

Modelling of Flexible Pavements by the Finite Element Method: Application to the Calculation of the Rutting

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Abstract In this article, study presents finite element modeling of rutting of flexible pavement structures. The choice of a flexible pavement structure of length 25R, width 25R and height 55R is adopted to minimize edge effects that influence pavement responses in terms of stresses and strains ($R=125$ mm is the radius of the tire's circular footprint). The study was carried out using the ABAQUS calculation code. The latter takes into account the actual behavior of all the materials making up the various layers (viscoelastic for the wearing course and non-linear for the base courses). The rutting calculation based on the linear, viscoelastic behavior of the wearing course demonstrates the importance of taking into account the viscoelastic behavior of asphalt concrete in the design of flexible pavement structures. The rutting depth of the pavement obtained with Bakel sandstones in the base course is significant compared with that of Diack basalt, which is a reference material in road construction in Senegal, and consequently treatment of these sandstones is necessary for their possible use in the base course.

Keywords: Modelling, finite elements, flexible pavement, ABAQUS, rutting, basalt, sandstone

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1. Introduction

Flexible pavements consist of an asphalt surface dressing or a thin asphalt concrete wearing course over the pavement base. The sub-base is made up of a base course and a sub-base course of untreated gravel, all resting on the excavated subgrade. The fact that the base course is made up of cohesion less materials and the wearing course is thin, gives the pavement reduced structural rigidity. This type of pavement is therefore only designed to withstand light traffic. Repeated traffic loading causes the base of the bitumen layer to undergo flexural tension cycles, which can lead to cracking. In addition to deterioration through cracking, flexible pavements can also deteriorate through rutting. This is essentially due to the accumulation of plastic deformations in layers made of unbound materials. Traffic thus leads to an incremental collapse, in the case of pavements of poor structural quality, which manifests itself on the surface by the appearance of subsidence of depths of the order of a centimeter. This deterioration of the pavement's longitudinal profile is detrimental to service quality and safety. In order to reduce maintenance costs, proper sizing is therefore essential. Hence the proposal in this article to determine rutting depth based on a finite element calculation using the ABAQUS calculation code. The principle consists in dividing each layer into several sub-layers and calculating the plastic deformation in each sub-

layer. The plastic deformation is the resultant of the plastic deformations of the various sub-layers.

2. Theoretical Study

Rutting due to permanent deformation of unbound materials (untreated gravel sub-base) is one of the main ways in which flexible pavements deteriorate.

2.1. Description of Rutting

Rutting is one of the main degradation mechanisms of flexible pavements. It is manifested by the sinking of the superstructure into the wheel track and the formation of bulges along the edge of the track (figure 1). This is in fact a permanent deformation of the pavement, which can extend to different depths. A distinction is often made between rutting affecting only the top layers and rutting affecting the base layers. The probable causes of this phenomenon are:

- Creep of asphalt mix in the upper layers due to unsuitable mix design, high compaction or excessively soft binder. This phenomenon is accentuated by high temperatures and strong sunlight, and therefore occurs mainly during hot periods.
- Vertical deformation of base layers and/or soil due to undersizing of lower layers. This phenomenon can be accentuated by repeated freeze-thaw cycles,

or by the action of precipitation when the pavement is cracked.



Figure 1. Rutting for a pavement structure [1]

The formation and propagation of rutting can initially have a direct impact on user safety (accumulation of water in ruts, formation of beads, traffic "channeling" effect, etc.), then subsequently have an impact on structural performance (deterioration of subgrade, cracking at the edge of ruts, appearance of potholes, etc.) [2].

2.2. Factors Influencing Rutting

The stress level in a pavement structure is a determining factor in the rutting mechanism. It depends on pavement thickness and loading amplitude [3]. In the case of thin pavements, poor compaction of the subgrade accelerates rutting. Permanent deformation also depends on the thickness of the wearing course. In the case of a thin layer, loading is poorly distributed, leading to high stresses in the base layer, which in turn produce permanent deformation [4]. These deformations lead to instability rutting. [5,6] and have shown that the influence of inflation pressure is moderate in thick asphalt layers (over 150 cm).

Pavement performance is controlled by the properties of the bituminous binder, which behaves like a viscous fluid at high temperatures and/or long loading rates [7]. According to [8], the binder's viscous properties are the physical cause of permanent deformation. The use of harder, less temperature-sensitive binders considerably reduces the risk of rutting [9,10]. Researchers [11] have shown that high-modulus asphalt mix has a high resistance to rutting. Experimental results show that asphalt's resistance to permanent deformation, and consequently its resistance to rutting, increases when hot mix treatment is used [12]. Structural rutting is reduced by stabilizing the lower pavement layers with cement or lime [13]. [14] have shown that the use of bitumen in the lower layers reduces stresses and strains in the pavement, and consequently rutting. The number and spacing of axles are decisive factors in the transmission of loads to the road surface. Increasing the number of axles reduces the load transmitted to the road surface for the same load [15]. A single axle produces more damage than a tandem axle [16]. A tridem axle also produces less damage than a tandem axle.

2.3. Presentation of Abaqus Software

The Abaqus software used here to calculate rutting is a finite element calculation code. It comprises four main

codes: Abaqus/Standard (resolution by an implicit static algorithm), Abaqus/Explicit (resolution by an explicit dynamic algorithm), Abaqus/CFD (resolution of fluid dynamics problems) and Abaqus/Electromagnetic (resolution of electromagnetic problems). The use of this software in this study is explained by its ability to define numerous interactions, constraints, meshes and different types of loading, making it a complete software package capable of performing highly complex non-linear analyses [17].

3. Parametric Study

For the creation of the pavement structure model, certain factors were studied. These may have an effect on the results of the analysis, namely the dimensions of the model and the size of the discretization elements. A parametric analysis was carried out to study the impact of horizontal and vertical model and mesh dimensions on pavement response. The thicknesses of the wearing course and base layers were kept constant, while that of the subgrade layer was varied until an optimum pavement height was obtained. The behavior of all layers is assumed to be elastic and linear (Table 1). The wearing course consists of BBSG 0/14 ($T = 34^{\circ}\text{C}$ and $N = 20$ Hz), while the base and sub-base courses are made of Diack basalt and Sindia laterite respectively, all on a PF2 subgrade.

Table 1. Material parameters for S1 structure

Pavement layers	Pavement materials	Thickness (m)	Poisson's ratio	Young's modulus
Surface	BBSG 0/14	0.06	0.45	1512
Base	Diack basalt	0.25	0.35	400
Sub-base	Sindia laterite	0.25	0.35	274
Subgrade	PF2	∞	0.25	130

The load is that of a 6.5 tons dual wheel (standard French axle). It is distributed and applied on two circular indentations finely meshed with tetrahedral elements located on the wearing course (figure 2).

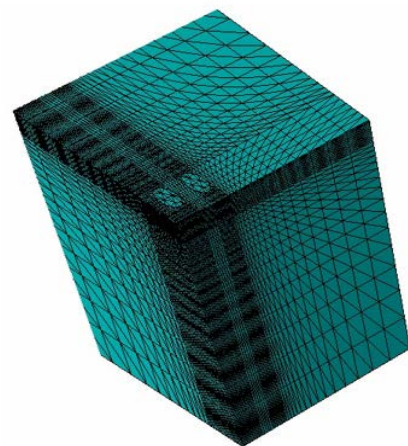
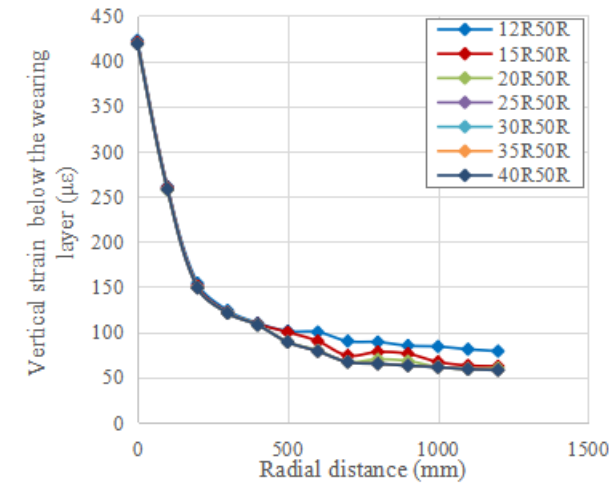


Figure 2. Model mesh (tetrahedral elements)

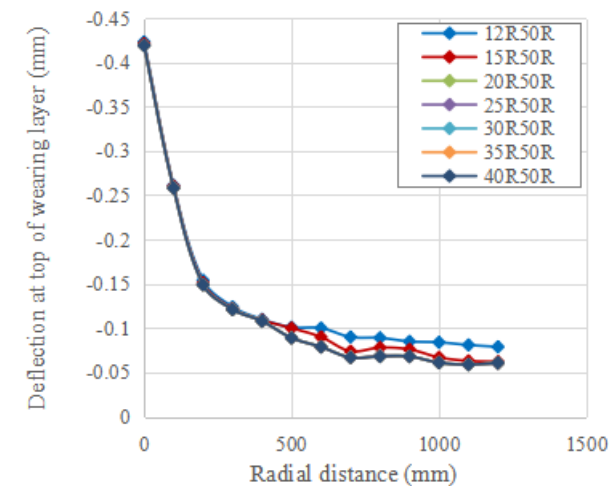
3.1. Effect of Horizontal Model Dimension

The initial model is that adopted by [18], that is, 12R (R is the radius of the loading footprint) in the horizontal

direction and 50R in the vertical direction to minimize edge effects on pavement behavior. For the study of the effect of the horizontal dimension, the height of the pavement is set at 6250 mm, that is 50R ($R=125$ mm), and the length is made varied from 12R, 15R, 20R, 25R, 30R, 35R, 40R. As shown in Figure 3 and Figure 4, the results start to converge from a length of 25R and a width of 25R.



a)



b)

Figure 3. Pavement responses according to model dimensions: a) vertical strain above the wearing course b) deflection at the top of the wearing course

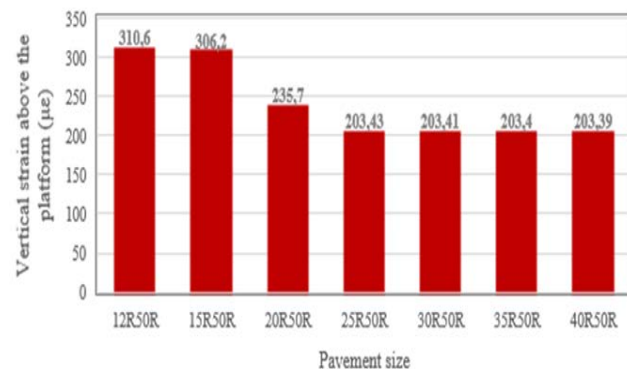


Figure 4. Effect of horizontal model dimension on vertical deformation above the platform layer

3.2. Effect of Vertical Model Dimension

The dimensions in the horizontal direction are set at 3150 mm, that is 25R, and to study the influence of the vertical dimension on pavement behavior, six models were developed, that is, 50R, 55R, 60R, 65R, 70R, 75R in height. The impact of this variation is shown in figure 5 and Table 2. The pavement responses converge from a total pavement depth equal to 55R, that is 6875 mm. Hence a platform thickness equal to 6250 mm.

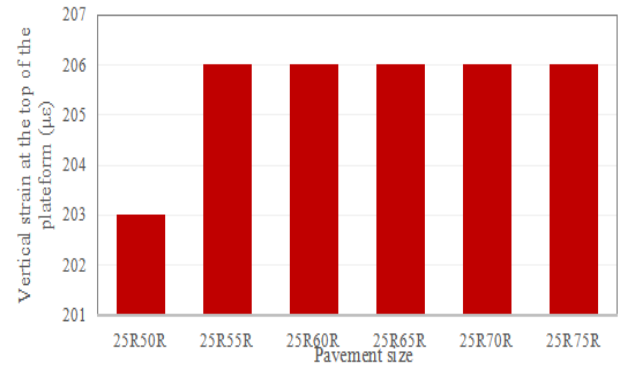


Figure 5. Effect of the vertical dimension of the model on vertical deformation at the top of the platform

Table 2. Effect of vertical dimension on deflection above the wearing layer

Radial distance (mm)	Pavement dimension					
	25R50R	25R55R	25R60R	25R65R	25R70R	25R75R
0	-0.406	-0.345	-0.345	-0.345	-0.345	-0.345
100	-0.318	-0.262	-0.262	-0.262	-0.262	-0.262
200	-0.301	-0.202	-0.202	-0.202	-0.202	-0.202
300	-0.211	-0.189	-0.189	-0.189	-0.189	-0.189
400	-0.203	-0.177	-0.177	-0.177	-0.177	-0.177
500	-0.161	-0.104	-0.104	-0.104	-0.104	-0.104
600	-0.123	-0.098	-0.098	-0.098	-0.098	-0.098
700	-0.098	-0.079	-0.079	-0.079	-0.079	-0.079
800	-0.074	-0.065	-0.065	-0.065	-0.065	-0.065
900	-0.051	-0.039	-0.039	-0.039	-0.039	-0.039
1000	-0.038	-0.021	-0.021	-0.021	-0.021	-0.021
1100	-0.014	-0.020	-0.020	-0.020	-0.020	-0.020
1200	-0.011	-0.010	-0.010	-0.010	-0.010	-0.010

Throughout the rest of the modeling, we consider, in the horizontal direction, a pavement structure 25R (3125 mm) long and 25R (3125 mm) wide. In the vertical direction, the total height of the pavement is 55R (6875 mm), distributed as follows: 60 mm wearing layer, 250 mm base layer, 250 mm sub-base layer and 6315 mm subgrade layer.

3.3. Mesh Selection

The model mesh is chosen to provide better, more accurate results. Hence the choice of C3D8R quadratic elements to improve the convergence rate. These elements give better results than linear interpolation elements [19]. The C3D8R element has the ability to represent large deformations, geometric and material non-linearity. It also features three degrees of freedom at each node, with

translations in the nodal x, y and z directions. The pavement layers are simulated with the same shape for node continuity between sequential layers. A fine mesh is used around the loading zone, along the wheel path where stress and strain gradients are highest.

3.4. Modeling Tire and Rolling Loads

The contact surface is an important parameter in the analysis of pavement behavior. In most analyses, the shape of the tire footprint is assumed to be circular [20]. In reality, however, it is closer to a rectangle than to a circle. [21] confirmed that the use of a circular footprint geometry is insufficient. Figure 6 shows the cross-section of the contact surface equivalent to a rectangle, which simplifies the shape of the actual footprint.

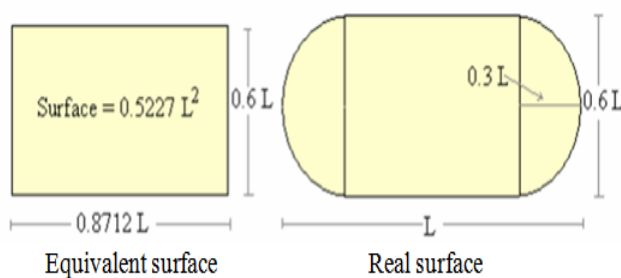


Figure 6. Simplification of tire loading [22]

The application of layer theory to flexible pavement design includes the assumption of a circular contact surface for each tire [19]. To simplify the analysis of the flexible pavement, a single rectangular area with the same contact surface as the dual tires is used to simulate a set of dual tires instead of using two rectangular areas. This assumption is not correct, but the error is very small (Figure 7). In the remainder of the study, and for the sake of simplification, the dual wheel will be replaced by the simplified dual with the same surface area as that of the dual wheels on the standard French axle, that is $2\pi R^2$ ($R=125\text{mm}$), or 0.098 m^2 . Since the length of the elliptical footprint is known ($L=0.43\text{m}$), the dimensions of the rectangular footprint are: $0.8712 \cdot L = 0.38\text{ m}$ and $0.6 \cdot L = 0.26\text{ m}$.

The spatially and temporally varying moving load was simulated in this study using the ABAQUS computer program, which allows the user to apply several types of load, magnitude, location and direction through the application of the "load" module to determine the rutting damage caused by each passage of the wheel load on the flexible pavement. In the Abaqus software, wheel loads were modeled by programming the DLOAD user subroutine in Fortran. This user subroutine allows the loads applied along the entire length of the model to evolve in order to simulate rolling loads. 20000 wheel cycles are applied to the pavement layer to observe the plastic analysis in the structure over an interval of 200 seconds, corresponding to 0.01 seconds for a single pass. The trajectory of the moving load is the longitudinal distance divided into 14 steps (the 14 steps correspond to one-wheel cycle) to reproduce the moving load on the pavement surface, which can be achieved using the "step" module.

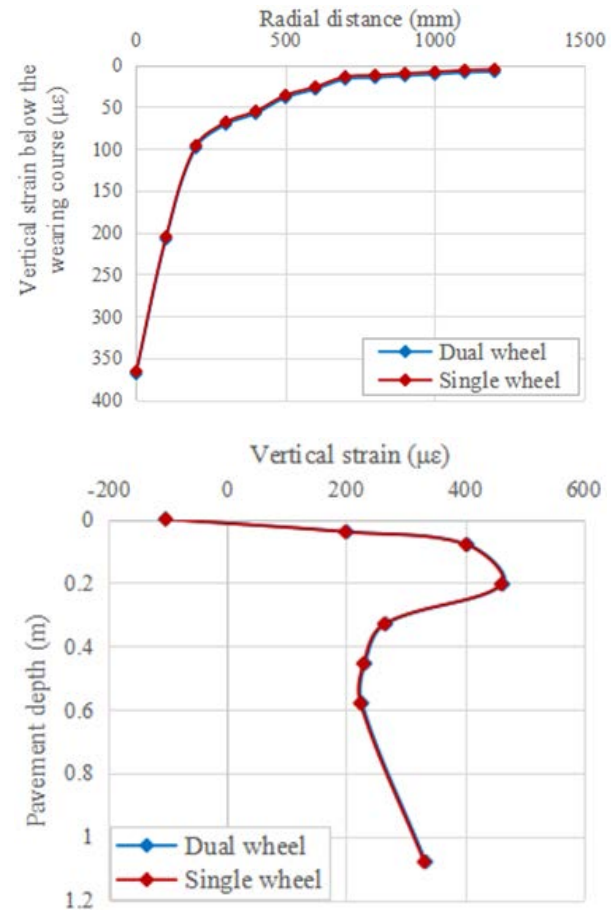


Figure 7. Comparison of pavement responses between the dual wheel and the simplified dual wheel system

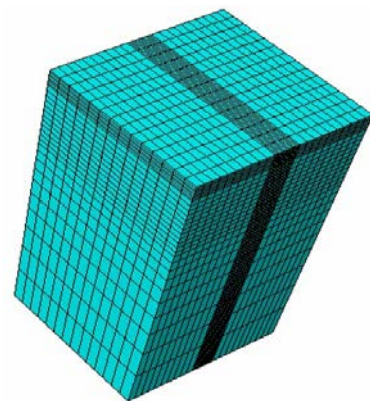


Figure 8. Model mesh

3.5. Modeling Material Behavior in ABAQUS

The mechanical properties of linear viscoelastic materials can be determined from a variety of tests, including creep, relaxation and complex modulus tests. The latter is used to define the viscoelastic behavior of asphalt mixes in mechanistic-empirical pavement design methods. For small deformations, Abaqus software defines the linear viscoelasticity of materials using the relaxation modulus [23]. The generalized Maxwell model is suitable for describing the behavior of a viscoelastic material during a relaxation test [24]. The model consists of a spring in parallel with n simple Maxwell models

(figure 9). The simple Maxwell model consists of a spring of stiffness E in series with a damper of viscosity η .

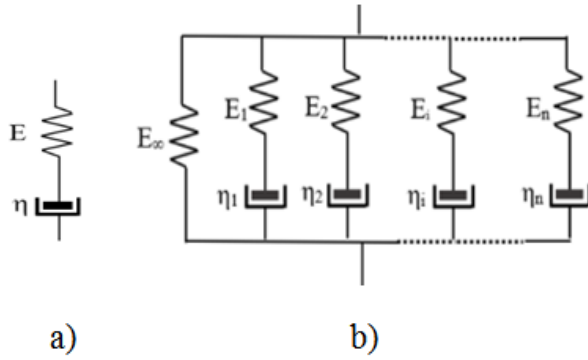


Figure 9. Maxwell model: a) simple model b) generalized model

The model is expressed mathematically by a Prony series with parameters E_i and τ_i . The Prony series is used in this study to describe the relaxation behavior of asphalt concrete, which is subjected to rolling load. The i th Maxwell element has shear relaxation modulus G_i , viscosity η_i and relaxation time τ_i . The higher the number of chains, the more accurately the model describes the material. Fitting the experimental behavior of bitumen by the Prony series means minimizing the error between predicted and experimental values by adjusting the number n (number of model elements) and coefficients.

$$E(t) = E_0 - \sum_{i=1}^n E_i \left(1 - \exp\left(-\frac{t}{\tau_i}\right) \right) \quad (1)$$

$$E_0 = E_\infty + \sum_{i=1}^n E_i \quad (2)$$

$$\tau_i = \frac{\eta_i}{G_i} \quad (3)$$

τ_i : relaxation time

E_i : relaxation modulus

E_0 : instantaneous modulus

However, in Abaqus, the Prony series defines the shear moduli $G(t)$ of the relaxation test.

$$G(t) = G_0 \left[1 - \sum_{i=1}^N g_i \left(1 - \exp\left(-\frac{t}{\tau_i}\right) \right) \right] \quad (4)$$

$$G(t) = \frac{E(t)}{2(1+\nu)} \quad (5)$$

$G(t)$: shear relaxation modulus

$E(t)$: relaxation modulus, t is the loading time

ν : Poisson's ratio

Prony series are calculated directly in Abaqus. Simply enter the normalized results for the shear relaxation modulus $G(t)$.

$$g(t) = \frac{G(t)}{G_0} = 1 - \sum_{i=1}^N g_i \left(1 - \exp\left(-\frac{t}{\tau_i}\right) \right) \quad (6)$$

$g(t)$: normalized shear relaxation modulus

N : number of terms in Prony series

g_i : dimensionless terms ($0 \leq g_i < 1$)

There are relationships between relaxation, creep and complex modulus functions. Thus, knowledge of one function can be used to determine another by applying a conversion method such as that developed by [25]. The

relaxation modulus is determined by the following relationship:

$$E(t) = \frac{1}{\lambda} E'(\omega) \quad (7)$$

$$\lambda' = \Gamma(1-n) \cos\left(\frac{n\pi}{2}\right) \quad (8)$$

$$n = \frac{d \log E'(\omega)}{d \log \omega} \quad (9)$$

ω : frequency

E' : real part of the complex modulus

Γ : gamma function

λ' : adjustment factor

n : slope of $E'(\omega)$ in the log-log reference frame

The data used to calculate the parameters of the viscoelastic model are taken from the work of [26]. To determine the model parameters (g_i and τ_i), we used an Excel spreadsheet option (solver). And based on the method of least squares, a set of parameters is made to minimize the deviations between the experimentally measured values and the values calculated by the model.

Table 3. Summary of viscoelastic model parameters (g_i and τ_i) as a function of bituminous layer temperature

Temperature (°C)	$E(t)$ (MPa)	$g(t)$	g_i	τ_i (s)
10	9507	314	0.76	12.23
20	5424	179	0.88	11.76
30	2840	94	0.84	14.59
40	1214	40	0.97	10.41
50	217	7	0.99	9.34

The behavior of untreated gravel subbase materials is described by an associated elastoplastic model. The plastic part uses the Mohr Coulomb flow surface.

$$F = R_{mc} - p \tan \phi - c \quad (10)$$

$$R_{mc}(\theta, \phi) = \frac{1}{\sqrt{3} \cos \phi} \sin\left(\theta + \frac{\pi}{3}\right) + \frac{1}{3} \cos\left(\theta + \frac{\pi}{3}\right) \tan \phi \quad (11)$$

c : material cohesion

ϕ : angle of friction

q : Von Mises equivalent stress

$$q = \sqrt{3/2(s:s)} \quad (12)$$

$$s = \sigma - PI \quad (13)$$

P : average stress

$$P = \text{tr}(\sigma)/3 \quad (14)$$

$$r = (9/2 s:s)^{1/3} \quad (15)$$

r : third constraint invariant

$$\cos(3\Theta) = (r/q)^3 \quad (16)$$

Θ : Lode angle

The elastic part is described by Hooke's law, involving Young's modulus E and Poisson's ratio ν . The direct shear test used to obtain the material strength parameters (c and ϕ) for the study is carried out at the geotechnical laboratory of the Thiès Polytechnic School (EPT). These parameters are summarized in Table 4.

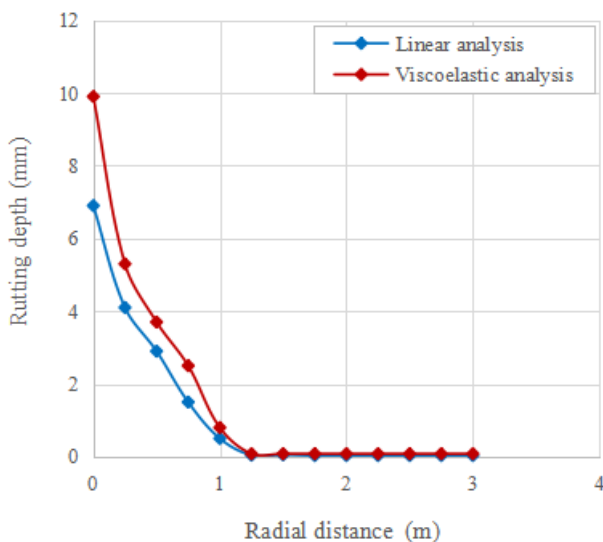
Table 4. Strength parameters for study materials

Material	Friction angle ϕ (°)	Cohesion C (kPa)
Diack basalt	33	17.4
Sindia laterite	35	20.5
Bakel sandstone	32	20.6

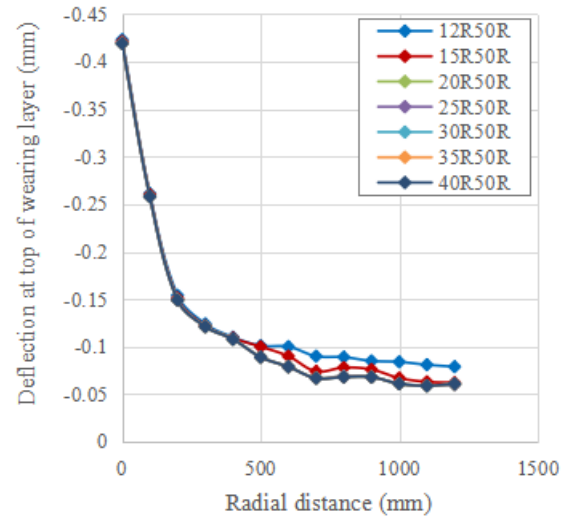
Table 5. Material parameters for structure S2

Pavement layer (Material)	Linear model		Viscoelastic model (Maxwell)		Nonlinear model (Mohr Coulomb)	
	E	ν	g_i	τ_i	C (kPa)	ϕ (°)
Surface (BBSG 0/14)	1512	0.45	0.84	14.59	-	-
Base (Basalte de Diack)	400	0.35	-	-	17.4	33
Sub-base (latérite de Sindia)	274	0.35	-	-	20.5	35
Subgrade (PF2)	130	0.25	-	-	-	-

In order to take into account the importance of considering the viscoelastic behavior of asphalt mixes in the design of flexible pavement structures, a calculation of rutting depth is made according to whether the asphalt concrete wearing course has linear or viscoelastic behavior. Compared with the elastic behavior, the rutting depth in the viscoelastic case is greater (Figure 10). This is because pavement stiffness is lower when wearing course behavior is considered viscoelastic. Therefore, the assumption of elastic asphalt behavior could underestimate pavement response and lead to undersizing of the structure. However, full-scale measurements could be carried out to determine which behavior (elastic or viscoelastic) would be closer to reality.



a)



b)

Figure 10. Analysis of rutting depth as a function of wearing course behavior: a) total pavement rutting b) base course rutting

3.6. Influence of Number of Loading Cycles on Rutting

Figure 11, Figure 12 and Figure 13 show the evolution of rutting depth as a function of the number of cycles for structures S2, S4 and S5. What differentiates these three structures is the base layer. It is made of Diack basalt, Bakel black sandstone and Bakel red sandstone for structures S2, S4 and S5 respectively. In addition, the base and sub-base layers are all compacted to the optimum moisture content and dry density. The base course for all structures is made of Sindia laterite. The wearing course is BBSG 0/14.

Table 6. Material parameters for structure S4

Pavement Layer (material)	Linear model		Viscoelastic model (Maxwell)		Nonlinear model (Mohr Coulomb)	
	E	ν	g_i	τ_i	C (kPa)	ϕ (°)
Surface (BBSG 0/14)	1512	0.45	0.84	14.59	-	-
Base (Bakel black sandstone)	320	0.35	-	-	20.6	32
Sub-base (Sindia laterite)	274	0.35	-	-	20.5	35
Subgrade (PF2)	130	0.25	-	-	-	-

Table 7. Material parameters for structure S5

Pavement layer (Material)	Linear model		Viscoelastic model (Maxwell)		Nonlinear model (Mohr Coulomb)	
	E	ν	g_i	τ_i	C (kPa)	ϕ (°)
Surface (BBSG 0/14)	1512	0.45	0.84	14.59	-	-
Base (Bakel red sandstone)	300	0.35	-	-	20.6	32
Sub-base (Sindia laterite)	274	0.35	-	-	20.5	35
Subgrade (PF2)	130	0.25	-	-	-	-

It can be seen that rutting depth increases with the number of loading cycles. Compared with Diack basalt, taken as a reference and for a number of loading cycles

equal to 20000, we note a relative variation in rutting depth of 53.8% for a Bakel black sandstone base layer, while this variation is 107.7% in the case of a Bakel red sandstone base layer. Structure S5 (Bakel red sandstone base course) is more sensitive to permanent deformation than structure S4 (Bakel black sandstone base course). This could be explained by the difference in rigidity of the two materials making up the base layers of the structures. Black sandstones appear to be more resistant than red sandstones. However, in all structures, this rutting depth did not stabilize up to 20000 loading cycles.

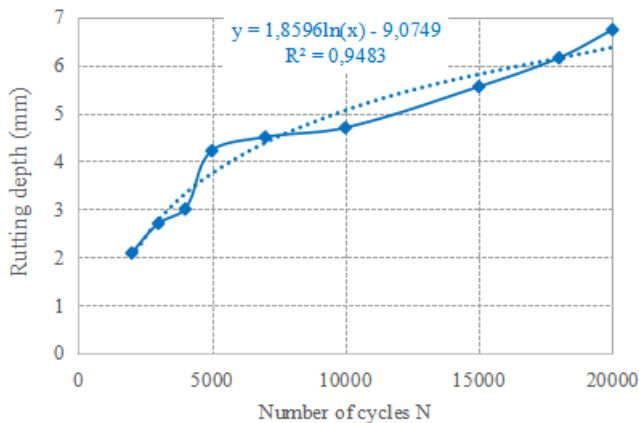


Figure 11. Trend in rutting depth as a function of number of cycles (Bakel red sandstone)

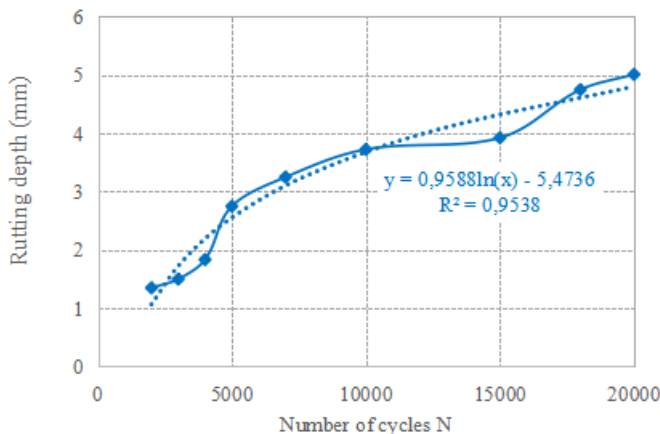


Figure 12. Trend in rutting depth as a function of number cycles (Bakel black)

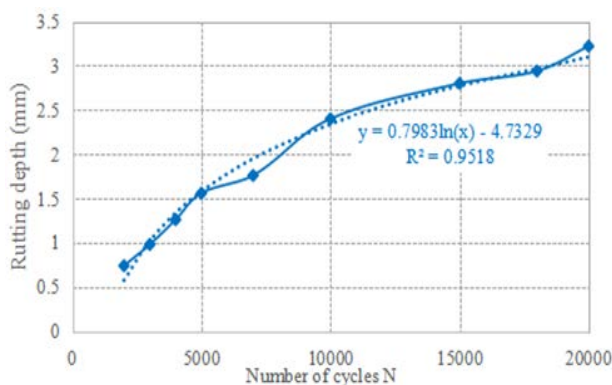


Figure 13. Trend in rutting depth as a function of number of cycles (Diack basalt)

4. Conclusion

The study has shown that the vertical and horizontal dimensions of the pavement influence its responses. Hence the need to select optimum pavement structure dimensions for finite element modeling, in order to minimize the effects of edges on pavement behavior. For better design of flexible pavement structures, the actual behavior of the materials making up the various pavement layers and the type of loading (static or cyclic) are fundamental. Hence the choice of the Abaqus calculation code in this study. The differences in rutting depth between the linear and viscoelastic analyses of the wearing course show just how damaging the assumption of linear behavior of the wearing course could be for the design of the various pavement layers, leading to premature failure. The significant differences in rutting depth between Diack basalt and Bakel sandstone, all used in the base course, illustrate the strength of basalt compared with sandstone. Consequently, the use of these sandstones in base courses would require treatment, for example cement.

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