Numerical Simulation of Pavement Life Deterioration: Tree-Roots' Effects

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Flexible pavement is usually designed to last for at least 20 years, however sometimes the first failure is formed after the first year of use. This failure has been associated with; overloading of the structure, use of poor materials, drainage problem and inadequate pavement thickness, and poor compaction; without considering presence of tree-root in pavement layers. However, with the numerous advantages of finite element model (FEM) in designing pavement structure and coupled with the fact that it's a non-destructive tool, it makes its use sustainable. Therefore, this study focuses on investigating the impact of tree-roots on design life of flexible pavement using FEM. Results of the study show that tree-roots within any layer, and most especially within the subgrade layer, have a great effect on its bearing capacity. Moreover, it was found that this effect decreases subgrade life by approximately 13 - 67 %, with respect to the root thickness and this consequently decreases the entire pavement life.

Keywords: Tree-root's effect, Numerical Simulation, Pavement deterioration

1. Introduction

1.1. *Pavement and the Environs*

Pavement is one of the essential infrastructures for a nation development. However, this structure is not a stand-alone, as it interacts with its environs. Pavement structures have got various environs such as; drainages, pedestrian walkway, traffic communication tools, and the vegetation. All of these environments have great contribution towards the performance of pavement, yet if not properly monitored or maintained, sometimes impact the life span of the pavement negatively. This talks with regards to the vegetation mostly; vegetation such as trees and grasses are conserved or planted during road construction, as a result of their enormous importances to the ecosystem at large[1]. Some of these importances are; (i) ecologically: improving air quality, climate amelioration, conservation of water, reduction of carbon foot print and global warming effect[2], and (ii) environmentally: it creates a peaceful and aesthetically pleasing environment for the road users.

Nevertheless, despite vegetation's importance, they have also contributed negatively to the problem which surrounds pavement such as road accidents[1] and even pavement failures[3]. On the failure, vegetation such as tree has always been noted for its conflicts with nearby infrastructures. Most of these conflicts result from the interaction of its root with the infrastructures. Although, these roots serves as an anchor to the ground and helps with the supply of water and nutrients which serves all parts of the tree for its reproduction, survival and energy storage. Nevertheless, tree-roots differs from one species to the other and, falsely has been considered to essentially grow vertically downward with limited lateral spread, yet, this is not true for all trees. In most cases, tree-root grows and expands in a radial pattern (at least 3 times its crown), consequently deforms the top soil above it by pressure exerted. The deformation process generates stresses and strains in the above layers of soil which might lead to the failure of the structure on such soil.

2. Tree-roots' Interactions

Various infrastructural conflicts exist with tree-roots some of which are sewer, storm water drains, water supply lines, foundations, sidewalks, walls, swimming pools, and pavement structure[1,3]. Of all these conflicts, tree-root versus pavement is one of the most pervasive and costly problems[2]. This subsequently, results in pavement needing regular maintenance and rehabilitation which increases the operational cost of the road and that of the road users.

Previously, various studies on the effect of tree-roots on different infrastructures have been considered with numerous recommendations which include appropriate selection of tree species, application of root barriers, root pruning and herbicide impregnated geotextile fabrics[2]. Most of these recommendations are from an arboriculturist's point of view[2], with few research contributions from pavement engineers[3]. As a result, till date pavement structure still experience failures such as cracking, surface deformation, disintegration and surface defect[4]. Although, the majority of these failures have been associated with; overloading of the structure, use of poor materials in the layers and base drainage and inadequate pavement thickness and compaction without considering the presence of tree-root in pavement layers. However, with the new perspective of pavement design, this challenge can be appropriately addressed.

2.1. *Pavement Design: Recent Trends*

Using mechanistic-empirical design method (ME-DM) over traditional methods is continually gaining interest over decades. This results from the inaccuracy of design and failure experienced in the use of traditional methods[5], and the advantages of using ME-DMs, which are ability; to determine stress and strain, to analyze static and time-dependent problems, to incorporate non-linear material characterization, large strain/deformations, dynamics analysis and other sophisticated features. ME-DM analysis is based on the inputs such as pavement thickness, material properties, loading condition (in terms of static and dynamic) and other substances interacting with it.

According to Darwish[6], the critical points of consideration when using ME-DM such as; bottom of the surface course, top/bottom of base/sub-base layer and top of subgrade, always experience most of the interaction with visiting substances such as tree-roots[3]. Consequently, the presence of these roots at any layer of pavement can contribute to the failures experienced. Nevertheless, 3D Finite element method (FEM) of ME-DM is up to the task, as it has got the capacity for real-life monitoring of pavement behavior. This is of an advantage as it is a non-destructive testing and thus makes FEM of pavement design an environmental sustainable method.

2.2. *Pavement Life Estimation*

Generally, the flexible pavement is designed to last for at least 20 years, but often the first failure is formed after the first year of use. Furthermore, researches have shown that before the design life is attained most pavements have failed beyond maintenance revitalization capacity[7]. As earlier mentioned, FEM calculates the stresses and strains in pavement structure; these outputs are further used in the distress model which is one of the empirical aspects of ME-DMs. Distress prediction models are formulated based on accumulated empirical data. In addition, these models derived based on observation and performance study of pavement in relations to observed failures and initial strain under loads, thereby computing the pavement life span (in terms of number of loading cycles to failure). Of all the numerous distress models[5] that exist, two are of major concern which are; (i) fatigue cracking in asphalt and (ii) deformation in the subgrade. In like manner, the aforementioned model designed by Asphalt Institute is the most commonly used and would be considered in this study (Eq. (1) and (2)).

$$N_f = 0.0796(\varepsilon_t)^{-3.291}(E)^{-0.854} \quad (1)$$

Where; N_f = Number of repetitions for fatigue cracking; ε_t= Tensile strain at the bottom of the asphalt surface in microstrain; E = resilient modulus of asphalt in psi.

$$N_r = 1.365x10^{-9}(E_c)^{-4.477} \quad (2)$$

Where; N_r = Number of repetitions for subgrade rutting failure; E_c = Compressive strain on top of the subgrade.

2.3. *Scope of the Study*

The involvement of tree-roots towards pavement failure in term of fatigue cracking, surface deformation, disintegration and surface defect, is at an alarming rate[4]; thus far has been considered as an expensive nuisance and liability risk[1]. Until now, tree-roots are still found within the pavement, although, if these roots exist under the asphalt layer, the effect can be noticed visually. Yet, this question remains; what is the effect of tree-roots on pavement design life, if not within the upper layers? Thus, this paper focuses on investigating the impact of tree-roots on the design life of the flexible pavement.

3. Simulation Design

In this study, four scenarios are developed. The first serves as a control model with the absence of tree-roots in the pavement layers while second contains tree-roots under the surface layer. Moreover, models with tree-roots underneath the sub-base and within the subgrade serve as third and fourth models respectively. In scenarios 2, 3 and 4, the tree-roots thickness are varied in a range (25 mm-100 mm) to check for the continues effect, as the root grows. These scenarios are modelled in three-dimensional finite element model using Abaqus and the control model results are compared with those obtained using mePADS, as a validity check.

3.1. *Model Geometry & Material Characterization*

The geometry is basically 10 000 mm length by 5 000 mm and a total height of 2 350 mm, these along with the material characterization (Table 1) were adopted from a previous research by Rahman et al.. Dimensions and materials characterization are the same for all scenarios, with the exception of the tree-roots system for control model. Overall, this model geometry was considered to avoid edge errors. Materials characterization and dimensions of an average pine species tree-root with 12% moisture content are used based on a study by Green et al. Additionally, the dimension of tree-root is assumed to ranges from 25mm-100mm and the pressure exert by its movement is taken as 0.4 MPa, this is essential to simulate the movement of tree-roots. All layers of the pavement (Asphalt surface, Granular base and Subgrade) are assumed to be linearly elastic in behavior for simplicity.

Table 1. Material property of pavement layers & tree-roots

Data	Asphalt Surface	Granular Base	Subgrade	Tree-Roots
Thickness (mm)	100	250	2000	25-100
Modulus of Elasticity(MPa)	2175	415	52	12500
Poisson's Ratio	0.35	0.4	0.45	0.33

3.2. *Finite Element Types & Mesh Size*

All scenarios are modelled using the 8-node continuum three-dimensional brick element (C3D8R) with reduced order numerical integration available in Abaqus® (6.13). C3D8R element has the capability of representing large deformation, geometric and material nonlinearity. Instead of the commonly used random mesh, structured mesh was defined for all layers of pavement structure, so that the tire contact area can be controlled while sweep mesh was used for the tree-root.

3.3. *Boundary Condition, Loading & Contact modelling*

On boundary and loading condition aspects, the models are all subjected to a static load in a linear perturbation analysis and the models are restrained in horizontal directions (i.e. degree of freedom 1 and 3) with the subgrade base in all directions. Further, loading contact area is assumed to be rectangular (61575 mm^2) with wheel pressure of 0.67 MPa. Tie constraints are assumed as the interaction between the interfaces of the layers (i.e. layers are fully bounded with no friction) for control while embedded constraints are used for interactions between tree-root and pavement layers.

4. Results and Discussions

4.1. *Control model and Comparative Analysis*

The results for the control models (Abaqus and mePADS) are presented in Figures 1, and those of Abaqus were found to be a close match with results obtained by Rahman et al. Figure 1 shows that the compressive strain decreases downward the depth. More so, the results were of close march for both software; 1.59×10^{-4} µstrain for Abaqus and 1.16×10^{-4} for mePADS. These aforementioned results serve as a performance check for the models developed in Abaqus and was found to be valid.

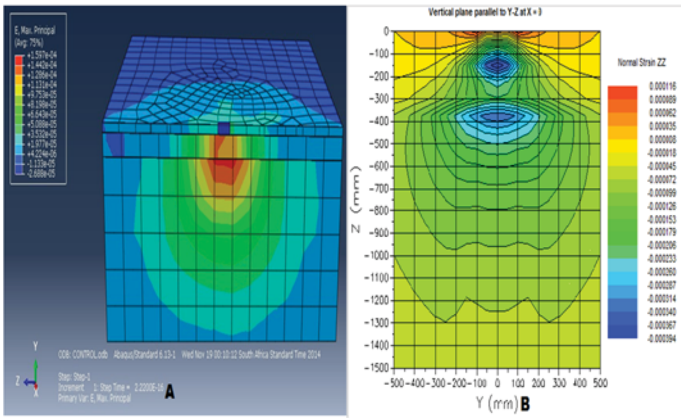

Fig. 1. Strain distribution for control model (A- Abaqus Model and B- mePADS Model)

Furthermore, on an average, the results (Table 2) using Abaqus are significantly less by 70% than those of mePADS in terms of the strains generated at the bottom of the asphalt and top of the subgrade layers. Consequently, the pavement lifecycle obtained for Abaqus using Asphalt Institute damage model, although higher in terms of the asphalt layer life, yet lower in the subgrade, this implies that mePADS tends to overdesign.

Table 2. Control model design life using mePADS and Abaqus

mePADS		Abaqus	
AC Capacity (No. of Load Repetitions to Failure)	*Subgrade Capacity (No. of Load Repetitions to Failure)*	*AC Capacity (No. of Load Repetitions to Failure)*	*Subgrade Capacity (No. of Load Repetitions to Failure)*
9.00×10^5	5.16×10^{10}	5.36×10^8	1.35×10^8

The results of models with tree-root are presented in Table 3. From the table, the presence of tree-root (thickness-25 mm) underneath the asphalt shows a slight decrease in the capacity of asphalt layer and increase the bearing capacity of the subgrade layer, when compared with the control model. Also, for subsequent tree-root thickness under the asphalt, the capacity of asphalt and subgrade layer however increases. This implies that the presences of tree-root underneath the asphalt layer do not necessary reduce the pavement capacity but this, in most cases expose the asphalt layer to fatigue cracking and surface lifting which allow the infiltration of water into other layers, consequently result to other forms of failure. Furthermore, the capacity of the asphalt layer was observed to increase with the presence of tree-root under the base layer but the subgrade capacity starts to experience a decrease, this implies that the stress in the layer was redistributed[3].

Table 3. Effect of tree-roots on pavement layers' design life

	Tree-Root Under Asphalt		Tree-Root Under Base layer		Tree-Root in Subgrade	
Tree-Root Thickness (mm)	*AC Capacity (No. of Load Repetitions to Failure)*	*Subgrade Capacity (No. of Load Repetitions to Failure)*	*AC Capacity (No. of Load Repetitions to Failure)*	*Subgrade Capacity (No. of Load Repetitions to Failure)*	*AC Capacity (No. of Load Repetitions to Failure)*	*Subgrade Capacity (No. of Load Repetitions to Failure)*
25	4.29 x 10^{8}	4.88 x10^{8}	6.33 x 10^{8}	1.64 x 10^{8}	5.79 x 10^{8}	1.17 x 10^{8}
50	8.98 x 10^{8}	3.65 x 10^{8}	7.75 x 10^{8}	4.54 x 10^{7}	7.26 x 10^{8}	1.35 x 10^{8}
75	4.36 x 10^{8}	3.79 x 10^{8}	8.30 x 10^{8}	3.5 x 10^{7}	7.83 x 10^{8}	1.11 x 10^{8}
100	6.21 x 10^{8}	6.65 x 10^{8}	11.39 x 10^{8}	6.70 x 10^{7}	7.83 x 10^{8}	4.44 x 10^{7}

However, tree-roots within the subgrade layer have a great effect on the bearing capacity of the subgrade, as it decreases the capacity of the layer by approximately 13 – 67 %, with respect to the root thickness. These results raise an alert, as the pavement engineers are majorly concerned about the tree-root presences in the upper layer of the pavement. This is because by mere visual inspection one can see the effect (such as surface lifting and cracking) of tree-root when present in the upper layers. In addition, during maintenance process, one of the engineer's solutions is cutting off the life-supply to the tree-roots; yet, the roots are left in the pavement layers. This solution tends to worsen the situation as the root easily decay and consequently, create a void in the layers of pavement, which can result in the formation of potholes. Overall, it is worthy to note that the presence of tree-roots in lower layers of pavement contributes significantly to its deterioration and shorten its life span.

5. Conclusion

In this study, the effects of tree-roots on pavement life deterioration were considered. As a result, the following conclusions were drawn:

- The presence of tree-root presences in pavement structure can lead to its failures such as; surface cracking and lifting, potholes, raveling …etc.
- The presence of tree-root on/within the lower layers contribute more damage, thus, should be given the same attention as those within the upper layers.
- During maintenance process effort should be made, to totally removing the tree-root in the pavement layers, as dead roots contribute more damages to pavement failure.

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