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Modeling of tree-roots effects on pavement stresses and strains

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ABSTRACT: Using stress and strain in pavement design has become more prevalent through mechanistic-empirical design methods. Stresses and strains at any layer of the pavement determine the overall performance of such structure. Thus, the redistribution of these stresses and strains affects the stability of the pavement structure. Over the years, tree roots in pavement layers have contributed to its failure, although different recommendations to obviate the tree-roots effect have been suggested by arboriculturists and only a few contributions have been made by pavement engineers. Consequently, to date, pavement structure still experiences failure. However, with the help of the finite element model, the impact of tree roots in flexible pavement structure can be simulated and its effect on the stress and strain redistribution in pavement layers can be examined. The result of this study indicates that more stress is generated in overlay layers (asphalt and base layer) due to the presence of tree roots, which may later lead to cracks.

1 INTRODUCTION

Sustainability of pavement structure life has been a long-time global challenge to pavement engineers as a result of the continuously increasing cost of design, construction, maintenance and rehabilitation, with the design aspect being a major concern of all. Thus, the use of stress and strain in pavement design has become more prevalent through Mechanistic-Empirical Design Methods (ME-DM). The use of these methods are influenced by errors experienced and uneconomical reasons in the use of traditional empirical methods (Rahman et al. 2011; Shafabakhsh et al. 2013), and the inability of traditional methods to represent the actual scenario of pavement onsite. In ME-DM, stresses or strains at any layer of a pavement determine the overall performance of such structure. Consequently, redistribution of such stresses and strains further affects the stability and performance of the pavement structure.

Over the years, flexible pavement experience failures have been resulted from soil instability/expansion (Kordi et al. 2010), inappropriate use of materials, inadequacy in designs (Kordi et al. 2010; Shafabakhsh et al. 2013) and the presence of tree roots (D'Amato et al. 2002) in its layers. Focusing on the latter, tree is of great environmental importance in any urban design (Beecham 2012; Reavens 2001), yet its adverse effect (as a result of its roots) on the poor performance or sometimes failure experienced in pavement structure cannot be ignored.

1.1 *Tree roots and flexible pavement performances*

Tree is of great importance to any society. Some of its importance ranges from community and social values to ecological and environmental values (Beecham 2012; Reavens 2001; Roodt 2012). Ecologically, it sequestrates carbon dioxide and provides oxygen; improves air quality, climate amelioration and conserves water (Appleton et al. 2003; Rosenfeld et al. 1998), all of which contribute positively to the reduction of the global warming effect and carbon emissions. Also, trees are a positive component of urban infrastructure (Hauer et al. 1994), as they create a peaceful and aesthetically pleasing environment. Additionally, tree's shade has been found to be partially responsible for reduced pavement fatigue, cracking, shoving and other surface distress (McPherson & Muchnick 2005).

Contrary to the tree's importance, there have always been conflicts between it and the nearby infrastructures (Coder 1998; Randrup et al. 2003). Most of these conflicts result from the interaction of tree roots with the infrastructures. These roots serve as an anchor to the ground and gather water and nutrients that are transferable to all parts of the tree for reproduction, survival, energy storage and many other purposes (Russell & Culter 2003). Furthermore, roots are systems that differ from one species of the tree to the other (Day et al. 2010; Morgenroth 2011). Although, erroneously, it has been believed that roots mainly grow vertically downwards and have a limited lateral spread, but this is not true for all trees (Jim 2003). Roots are typically shallow and widely spread (Morgenroth 2011); they are found in the upper 1 m of the soil and spread up to three times the diameter of the tree crown (Jim 2003). The root grows and expands radially and deforms the soil above them by the pressure it exerts. It further modifies its environment and develops stress and strain on various types of structures, resulting in conflicts (Nicoll & Coutts 1997). Consequently, growth of tree roots is considered an expensive nuisance and liability risk in many societies (Coder 1998; Roodt 2012). 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 (Coder 1998; Morell 1992; Nicoll & Coutts 1997; Randrup et al. 2003; Roodt 2012). Of all these conflicts, tree-root versus pavement is one of the most pervasive and costly problems (Appleton et al. 2003).

On the pavement structure, especially in category B and C road (the South African National Road Agency Ltd 2013), the shallow root growth conflicts with the overlaying pavement layers. Generally, tree roots do not just grow in pavement layers, but the presence of essential and valuable resources or thermal changes between materials that provide pore spaces further enhance their growth (Kopinga 1994). In addition, the presence of roots in this structure places a tensile stress on the upper surface of the overlay (i.e. base layer or surface layer). This stress that later results in damage is typically progressive, with the degree of distortion that increases gradually over time (Barrell 2011). On a comparative note, flexible pavement has less tensile strength across the surface than the rigid pavement, so it is prone to show damage more easily when compared with the rigid one (Coder 1998). Yet, the use of flexible pavement is widely acceptable because of various factors that include less tire-pavement noise generation, smoothness of surface, environmental sustainability and its economic value (Asphalt Pavement Alliance 2010; Jain et al. 2013). Therefore, it is considered in this study.

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 (Appleton et al. 2003; Coder 1998; Hauer et al. 1994; Smiley 2003). Most of these recommendations are from an arboriculturist's point of view (Appleton et al. 2003; Coder 1998; Hauer et al. 1994), with few research contributions from pavement engineers. As a result, to date, pavement structure still experiences failures such as cracking, surface deformation, disintegration and surface defect (Adlinge & Gupta 2013). 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 (Pavement Failure Identification 2010; Rani 2007) without considering the presence of tree roots in pavement layers.

Among all these failures in the pavement structure, cracking is a major indicative of failure in pavement (Ahmed 2006) and one of the most common ones as it occurs in various forms: fatigue, longitudinal, transverse, block, edge, reflective and slippage (Adlinge & Gupta 2013; Kordi et al. 2010). Also, this failure further results in other failures such as potholes. Several reports have indicated its causes; however, only a few have considered tree-roots growth in the pavement layer as a possible cause. From Colombier's (1997) point of view, one of the causes of crakes in the pavement structure is the movements in the subgrade that results from shrinkage of clayey soil by excessive loss of moisture during a very dry period, which is aggravated by the presence of trees along the road. Likewise, D'Amato, et al. (2002) found that significantly root growth contributes to or worsens the cracks in the pavement, as its growth is located beneath the existing cracks that result from the increased soil aeration beneath the crack. The movement in the subgrade layer or of any layer in the structure (Fig. 1) affects the whole pavement that eventually results in the redistribution of stresses and strains in the structure. Therefore, these stresses and strains generated by tree roots need to be studied by the mechanistic-empirical design method for pavement analysis.

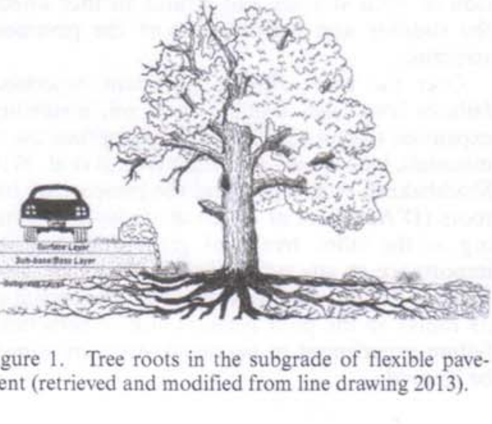

Figure 1. Tree roots in the subgrade of flexible pavement (retrieved and modified from line drawing 2013).

1.2 *Stresses and strains in pavement design*

Recently, there has been a shift in the design of pavement structure from the empirical design methods to ME-DM. This is as a result of limitations associated with the empirical design methods such as one climate condition, limited traffic, material type and new construction only (Huang 2004; Wang 2001). As with the empirical design methods, ME-DM exploits mathematical capability to calculate the stresses, strains and/or deflections in a multi-layered systems, such as pavement, when subjected to external loads (Hafeez 2010).

The stresses, strains and deflections generated in flexible pavements result from material properties, thickness of each layer, loading condition (Al-Khateeb et al. 2011) and in the presence of another substance therein. With the use of finite element-based methods, one can calculate the theoretical stresses, strains and deformations that occur anywhere in the structure. However, there are a few critical locations that are of interest and are often used in pavement analysis (Darwish 2012; NCHRP 2004, Pavement Interactive 2008) such as

- Surface deflection;
- Tensile horizontal strain at the bottom of the surface course (for surface course fatigue cracking);
- Compressive vertical stresses/strains within the base/sub-base layers (for rutting of unbound layers), and
- Compressive vertical stresses/strains at the top of the subgrade (for subgrade rutting).

Looking closely at these critical positions, the presence of tree roots in or underneath any layer of the pavement structure can contribute massively to the failures experienced. Nonetheless, trees are inevitable to our urban environment.

Although the use of ME-DM in pavement design is widely acceptable, the use of the 3D Finite Element Method (FEM)-based software appears to be the best approach (Rahman et al. 2011, Shafabakhsh et al. 2013). Abaqus® 3D FEM software has applications in pavement analysis. Various researchers have used Abaqus® 3D FEM for the design of flexible pavement that yields positive results: Shafabakhsh et al. (2013) who investigated on the pavement thickness impact, Al-Azzawi (2012) on geogrid material positing in pavement and Yin (2013) on pavement and interactions with its instruments. With 3D capabilities, real-life monitoring of the behavior of pavement structure and the presence of tree roots can be studied. As a result, proper understanding of the causes of cracks and other failures in pavement can be achieved.

Considering the fact that 3D FEM calculates stresses and strains in the pavement structure, the redistribution of stresses and strains in flexible pavement induced by tree roots can be simulated and studied; thereafter, design and construction intervention can be taken into consideration. Therefore, this study aims at investigating cracking failures in flexible pavement via the impact of tree roots on its stress/strain redistribution.

2 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 the second contains tree roots under the surface layer. Moreover, models with tree roots underneath the sub-base and in the subgrade serve as the third and fourth models, respectively. In scenarios 2, 3 and 4, the tree-root thicknesses vary in a range (25 mm–100 mm) to check for the continuous effect, as the root grows. These models are analyzed using the Abaqus® (6.13) 3D FEM software. However, for any successful FEM simulation, factors such as model geometry, material characterization, element type and meshing size, boundary condition and loading type need to be taken into consideration (Embraco 2006). Details of these factors for this present study are given below.

2.1 *Model geometry and material characterization*

The geometry and material characterization of the models are adopted from a previous research conducted by Rahman et al. (2011) (Table 1). Dimension and material characterization are the same for all scenarios, with the exception of the tree-roots system for the control model. Overall, this model

Table 1. Material property of pavement layers and 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

geometry was considered to avoid edge errors. Material characterization and dimensions of an average pine species tree root with 12% moisture content are used based on a study by Green et al. (1999). Additionally, the dimension of tree roots is assumed to range from 25 mm to 100 mm and the pressure exert by its movement is taken as 0.4 MPa (Hartley 2012); this is actually to simulate the movement of tree roots. All layers of the pavement are assumed to be linearly elastic in behavior for simplicity.

2.2 *Finite element types and mesh size*

All scenarios are modeled 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 (Ibrahim et al. 2014; Rahman et al. 2011). Instead of the commonly used random mesh, structured mesh is defined for all layers of the pavement structure, so that the tire contact area can be controlled while sweep mesh is used for the tree root.

2.3 *Boundary condition, loading and contact modeling*

Under boundary and loading conditions, the models are all subjected to the static load in a linear perturbation analysis and the models are restrained in horizontal directions (i.e. degree of freedoms 1 and 3) with the subgrade base in all directions. Furthermore, the loading contact area is assumed to be rectangular (61575 mm²), with a wheel pressure of 0.67 MPa (Rahman et al. 2011). Tie constraints are assumed as the interaction between the interfaces of the layers (i.e. layers are fully bounded with no friction) for the control model, while embedded constraints are used for interactions between tree-root and pavement layers.

3 RESULTS AND DISCUSSION

3.1 *Control model*

The results for the control model are presented in Figures 2 and 3, and these results are found to be of close match with those obtained by Rahman et al. (2011). From these figures, the strains and displacements in pavement layers are presented. Figure 3 shows that the compressive displacements generated in pavement layers by wheel loads decrease down the depth, and Figure 2 shows the increase in compressive strain through the layers. This is as a result of the arrangement of the layer with the highest load bearing capacity material (Asphalt) on the top and the lowest load bearing capacity material at the bottom.

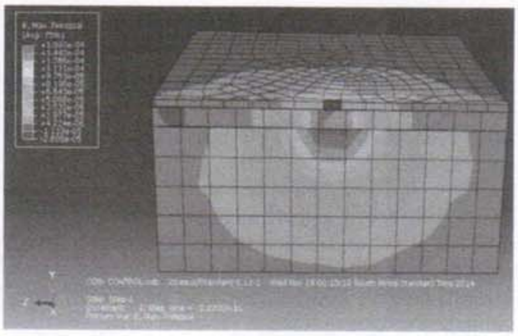

Figure 2. Strain distribution for the control model.

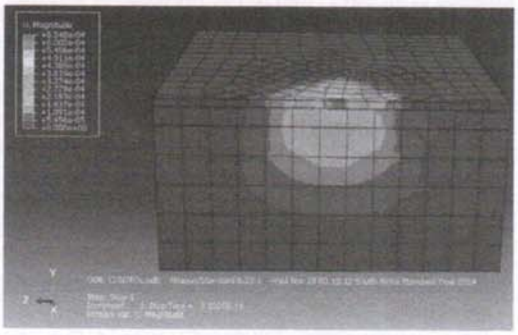

Figure 3. Deflection distribution for the control model.

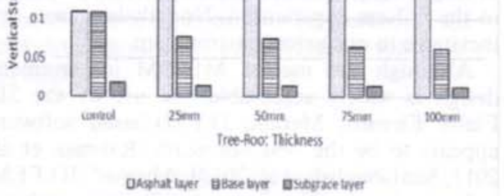

Figure 4. Stress redistribution for tree roots under the asphalt layer.

3.2 *Models with tree roots between the layers*

The results of these models, compared with the control model, are shown in Figures 4–9. Figures 4–6 show comparative graphs of the presence of tree roots underneath the asphalt (scenario 1), which show a decrease in vertical deflection (rutting) and strain in pavement layers; however, it was further observed to have increased the vertical stress in the asphalt layer that results in crack generation, while those of base and subgrade decrease. This implies that the stress that needs to be distributed downward the layers of the pavement is obstructed. Furthermore, Figures 7–9 show comparative graphs for stresses, strains and deflections by 100 mm-thick tree roots. The presence of tree roots underneath the base layer (scenario 2) shows a redistribution of stress and strain, as the vertical stress in the asphalt layer increases with the thickness of the tree root and the vertical strain increases in the subgrade layer, while the deflection decreases as in scenario 1. In scenario 3, the vertical stress and strain in the subgrade increases with little or no change in the other layers and the deflection still decreases. These results show that the presence of tree roots in the subgrade results in crack formation in the asphalt layer as the stress and strain are redistributed. Overall, in all scenarios, it was observed that the presence of tree roots in any pavement layer

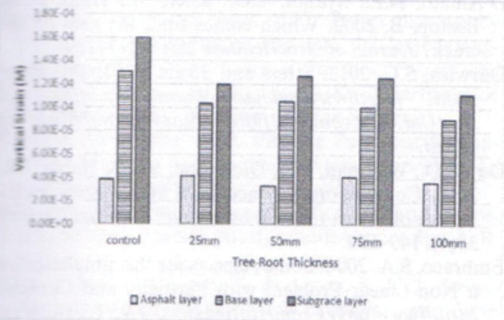

Figure 5. Strain redistribution for tree roots under the asphalt layer.

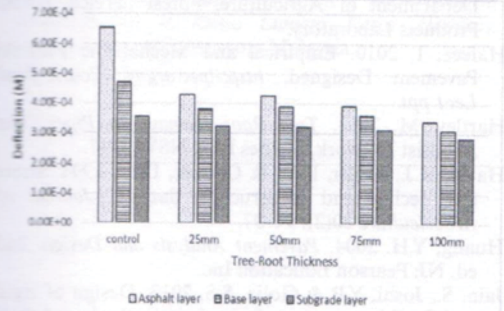

Figure 6. Deflection redistribution for tree roots under the asphalt layer.

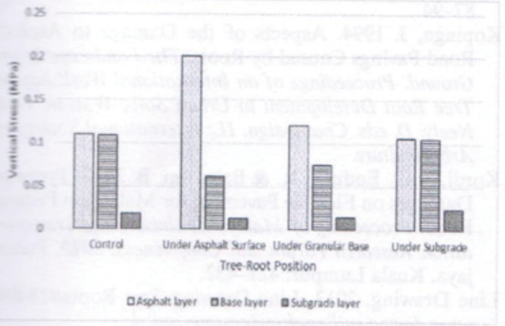

Figure 7. Stress redistribution for 100 mm tree roots.

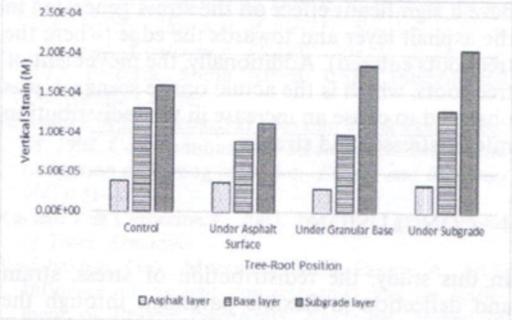

Figure 8. Strain redistribution for 100 mm tree roots.

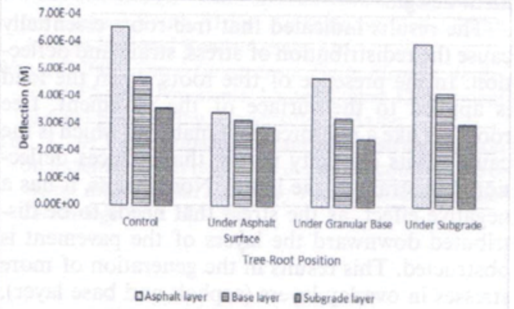

Figure 9. Deflection redistribution for 100 mm tree roots.

have a significant effect on the stress generated in the asphalt layer and towards the edge (where the tree roots entered). Additionally, the movement of tree roots, which is the actual onsite scenario, was observed to cause an increase in the redistribution rate of stresses and strains.

4 CONCLUSION

In this study, the redistribution of stress, strain and deflection in flexible pavement through the tree-root impact is presented. A 3D FEM Abaqus® Software was used to analyze and understand the interaction between pavement layers and tree roots, and the results in terms of failures in pavement design.

The results indicated that tree roots essentially cause the redistribution of stress, strain and deflection. In the presence of tree roots, when the load is applied to the surface of the pavement, tree roots act like a reinforcement material, which is the cause of its elasticity nature that reduces deflection and strain in the layers. Nonetheless, it has a negative effect, as the stress that needs to be distributed downward the layers of the pavement is obstructed. This results in the generation of more stresses in overlay layers (asphalt and base layer), which later results in cracks. If these cracks are not maintained on time, it can lead to other failures such as surface lifting, potholes and raveling in the pavement structure.

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