 122 cm has the Elasticity Modulus $E = 90$ MPa. The Poisson ratio $\nu=0.35$ is the same for both the roadbase and the support foundation (Perret, 2003). The equivalent 20-cm-concrete layer is considered to elastically behave with Elasticity Modulus $E=20000$ MPa and the Poisson ratio $\nu=0.15$. Triaxial tests were done to values of the cohesion coefficients $c = 10.0$ kPa for the roadbase and 1.0 kPa for the support foundation, and of the friction angles $\phi=35^\circ$ for the roadbase and $30^\circ$ for the support foundation.

The Implemented Program in CASTEM

The application of the theory developed above is obtained with the help of the CASTEM software (Fichoux, 2007) offering various functions and facilities to compile and to visualize complex mathematical operations. CASTEM is a computer code for the analysis of structures by the linear and nonlinear finite element method. This code was developed by the Department Mechanics and Technology (DMT) of the French Police station with Atomic Energy (ECA). The development of CASTEM enters within the framework of an activity of research in the field of the mechanics of which the goal is to define a high level instrument, being able to be used as support for the design, the dimensioning and the analysis of structural components, in the field of the nuclear power as in the traditional industrial sector. In the present work the implemented program is subdivided into different logic subroutines accomplishing specific tasks from data input to output visualization given as: the choice of the geometry and the grid (definition of the points, lines, surfaces and volumes, discretization); the definition of the mathematical model (definition of the data characterizing the model, the material properties, the geometrical properties, the boundary conditions and initial conditions); the resolution of the discretized problem (assembly of the matrices of rigidity and mass of the complete structure, application of boundary conditions and loadings, Resolution of the system equations); the analysis and the post-processing of results (Local quantities and their optimal values: displacements, constraints, deformations, etc...).

RESULTS AND DISCUSSIONS

Effects of the motion variation

We notice from three-dimensional analytical results given in Figure 6.a that tire motions induce permanent compressive stresses along its path on the running surface. Thus every contact
between the tire and the pavement results in the appearance of compressive stresses in the pavement body, mainly in the surfacing. These stresses decrease in magnitude with the horizontal or vertical distance from the contact area so that traction stresses are even observed further. Stress variations with the distance, from compressive to tensile in the pavement body during the motion, explain why the rutting process is accentuated in pavements of roads with smaller width. Stresses resulting from that process can also turn into positive or negative permanent deformations and vertical displacements of materials in the running surface.

![Image](image1.png)  

(a) With constant velocity 60 km/h  
(b) With variable velocity

**Figure 6:** Tire action induced vertical stresses (kgf/mm²) on the pavement: super single tire, inflated pressure 800 kPa, axle load 8 Tons.

The case of acceleration and deceleration of motion in abrupt velocity variation shows clearly in Figure 6.b that a vehicle that starts its motion from rest to a specified speed (or vice-versa) induces more permanent stresses than a vehicle moving at that specified speed. The rutting process is thus accentuated with abrupt variation of the moving velocity as a direct correlation to the appearance of permanent deformations. This fact explains why we find a strong growth of rutting on points with absolute speed variation like road intersections, crossroads, tollgates and parking lots. The same findings are given in the work of Bassem (2006) which shows that there is 100% corresponding rutting increment when the running speed changes from 60 to 10 km/h.

### Stresses and deformations

Besides calculating induced stresses for a given truck configuration we also present in this section the resulted permanent deformations in various directions. One can see from Figure 7.a the influence of the axle load on vertical stresses with the maximal value in compression near the area of load application and with the tensile value away from the tire-pavement interface. Horizontal stress distribution (Figure 7.b) in the y-axis displays an alternation of compressed and tensile stresses starting from the interface area, a situation that explains the development of longitudinal saddles, in and out of the interface area along the road axis, that might result in severe rutting or in longitudinal surface cracking as seen in Figure 1.a. Shear stresses (Figure 7.c) are longitudinally concentrated in both zones adjacent to the contact area of the interface, and if
their values are relatively higher to integrate their effect in the resilient strain modulus given in Equation 1 we will have an increase of the rutting and fatigue cracking rates of pavement layers.

Figure 7: Pavement response diagrams: super single tire, inflated pressure 800 kPa, axle load 8 Tons.
The performance criterion for total permanent deformation (rutting) after a specified number of load cycles is defined in terms of the maximum rut depth in the wheel path. The permanent deformation is calculated at the mid-depth of each sublayer within the pavement so that the overall permanent deformation is the summation of the permanent deformation for all the layers. Vertical deformations (Figure 7.d) are localized in the running area of the tire with the maximal value at its center decreasing in magnitude with the outside distance. In Figure 7.e considered horizontal deformations are concentrated inside the vehicle path with a decreasing magnitude toward its center. Three-Dimensional deformation analysis of the pavement after 500,000 load cycles shows that increasing the load cycle also increases the rutting rate in the vertical and horizontal directions as seen in Figure 7.f with amplified values. Considering the findings of this work we see that stress analysis and deformation analyses in various directions are not sensitive in the same manner with sublayers’ properties. For example shear stresses and horizontal deformations are not too much influenced by base materials properties while vertical stresses and vertical deformations are sensitive to the base properties.

Figure 8: 2D pavement response diagrams: stress distribution (kgf/mm²) and rutting accumulation with loading cycles. Super single tire, inflated pressure 800 kPa, axle load 11.5 Tons at 50°C.

Figure 8—Continues in the next page.
After 150000 cycles $Z_{\text{max}} = 2.08\text{mm}$

After 300000 cycles $Z_{\text{max}} = 3.52\text{mm}$

After 450000 cycles $Z_{\text{max}} = 4.67\text{mm}$

**Figure 8:** 2D pavement response diagrams: stress distribution (kgf/mm²) and rutting accumulation with loading cycles. Super single tire, inflated pressure 800 kPa, axle load 11.5 Tons at 50°C.

From a close look on the 2D mechanical behavior, using Four-node rectangular elements, a 11.5 Tons axle load at 50°C temperature, and a denser mesh refinement in the area under the load application segment as shown in Figure 8.a, we can draw the following remarks: 1) In Figure 8.b compressive stresses are localized on the area of load application with a decreasing magnitude from its distance that gives place to tensile stresses later; 2) Figure 8.c displays two mechanisms in rutting development: the consolidation mechanism represented by area with moderate compressive stresses, and the distortion mechanism characterized with higher compressive stresses and with the development of excessive locally concentrated compressive or tensile stresses that can lead to excessive rutting and cracking. One can easily see as revealed in Equation 2 that the rutting rate is higher in the consolidation mechanism than in the distortion mechanism; 3) accumulation of rutting, presented in Figures 8.d, 8.e and 8.f, increases with respect to the loading cycle $N$ (equal to 150000, 300000 and 450000) and agrees with experimental results presented by Perret (2003) in which the experimental value is 10 % less than the computed one.

**Parametric studies**

The present work shows that the rutting process is differently influenced by certain factors such as the value of the axle loading, the tire inflated pressure, the type of the tire, the vehicle running speed, the running surface elasticity modulus and the pavement maintenance level. An understanding of the effect of each of these factors will provide optimal pavement maintenance with limited resources to local regional highway agencies, and these factors can serve as an analytical tool to predict the remaining life of a pavement or any corresponding structure with reasonable accuracy. The influence of the axle loading (single tire system, inflated pressure 800 kPa at 30°C) on the rutting process is presented in Figure 9.a), and it is easy to see that an increment of the load from 8 to 12 tons (50 % increment) results in a 22% increment of the rutting depth. Numerical results displayed in Figure 9.b) show that increasing abruptly the tire inflated pressure will only change moderately the rutting process. If the axle loading is constant
(single tire system, 11.5 axle loading at 30°C) an increase of the tire inflated pressure reduces the contact surface of the tire and thus resulting in the stress concentration and in the moderate pavement deformation. We see that a change of the pressure from 600 to 800 kPa (34 %) produces almost a 5 % increase in the rutting depth.

The tire type (11.5 axle loading and inflated pressure 800 kPa at 30°C) also modifies the form of the rutting as shown in Figure 9.c) where a single tire produces a 5.31 mm maximal rutting depth while the super single counterpart produces a 4.83 mm value, resulting almost to a 8 % reduction. This result was expected since the contact area (with resulted stress concentration) of the super single tire is less than the double tire counterpart. Since the loading duration decreases with the vehicle running speed, it is seen in Figure 9.d) that the rutting depth decreases with high running speeds and increases with reduced lower speeds. For example when the speed changes from 10 to 60 km/h there is a 52 % rutting depth reduction, this result is materialized at crossroads and parking lots with abrupt changes in velocity and resulted rutting and cracks formation. Mechanical behavior of a particular layer depends on its mechanical properties and, in Equation 7, the modulus of elasticity $E$ depends on parameters $E_T$ and $a_T$ representing viscous behaviors of flexible pavements. Figure 9.e) proves that flexible pavements with higher deformation modulus offer a better resistance to ruts. When the rutting process reaches a critical factor (a critical depth for example) the deformed layer (the wearing or the base course) with its stress concentrations must be replaced by a new layer preferably of the same material or of a material with a higher deformation modulus. Figure 9.f shows that the rutting process increases faster when the deformed (or degraded) layer is not replaced by a new layer. Thus replacement works on flexible pavements must be carried on all layers if their effect must be efficient and effective as a predictive component of the predictive maintenance.

(a) Influence of axle loading

(b) Influence of Tire inflated pressure

(c) Influence of the tire type

(d) Influence of the running speed
CONCLUDING REMARKS

This paper presents the modeling of three- and two-dimensional FE rutting analysis of flexible pavements based on experimental results done by other researchers, and it opens the way to predictive pavement management in Cameroon. The pavement theoretical model is based on the superposition method in each layer and it consists of the elasto-visco-plastic model of the surfacing course taking into consideration the temperature influence, and of the elasto-plastic model of the roadbase and foundation layers using the Mohr-Coulomb creep formulation. The work areas consists of different FE analyses based on comparative case studies to display the responses of the considered MR11/HMT22s pavement base course when subjected to different input conditions of the moving vehicle. All these studies helped us to determine and to understand pavement responses related to pavement structural performances such as stresses and deformations in various directions from the pavement running surface, in order to better characterize the rutting process in flexible pavements and to advance the state-of-the-art in various local highway agencies.

Significant research findings of this study can be summarized as follows: tire motions induce permanent compressive stresses and deformations on the running surface; these stresses decrease in magnitude with the horizontal or vertical distance from the contact area so that traction stresses are even observed further; the rutting process is accentuated with abrupt variation of the moving velocity as a direct correlation to the appearance of permanent deformations; stress analysis and deformation analysis in various directions are not sensitive in the same manner with sublayers’ properties; an alternation of compressed and tensile stresses starting from the tire interface area results in severe rutting or in longitudinal surface cracking; accumulation of rutting increases with respect to the axle loading, the loading cycle \( N \), the tire inflated pressure and the poor maintenance level of foundation layers, while it decreases with high values of the material elasticity modulus, of the vehicle speed and of an increase in number of wheels per axle.

The present theoretical model was analyzed on experimental data obtained from European pavement models, and it is evident from the literature that there is an acute need to develop, to contextualize and to apply these findings on local pavement materials and local traffic conditions as stipulated by the NOCE (National Order of Civil Engineers of Cameroon) technical regulations. The contextualization of the present findings is highly encouraged by the
LABOGENIE laboratory which has requested the Yaoundé 1 University LMM laboratory, through its General Manager, to consider in the near future additional factors on local civil engineering materials such as the material anisotropy, errors between prediction and deflection measurements, the gape between horizontal modulus and the vertical modulus, and time and seasons of measurements.

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