

# THREE-DIMENSIONAL FINITE ELEMENT MODELING OF PERVIOUS CONCRETE PAVEMENT: VERTICAL POROSITY DISTRIBUTION APPROACH

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## Abstract

Pervious concrete has the unique characteristic of allowing water to pass through its porous matrix. Pervious concrete pavement systems usually have three main layers, pervious concrete on the top, a subbase layer of aggregate for water storage in the middle and the subgrade (soil) layer below. Finite element modeling of this novel material is challenging due to its complex porous characteristics. In this paper, a method has been proposed to model pervious concrete pavement using finite element methods, which includes a modified approach to capture the unique vertical porosity distribution in the pervious concrete layer by averaging the distribution in three distinct vertical sections. The mechanical properties of the pervious concrete layer are assumed to vary along its depth since the porosity of the pervious concrete also varies with depth. ABAQUS, a general-purpose finite element software package was used to develop the model and perform the analysis. The model was validated through a convergence study, and in comparison with the analytical theory of tensile stress and deflection for traditional concrete pavement. In addition, the significance of the porosity distribution model was validated by comparing the results from EverFE – a specific software for pavement structure analysis. It was found that there is significant difference in tensile stress if modeled using the modified vertical porosity distribution in the pervious concrete layer to more fully capture its vertical porosity distribution, as compared to an averaged porosity model in the pervious concrete layer. It was also noted that compressive stress demand may have increased importance for pervious concrete, but only for highly porous applications which are not commonly used.

**Keywords:** pervious concrete, vertical porosity, finite element, critical loading, stress, deflection

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## 1. INTRODUCTION

Pervious concrete is a cementitious material that is gaining popularity and acceptance in the construction industry due to its contribution to sustainable designs. It is regarded as one of the stormwater best management practices with low impact design attributes, and its use has numerous environmental benefits including improved water quality, better maintenance of water levels, and improved land utilization [1, 2]. Other benefits include reduced hydroplaning and glare, and reduced road noise compared to traditional pavements [3, 4].

Pervious concrete was first reported to be used in the residential walls in Europe in 1852 [2]. In the U.S., pervious concrete is generally used in residential streets, driveways and paths, sidewalks, and parking lots for stormwater management [5]. It has also been used in low volume highway applications in Minnesota and in Europe, Australia, and Japan [5, 6]. One reason for its limited use is the ambiguity in characterizing the strength and performance of pervious concrete [7]. While these characteristics can be evaluated by experimental study of field applications, another approach for evaluating the stress

and deflection demand in pervious concrete pavement is the application of finite element (FE) methods. The FE method includes modeling and analysis through discretization of field problems, and it has advantages over most other numerical analysis methods because of its physical appeal and versatility [8]. A finite element model simulates the stress and deformation behavior of a structure or structural member for variable geometry, boundary conditions, material properties and intensity of loading. Thus, a structure can be modeled and analyzed for preliminary performance evaluation prior to building or constructing an actual prototype.

Different FE modeling techniques have been considered for rigid and flexible pavements. For example, while investigating the response of rigid concrete pavement to static loading and various environmental conditions, thin interface elements were used to model the behavior of the top layer of the soil under the slab, and concrete joints were represented by interface elements [9]. In another study, the rigid pavement structure was modeled with multi-layer elastic materials and linear elastic joint behavior was assumed along the length of the joint in the connected slabs [10]. For flexible pavements,

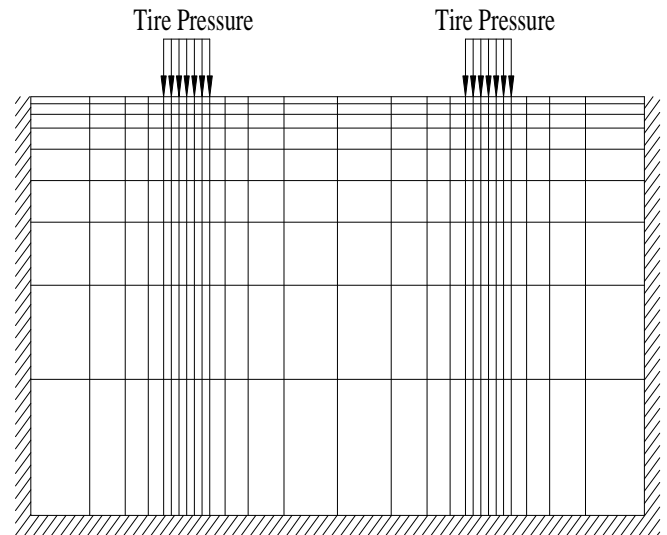
models have included a three layer pavement system (i.e. asphalt concrete layer, base layer, and subbase layer) with linear elastic, nonlinear elastic, and viscoelastic materials [11] and a pavement system with semi-infinite solid material to obtain guidelines for model size and mesh fineness [12]. To develop a three-dimensional (3-D) FE based pavement design procedure for airport rigid pavements, two types of foundations were considered to represent the infinite depth in the subgrade layer [13]. One approach for modeling the subgrade layer was by using a Winkler foundation consisting of discrete springs at the nodal points beneath the subgrade layer, while the other approach was to consider a linear elastic foundation with given modulus of elasticity and Poisson's ratio.

While traditional rigid or flexible pavement has a complex structure, pervious concrete has additional complexity due to its porous matrix, which varies with depth, and its unique properties in the subbase and subgrade. Pervious concrete pavement systems usually have three main layers, pervious concrete on the top, a subbase layer of aggregate for water storage in the middle and the subgrade (soil) layer below, which usually has less compaction for improved infiltration than under traditional pavement systems. Microstructures in the pervious concrete layer have been modeled using a 3-D reconstruction algorithm to determine the linkages between microstructure, percolation, and permeability properties [14]. However, modeling and analysis of this novel material using FE methods to evaluate the structural performance has been limited and there needs to be further validation for defining a modeling procedure [15]. The objective of the work of this paper was to develop a 3-D FE modeling procedure to evaluate the stresses and displacements in pervious concrete pavement systems. The modeling procedure included defining a modified vertical porosity distribution in pervious concrete [16], from which elastic material properties were obtained from the investigation of pervious concrete samples from other studies [17]. The analysis results were then to be validated through convergence theory for FE formulations, and also compared with classical analytical theory for traditional rigid concrete pavement. This convergence theory states that FE formulations converge toward exact mathematical solutions with mesh refinement [8]. The analytical theory for traditional rigid concrete pavement is based on a plate on an elastic foundation and modeled for edge, center and corner loading. It states that the maximum flexural stress will be obtained for wheels positioned at the edge of the pavement, and that wheels positioned at the corner of the pavement will provide maximum displacement [18].

**2. FE FORMULATION OF PAVEMENT SYSTEMS**

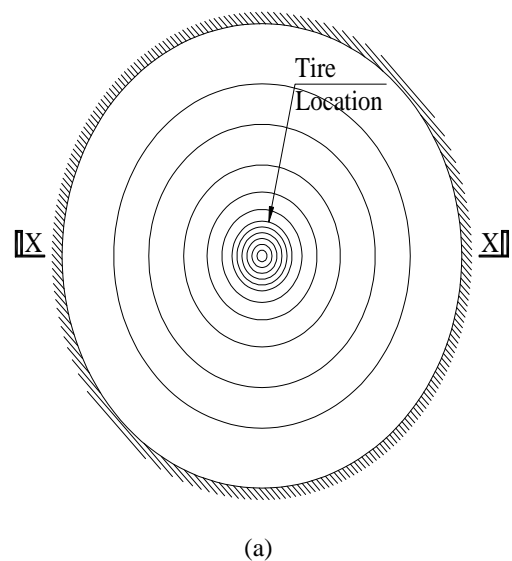
The FE formulation methods for modeling pavement systems are divided into three categories: plane strain, axisymmetric, and 3-D [19 – 23]. Plane strain models (Fig-1) use 2-D formulations and they are often chosen by analysts to model

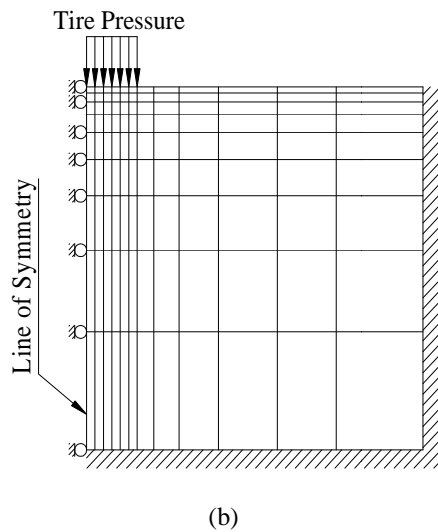
pavement since they require minimal computer memory and relatively short computational time [19, 20]. However, plane strain modeling has the limitation of being unable to simulate the traffic load accurately [24].



**Fig-1: Plane strain model of the pavement**

The axisymmetric modeling (Fig-2) approach takes slightly more computational time compared to the plane strain modeling approach. This approach has the advantage of modeling an actual 3-D pavement in cylindrical coordinates, and constant material properties are assumed in the horizontal planes. The limitations of this model include improper simplified representation of traffic loading since only a single circular load can be modeled, and the inability to include pavement discontinuities and the shoulder.

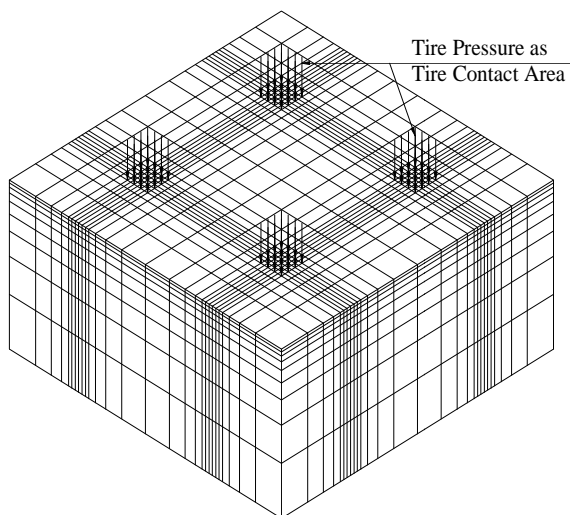




**Fig-2:** (a) Top view of axisymmetric model of a pavement, (b) Section X-X of the pavement for FE formulation

A 3-D formulation (Fig-3) is the most computationally demanding and labor intensive way to model the pavement system or any other type of structural system. This approach can represent the pavement configuration accurately and can include different loading patterns and types, pavement discontinuity, and the shoulder in the pavement.

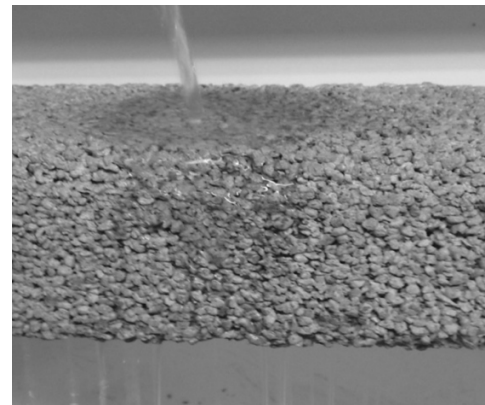
In this paper, a 3-D FE formulation has been applied to model a pervious concrete pavement system to more accurately represent the pavement configuration and different loading patterns for critical wheel positions at the edge, center, and corner of the pavement.



**Fig-3:** 3-D model of pavement

### 3. CHARACTERISTICS OF PERVIOUS CONCRETE

The defining material characteristics of pervious concrete (Fig-4) are unit weight, tensile and compressive strength, moduli of elasticity, porosity, infiltration rate, and hydraulic conductivity. It has been found that unit weight, strength, elasticity, infiltration rate, hydraulic conductivity, and structural performance of pervious concrete are all functions of its porosity [5, 25 – 32]. The porosity varies with many variables such as compactive effort and water to cement ratio in the concrete mix design. Although the infiltration rate and hydraulic conductivity increase with increased porosity [5, 29, 31], unit weight, flexural and compressive strength, and moduli of elasticity tend to decrease with increased porosity [5, 26 – 29, 32]. Thus, porosity may be used as the governing characteristic of pervious concrete, from which most other properties may be defined.



**Fig-4:** Pervious Concrete

In relating the material properties of pervious concrete with its porosity, it is often assumed that porosity is constant everywhere in the cross section. However, it has been reported that the porosity in a pervious concrete layer cross section varies from top to bottom along its depth with the lowest porosities on the top due to surface compaction [16]. A series of expressions have been developed to simulate the porosity in pervious concrete along its depth for varying levels of compactive effort. To simplify the analyses, instead of defining the porosity distribution continuously in terms of depth, the pervious concrete slab was divided into three vertical sections i.e. the top quarter, the middle half, and the bottom quarter, and it was assumed that the porosity in each vertical section remains constant. Two sets of expressions were developed for each of these vertical sections to determine their porosities: one set uses percent volumetric compaction while the other set represents the solution for the common range of volumetric compaction between 9 to 10%.

#### 4. ASSUMPTIONS IN MODELING PERVIOUS CONCRETE

Pervious concrete pavement systems usually have three or more different material layers, including the concrete top layer, an aggregate subbase layer, and the soil subgrade below. In modeling pervious concrete pavement systems using FE methods, the pervious concrete layer at the top of the pavement was represented by three vertical sections through the depth as defined by the averaged vertical porosity distribution, and each of those sections were considered to be composed of linearly elastic material. The subbase (aggregate/gravel) layer and subgrade (soil) layer were also considered as linearly elastic. Additional assumptions that have been considered in modeling the pervious concrete pavement system are listed below:

- The modulus of elasticity of pervious concrete is a function of the porosity, and the porosity varies as the top quarter, the middle half, and the bottom quarter along the depth of the pervious concrete layer.
- The Poisson's ratio is constant along the depth of the pervious concrete cross section.
- The porosity distribution is constant in the longitudinal and transverse directions of the pavement. Thus, the modulus of elasticity and Poisson's ratio are the same in all of the material directions for each layer considered.
- Westergaard's assumption that the slab is perfectly bonded with the subbase as well as that the subbase is perfectly bonded with the subgrade has been applied (Huang 2004).

#### 5. FE FORMULATION OF PERVIOUS PAVEMENT SYSTEMS

The ABAQUS general purpose finite element software package was used to model and analyze the pervious pavement systems. In this research, a linear analysis of a section of the pervious pavement system was performed for static loading conditions.

##### 5.1 Pervious Pavement Configuration

As previously noted, a pervious pavement system usually consists of a pervious concrete layer, a gravel subbase layer, and a natural soil subgrade layer (Fig-5). The subbase layer in a pervious concrete pavement system serves to enhance the structural performance of the pavement system in addition to its use for stormwater storage.

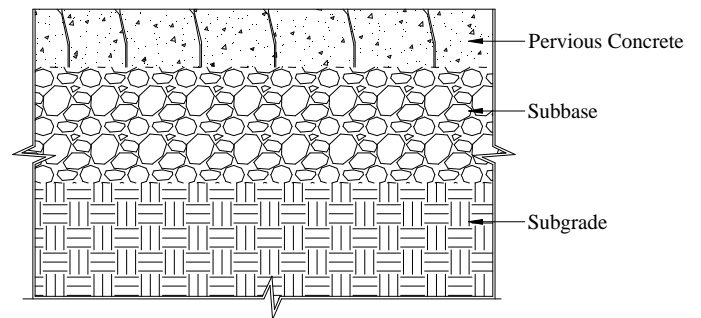
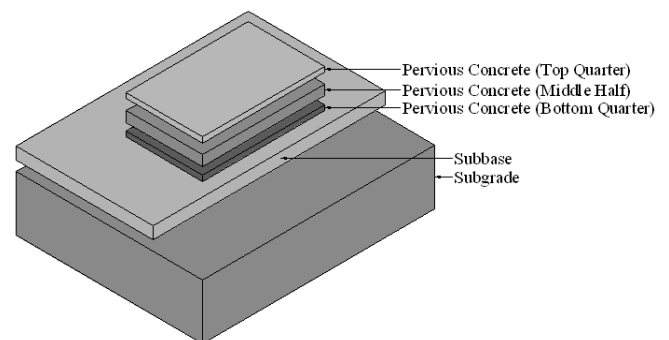
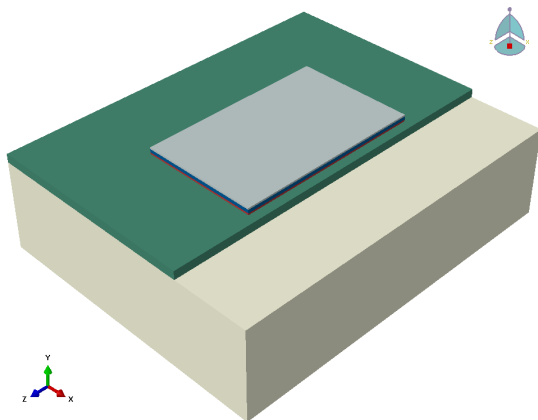


Fig – 5: Typical Pervious concrete pavement system

Typically, in a pervious concrete pavement system, the depth of the subbase layer is comparatively higher than the subbase depth used for traditional concrete pavement systems. Although the panels in the pervious pavement system are commonly jointed together at the bottom one-third along the depth of the pavement in the longitudinal direction, they are not commonly jointed together in the transverse direction. In this research an isolated pervious pavement panel was modeled which represents a single lane of a highway/street (not jointed in the transverse direction), but also not jointed in the longitudinal direction as a simplification. The panel dimension was 6.0 m in the direction of traffic and 3.66 m in the transverse direction, and it had a total depth of 200 mm divided into three layers: the top quarter (50 mm), the middle half (100 mm), and the bottom quarter (50 mm). The subbase layer had a depth of 250 mm and it was extended 300 mm beyond the outside edge of the pavement to mimic an actual pavement configuration (Fig-6).



(a)



(b)

**Fig-6:** (a) Layer by layer representation of pervious pavement system for FE formulation, (b) 3-D view of the pavement model from ADINA

## 5.2 Material Properties

The essential material properties for linear elastic materials within the FE method are the modulus of elasticity and Poisson’s ratio. As stated in the assumption, the modulus of elasticity for pervious concrete may be expressed as a function of porosity where the porosity varies along the depth of the pervious concrete layer cross section [16]. The relationship between the modulus of elasticity and the porosity was obtained from previous experimental investigations of samples prepared in the laboratory [17]. Subbase and subgrade material properties were obtained from previous studies [33 – 38].

### 5.2.1 Pervious Concrete

In the previous study, pervious concrete samples were extracted from a field placement and specimens were prepared in the laboratory to evaluate their structural performance [17]. Unit weight, compressive strength, porosity and exfiltration rate were determined for the core extracted samples while, for laboratory prepared samples, unit weight, compressive strength, modulus of elasticity, Poisson’s ratio, porosity and exfiltration rate were determined. For the pervious pavement field placement, undisclosed admixtures were used to strengthen the pervious concrete. For this reason, in the FE formulation, the moduli of elasticity of the laboratory prepared samples were used.

The relationships between the compressive strength and the porosity and between the modulus of elasticity and the compressive strength for the laboratory prepared samples may be expressed by Eqs. (1, 2), respectively [17]:

$$f'_c = 43.8 - 114P \quad (1)$$

$$E = 50.6 \times 10^{-6} w_{pc}^{1.5} \sqrt{f'_c} \quad (2)$$

Where  $f'_c$  is the compressive strength in MPa,  $P$  is the porosity in percent,  $E$  is the modulus of elasticity in GPa, and  $w_{pc}$  is the unit weight of pervious concrete in kg/m<sup>3</sup>.

Eqs. (3, 4, 5), respectively [16], express the porosity in the top quarter, middle half, and bottom quarter of a pervious concrete layer. It should be noted that the percent compaction values used in deriving these porosity distribution equations were between 9 and 10%.

$$P_{top} = 1.07P_{mean} - 7 \quad (3)$$

$$P_{mid} = P_{mean} \quad (4)$$

$$P_{bottom} = 0.93P_{mean} + 7 \quad (5)$$

Where  $P_{mean}$  is the average porosity of the pervious concrete layer in percent and  $P_{top}$ ,  $P_{mid}$ , and  $P_{bottom}$  are the percent porosity values at the top quarter, middle half, and bottom quarter, respectively.

Thus, if the average porosity of a pervious concrete layer is known, then the corresponding porosity at the top quarter, middle half, and bottom quarter of that layer can be determined through Equations 3, 4, and 5. For these porosity values, compressive strength and the corresponding moduli of elasticity in the three vertical sections of the pervious concrete layer can be evaluated from Equations 1 and 2 for a known unit weight of pervious concrete.

The average unit weight of the pervious concrete samples considered in the previous laboratory experiments was 1858 kg/m<sup>3</sup> and the mean porosity was 27% [17]. The unit weight and porosity of pervious concrete have also been reported to be between 1570 kg/m<sup>3</sup> and 1938 kg/m<sup>3</sup> and between 10% to 29%, respectively [25]. To determine the modulus of elasticity for the FE formulation, the unit weight and average porosity considered were 1850 kg/m<sup>3</sup> and 25%, respectively. In the FE formulation of pervious concrete, the Poisson’s ratio was kept constant in all three sections through the depth. The mechanical properties of pervious concrete that were considered in the FE formulation are listed in Table-1.

**Table-1:** Mechanical properties of pervious concrete for FE formulation

Unit Weight	1850 kg/m <sup>3</sup>	
Mean Porosity	25%	
Modulus of Elasticity	Top Quarter	18.55 GPa
	Middle Half	15.70 GPa
	Bottom Quarter	12.97 GPa
Poisson's ratio	0.22	

**5.2.2 Subbase and Subgrade**

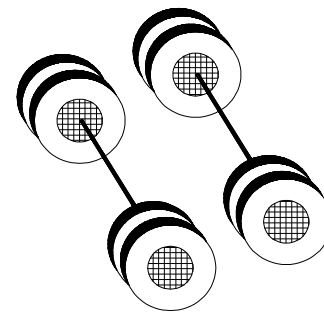
The modulus of elasticity of the subbase, typically composed of unbounded aggregate, depends on the type of aggregate [35] and, for the subgrade or soil; the dominating factor affecting the modulus of elasticity is the effective stress, which is a function of the water level in the soil layer [33]. In analyzing pavement, the modulus of elasticity of the subbase layer has been reported to range from 96 MPa to 500 MPa, and for the subgrade layer, the modulus of elasticity has varied between 24 MPa and 100 MPa [34, 36 – 38]. While the Poisson's ratio of the subbase was reported to have a constant value of 0.35 for all analyses [34, 36 – 38], the Poisson's ratio of the subgrade was reported to vary from 0.35 ~ 0.45. The properties of the subbase and subgrade materials considered in the FE analysis of pervious concrete pavement are given in Table-2. Average values were chosen for the aggregate subbase and conservatively low values for clayey soils were chosen for the subgrade.

**Table-2:** Mechanical properties of subbase and subgrade

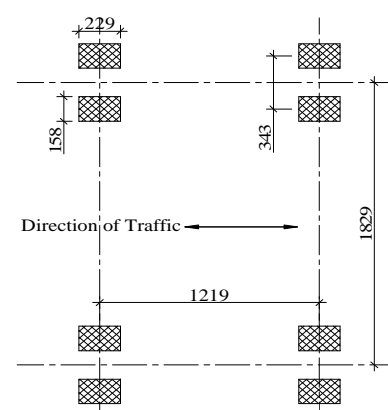
	Subbase	Subgrade
Unit Weight (kg/m <sup>3</sup> )	1800	1800
Modulus of Elasticity (MPa)	400	50
Poisson's ratio	0.35	0.40

**5.3 Loading on the Pavement**

The applied tire pressure on the pavement represents an equivalent 160-kN tandem axle load and the tire type corresponds to dual wheel tires (Fig-7a). Tire pressure with an equivalent 160-kN single axle load is a widely accepted approach to represent different axle load groups and to calculate load repetitions in pavement [18]. A standard semitrailer wheel configuration (Fig-7b) for tandem axle dual wheel tires was used to represent the tire pressure on the pavement.



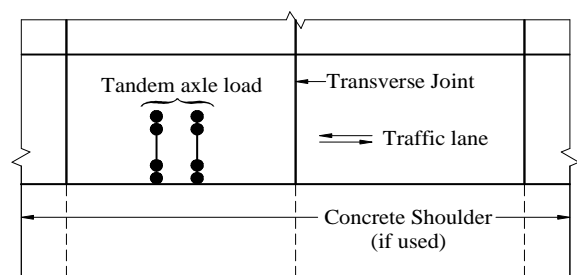
(a)



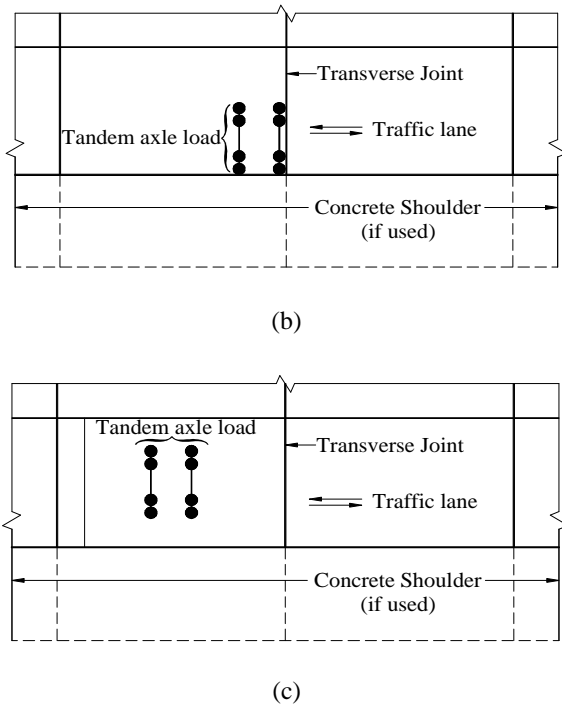
(b)

**Fig-7:** a) Tandem axle dual wheel tire, b) Wheel configuration

Whether from closed-form formulas, influence charts, or finite element methods, it was found that, for traditional concrete pavement, the critical location of the wheel for flexure is at the edge of the pavement (Fig-8a) and the critical location of the wheel for deflection is at the corner of the pavement (Fig-8b). The pervious concrete pavement in this study was analyzed for these wheel positions to validate the FE model. In addition, wheel placement at the center of the pavement was considered to identify any unique mechanistic response (i.e. tensile stress, compressive stress, or deflection) of pervious concrete that might occur for this loading condition.



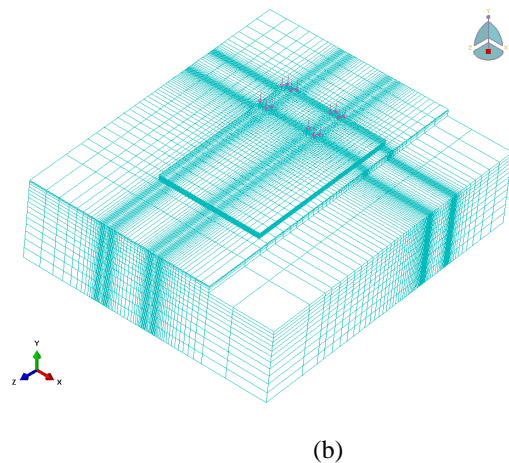
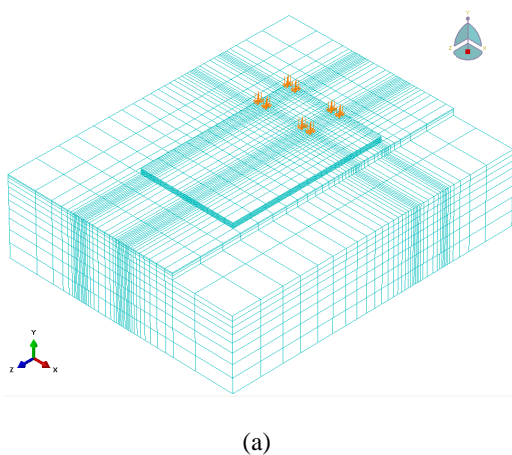
(a)



**Fig-8:** Wheel position at a) Edge, b) Corner, and c) Center of the pavement

**6. FE ANALYSIS**

3-D models of the pervious concrete pavement representing the coarsest and finest meshes used are shown in Fig-9 for wheels positioned at the edge of the pavement. The meshing pattern, which includes finer meshes in and around the tire location and coarser meshes away from the tire contact area, was selected for a uniform distribution of tire pressure in the pavement around the tire contact area and to reduce computational time.



**Fig-9:** Pervious pavement system with (a) Coarsest meshing and (b) Finest meshing

In the ABAQUS element library, there are a number of solid or continuum elements that can be used for linear 3-D FE analysis. The solid element library includes both first order (linear interpolation) and second order (quadratic interpolation) elements. Second order elements require higher memory storage and computation time, thus first order linear interpolation brick elements (8-node) were used in this study. In addition, the elements were enhanced by using incompatible modes to improve their bending behavior since for rectangular shape elements the incompatible mode elements perform similar to the second-order elements. The incompatible mode adds additional internal degrees of freedom and is significantly more economical than the second-order elements.

The FE modeling of the subgrade in the pavement system is important due to its infiniteness and it is also important to apply appropriate boundary condition. A dense liquid foundation or an elastic solid foundation are usually used to model the subgrade. However, a dense liquid foundation hinders the use of contact or friction between the layers [39] and thus, was not chosen for the analysis. To model the subgrade as an elastic solid foundation, the layers of the brick element should have to be extended to a depth at which the mechanistic response of the pavement system is negligible compared to the previous depth. A parametric study was performed to determine the depth for an elastic solid foundation and it was found that at a depth of 2.7 m the mechanistic response of the pavement system is almost identical to the previous analyzed depth at 2.4 m. To mimic the infiniteness of the subgrade layer in the horizontal direction, it was extended to 2.7 m in longitudinal and transverse direction of the pavement system.

### 6.1 Convergence Study for the Pervious Pavement

#### Model

A convergence study was performed for the case of the wheel position at the corner of the pavement system. The maximum tensile stress, compressive stress, and deflection values are plotted against the number of elements in Fig 10. The plot shows that the stresses and deflection in the pavement system increase with an increase in the number of elements in the model. While the deflection and compressive stress converged for the same number of elements in the pavement system, tensile stress required much finer mesh to reach the convergence.

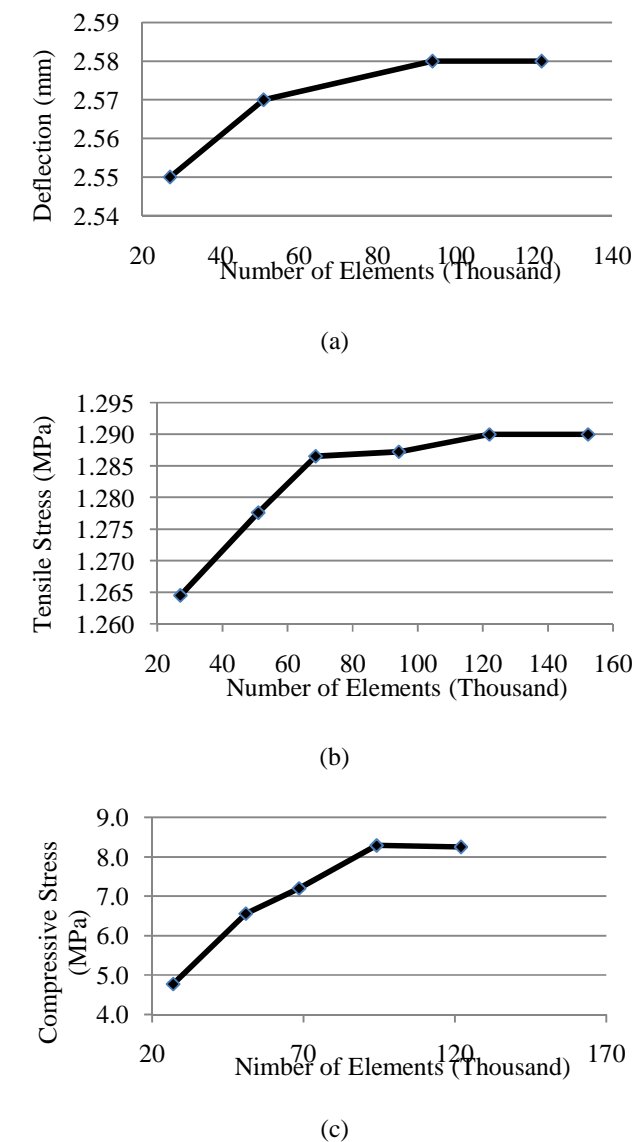
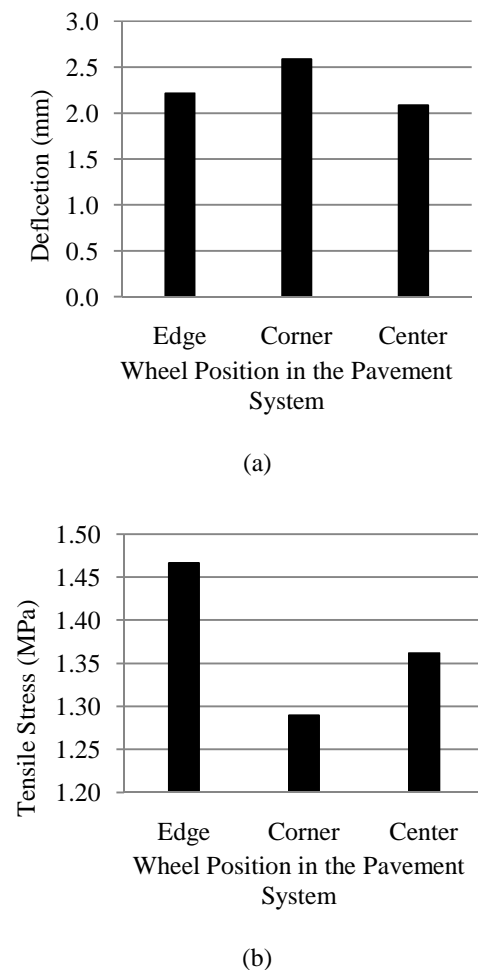
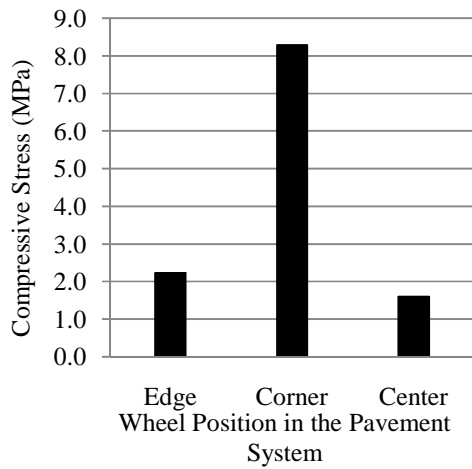


Fig – 10: Convergence of a) Deflection, b) Tensile stress, and c) Compressive stress for different mesh size in the pavement system

### 6.2 Evaluation of Stress and Deflection

To evaluate the stress and deflection in the pervious concrete pavement system, the loading conditions considered were wheels at the edge, corner, and center of the pavement. The finest meshing criterion from the convergence study was adopted to mesh the pavement system for edge and center loading on the slab. Bar charts have been used in the previous studies to compare stresses and deflection in the pavement [15] and the maximum tensile stress, compressive stress, and deflection obtained for the three loading conditions have been similarly plotted (Fig-11) to determine the critical loading conditions for tensile and compressive stress, and for deflection in the pervious concrete pavement. From Fig 11, the wheel position at the corner of the pavement is shown to yield the maximum deflection as well as the maximum compressive stress in the pavement system. The maximum tensile stress in the pavement system was obtained for edge loading. Thus, the critical loading conditions for pervious concrete pavement system is the same as the analytical theory of traditional concrete pavement with maximum tensile stress for edge loading and with maximum deflection for corner loading.





(c)

**Fig – 11:** Comparison of maximum a) Deflection, b) Tensile stress, and c) Compressive stress for different loading condition in the pavement system

While tensile stress is assumed to be responsible for the initiation of cracks in traditional concrete pavements [40], compressive stress in the pavement is typically not monitored in the published literature [18, 40]. The relatively high compressive stress in the pervious concrete reflects its porous matrix and it occurs for the wheel positioned at the corner of the pavement. The higher compressive stress for corner loading could be attributed to the confinement of tire pressure at the corner of the pavement due to corner position of wheels whereas for edge loading, the tire pressure can be distributed on both sides of the wheel position. However, the compressive stresses found are still much lower than the typical compressive strengths of most pervious concrete mixes.

### 6.3 Evaluation of Stresses for a Rigid Pavement

#### Model using EverFE

The significance of using the vertical porosity distribution approach to capture the unique porosity distribution in the pervious concrete pavement system by dividing the surface into three layers with three different moduli of elasticity has been validated here by analyzing the pervious concrete pavement system using a conventional pavement analysis software named EverFE with only one modulus of elasticity value in the pervious concrete layer [40]. EverFE is a 3-D FE analysis tool to simulate the mechanistic response of pavement system for different axle loads and environmental effects. In EverFE, four layers can be defined with only one layer in the surface. In the EverFE analysis, the modulus of elasticity and Poisson’s ratio of the surface layer was given the same values as the middle layer in the vertical porosity distribution

approach, representing a simpler average modulus of elasticity approach.

The critical stresses and deflections from this more simplified approach are listed in Table-3, in addition to the vertical porosity distribution model previously discussed with varying characteristics in the pervious concrete layer. In Table-3, the maximum deflection and compressive stress were for corner loading, and the maximum tensile stress was for edge loading in the simpler model, as was also found previously in the modified vertical porosity distribution model. It can be seen that the simpler average modulus of elasticity approach gives much higher tensile stress compared to the modeling approach which captures the vertical porosity distribution, which eventually will lead to a more conservative design. Apart from the average modulus of elasticity and three vertical section approach, the over prediction of tensile stress could be due to the incapability of EverFE to consider a widened subgrade layer in the longitudinal and transverse direction of the pavement system.

**Table-3:** Comparison of the modified vertical porosity versus average porosity in the pervious concrete layer modeling approaches

	Modified Vertical Porosity Approach	EverFE Analysis	% Difference
Deflection (mm)	2.59	--	--
Tensile Stress (MPa)	1.47	2.28	55.1
Compressive Stress (MPa)	8.29	2.48	233.3

### CONCLUSIONS

A 3-D FE model of pervious concrete pavement was analyzed incorporating a modified vertical porosity distribution in the pervious concrete to simulate the effect of its porous matrix. The validation criteria were convergence theory and the analytical theory of stresses and deflection of traditional concrete pavement. The model was also compared with a simplified average porosity modeling approach in a traditional pavement analysis software. The pervious pavement model with the modified vertical porosity distribution showed consistent convergence with mesh refinement. In comparison with the analytical theory for traditional concrete pavement, it was found that the behavior of pervious concrete pavement dictates that the compressive stress demand in pervious concrete pavement may be critical under conditions with very high porosities, but these conditions are typically not found in current practice. While tensile stress demand is higher for edge loading compared to, corner loading, compressive stress demand is clearly highest for corner loading. A significant finding is that the three vertical section modeling approach

approximating the vertical porosity distribution in pervious concrete has significantly less critical tensile stress and higher compressive stress compared to the simplified average pervious concrete layer modeling approach.

Limitations of the proposed FE modeling technique include the assumption of perfect bonding between the pervious concrete and subbase, and subbase and subgrade. Further mesh refinement is also needed for the true convergence of deflections and stresses. The modeling procedure presented here is for macro-scale modeling of pervious concrete pavement systems, and does not consider the effect of random zero porosity phase inside the pervious concrete. In the case of pervious concrete, there may be potential stress concentration at a paste-aggregate or a paste-aggregate-pore interface. Such modeling requires micro-scale modeling and was not considered in the full-scale modeling of a pervious concrete pavement systems presented here.

Future studies may include other types of tire configurations (i.e. single axle and tridem axle), cyclic loading, consideration of nonlinear elements in the pavement system, and inclusion of the friction coefficient between the pervious concrete and subbase, and subbase and subgrade. To imitate the more random porous matrix of the pervious concrete layer, meso-scale modeling could be used. Despite these limitations, it can be concluded that this newly developed modified vertical porosity distribution approach for simulating the pervious concrete layer in a pervious concrete system will facilitate pervious concrete research using FE formulation to study the numerous structural and environment effects on this novel material. This might be the basis for future dynamic and nonlinear analysis of pervious concrete pavement systems.

## ACKNOWLEDGEMENTS

The authors gratefully acknowledge the financial support from Transportation Northwest. The authors also appreciate the assistance from Evolution Paving and Will Goede in evaluating the performance of pervious concrete.

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