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Mechanistic Analysis of Geogrid Base Reinforcement in Flexible Pavements Considering Unbound Aggregate Quality

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Abstract

The structural response and performance of a flexible pavement can be improved through the use of geogrids as base course reinforcement. Current ongoing research at the University of Illinois has focused on the development of a geogrid base reinforcement mechanistic model for the analysis of reinforced pavements. This model is based on the finite element methodology and considers not only the nonlinear stress-dependent pavement foundation but also the isotropic and anisotropic behavior of base/subbase aggregates for predicting pavement critical responses. An axisymmetric finite element model was developed to employ a three-noded axisymmetric membrane element for modeling geogrid reinforcement. The soil/aggregate-geogrid interface was modeled by the three-noded membrane element and the neighboring six-noded no thickness interface elements. To validate the developed mechanistic model, the commercial finite element program ABAQUS™ was used to generate pavement responses as analysis results for simple cases with similar linear elastic material input properties. More sophisticated cases were then analyzed using the mechanistic model considering the nonlinear and anisotropic modulus property inputs in the base/subbase granular layers. This paper will describe the details of the developed mechanistic model and the effectiveness of geogrid reinforcement when used in different quality unbound aggregate base/subbase layers.

INTRODUCTION

Geogrid reinforcement appears to have the greatest potential for a successful and beneficial application in low to moderate volume roads having thin asphalt surfaces and substantially thick unbound granular layers. These benefits are often realized by extending pavement life or by reducing base course thickness with enhanced structural performance. Absence of suitable mechanistic based pavement design methodologies, however, limits the use of geosynthetic reinforcement in roadways and airfield pavements.

In the last decade, there has been a significant move towards adopting mechanistic based pavement design processes and procedures that relate pavement structural response variables, such as stresses, strains and deflections (σ, ε, Δ) produced by wheel loads, to the development of specific types of pavement distress such as cracking and rutting (e.g., the 2002 Pavement Design Guide developed for AASHTO adoption in the US). The general components of a mechanistic-empirical (M-E) design procedure are as follows: (1) a pavement

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structural model to calculate as accurately as possible the critical pavement responses (σ, ϵ, Δ) and (2) transfer functions or pavement distress models to translate those responses into measures of pavement performance. The design process then entails iteratively adjusting the pavement structure until the desired level of performance and reliability are achieved.

A finite element (FE) model of the pavement layered structure no doubt provides the most modern technology and the state-of-the-art sophisticated characterization of the pavement materials that can easily accommodate in the analysis nonlinear, stress dependent and often anisotropic pavement layer properties, irregular geometries, and geogrid base reinforcement. Such realistic geometries and advanced material characterizations accomplished through the use of FE solutions improve the ability to reliably predict pavement responses, which leads to a better design methodology.

This paper presents analytical findings obtained from an FE based structural model recently developed at the University of Illinois and used for the mechanistic analysis of geogrid reinforced flexible pavements. Finite element analysis results will be presented of nonlinear elastic layers with the assignment of isotropic or cross-anisotropic unbound aggregate properties. The impact of cross-anisotropy and stress dependency of the aggregate base stiffnesses on the computed pavement responses will be emphasized. Anisotropic modulus inputs for the unbound aggregate base layer will be shown to clearly establish differences among the different types and qualities of unbound aggregate materials, such as crushed stone and uncrushed gravel. This will in effect help to evaluate how geogrids can be more beneficial depending on the different aggregate materials and qualities used in the pavement construction.

PAVEMENT MATERIAL CHARACTERIZATION

Asphalt concrete and subgrade soil

In the pavement structure, both the top asphalt concrete (AC) layer and the subgrade soil are modeled as isotropic materials. The AC layer is modeled as linear elastic with only 2 elastic material constants, elastic or resilient modulus (M_R) and Poisson' s ratio (ν), used as inputs. For the subgrade layer, the nonlinear soil behavior is considered. The resilient modulus of fine-grained subgrade soils is dependent upon the stress state. Typically, soil modulus decreases in proportion to the increasing stress levels thus exhibiting stress-softening type behavior. The constitutive relationships are primarily established between the resilient modulus and the deviator stress for fine-grained subgrade soils. The bilinear or arithmetic model is the most commonly used resilient modulus model for subgrade soils [1]. The bilinear soil model used in the developed mechanistic model is expressed as follows:

$$M_R = K_1 + K_3 \times (K_2 - \sigma_d) \ when \ \sigma_d \le K_2 \quad (1)$$

$$M_R = K_1 - K_4 \times (\sigma_d - K_2) \ when \ \sigma_d \ge K_2 \quad (2)$$

where K_1, K_2, K_3, and K_4 are material constants obtained from repeated load triaxial tests and σ_d (= σ_1-σ_3) is the deviator stress. According to Thompson and Elliot [1], the value of the resilient modulus at the breakpoint in the bilinear curve, K_1, can be used to classify fine-grained soils as being soft, medium or stiff.

Unbound aggregate base

Resilient modulus models, such as the K-θ model by Hicks and Monismith [2], Uzan [3] model consider the effects of stress dependency for modeling the nonlinear behavior of base/subbase aggregates and are generally suitable for FE programming and practical design use. Especially, the Uzan model considers the effects of both confining and deviator stresses and therefore handles very well the modulus or stiffness increase with increasing vertical and horizontal stresses in an unbound aggregate layer. The Uzan [3] model is expressed as follows:

$$M_R = K_1(\theta / p_o)^{K_2}(\sigma_d / p_o)^{K_3} \quad (3)$$

where $\theta = \sigma_1 + \sigma_2 + \sigma_3 = \sigma_1 + 2\sigma_3$ = bulk stress, $\sigma_d = \sigma_1 - \sigma_3$ = deviator stress, p_0 is the unit pressure of 1 kPa, and K_1, K_2, and K_3 are multiple regression constants obtained from repeated load triaxial test data on granular materials.

Due to its simplicity and ease in material constant evaluation, the Uzan model is used in the developed mechanistic model as the nonlinear characterization model for granular materials. The unbound aggregate layers can be modeled either as isotropic with the assignment of M_R and ν or cross-anisotropic, which requires the following 5 material properties: horizontal modulus (M_R^h), vertical modulus (M_R^V), shear modulus (G_R), and in-plane (ν_h) and out-of-plane (ν_v) Poisson's ratios. An Uzan [3] type resilient modulus model can effectively be developed for all the three moduli in accordance with the cross-anisotropic characterization of pavement granular layers [4, 5].

Geogrid reinforcement

A three-noded axisymmetric membrane element is used in the FE mesh to model the geogrid reinforcement. The membrane elements are capable of resisting loads in tension but they have no resistance to bending. The membrane element, which is more of bar element in the axisymmetric plane, strain components are axial membrane strain and hoop strain meridional and circumferential directions. The axisymmetric membrane element was incorporated into the developed axisymmetric nonlinear FE program.

Soil/aggregate-geogrid interface

Conventional no-thickness interface elements have been used to model the soil/aggregate-geosynthetic interfaces [6-8]. In this study, a similar no thickness, 6-noded interface element was chosen to be compatible with the 3-noded membrane and 8-noded continuum elements. Figure 1 shows the 6-noded interface element, which considers shear and normal stiffnesses by the six springs connecting top and bottom nodes. The normal and shear spring coefficients, k_n and k_s, are in fact analogous and similar in units (kPa/m) to the modulus of subgrade reaction in the problem of a beam/slab resting on elastic foundation. The strain energy of a distributed uniform foundation modulus k is therefore equated to the strain energy of concentrated spring stiffness.

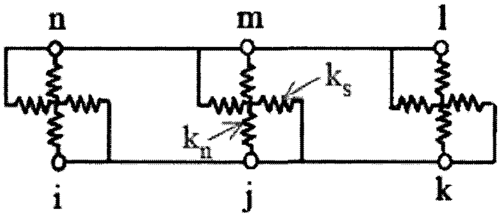

Figure 1. Six-noded no-thickness interface element detail

The linear elastic relation of the 6-noded interface element associating local stresses to relative local displacements can be expressed using shear stiffness, k_s, and normal stiffness, k_n, which depend on the applied normal stress σ_s and the roughness or friction properties of the interface [9]. Varying the shear stiffness of the interface element, one can specify various geosynthetic bonding conditions: perfect bonding; partial bonding; or no geosynthetic case for which shear strength of the corresponding aggregate layer or soil-aggregate interface is considered.

Importance of anisotropic modeling for predicting accurate pavement responses

The recent and ongoing research efforts at the International Center for Aggregates Research (ICAR) have focused on determining structural considerations of unbound aggregate pavement layers [10, 11]. The studies have mainly indicated that the unbound aggregate base material should be modeled as nonlinear and cross-anisotropic to account for stress sensitivity and the significant differences between vertical and horizontal moduli and Poisson's ratios. An anisotropic approach can adequately accommodate directional variation of granular material stiffnesses [12-14]. A special type of anisotropy, known as cross-anisotropy, is commonly observed in pavement granular materials due to stratification, compaction, and the applied wheel loading in the vertical direction. Laboratory and modeling studies to date also show that with anisotropic modeling a more realistic stress distribution can be achieved in unbound aggregate bases than can be developed when the aggregate base is considered to be linear and isotropic.

The recent research efforts by Kim et al. have focused on relating aggregate physical properties to the anisotropic resilient responses for unbound granular layers [15-16]. The studies also have indicated that the aggregate physical properties such as gradation, moisture content, and particle shape had influence on the elastic moduli of unbound base layers. Kim et al. proposed a simple procedure to account for the effects of aggregate properties to the cross-anisotropic modular ratio of unbound granular layers [15-16].

DEVELOPED MECHANISTIC RESPONSE MODEL

The geogrid-reinforced flexible pavements are modeled as axisymmetric solids consisting of either linear or nonlinear elastic layers to employ nonlinear resilient response models. Incremental loading is considered in the nonlinear analysis for a proper characterization of stress dependency and handling of residual compaction stresses.

A typical conventional flexible pavement studied consisted of a 76-mm thick AC layer and a 254-mm unbound aggregate base course. A uniform pressure of 828 kPa was considered to simulate an overloaded truck tire pavement loading applied over a circular area with a radius of 102 mm. The element types used and the material properties assigned in the developed FE model are given in Table 1.

The unbound aggregate base layer was modeled both isotropic, and cross-anisotropic. The Uzan model parameters used in the nonlinear isotropic and anisotropic unbound aggregate base models are given in Table 1. The unit pressure p_0 term was needed to make the K_1, K_2, and K_3 model parameters, assigned for the vertical, horizontal, and shear modulus models, to carry actual pressure units in kPa or MPa.

The geogrid modulus of 5516 MPa listed in Table 1 is typically greater than the typical values obtained from standard strength tests for geogrids. Since the mechanisms of soil/aggregate-geogrid interaction have not been clearly identified yet, such a high value of geogrid modulus was used to better show the experimentally observed benefits of geogrid reinforcement on pavement performances. This was primarily to offset the lack of understanding or proper modeling of the complex interaction and interlock between the soil/aggregate and geogrid.

Eiksund et al. also investigated the effects of varying geogrid stiffness on reducing pavement surface deformations and concluded that relatively high values of reinforcement properties and improved [17] interface analysis techniques were needed to best demonstrate the experimentally observed geogrid benefits.

Table 1. Material properties assigned in the linear and nonlinear mechanistic FE analyses

<table>
<tr><th>Materials</th><th>Element</th><th>Thickness (mm)</th><th>E (MPa)</th><th></th><th colspan="4">Material Properties</th></tr>
<tr><td>AC</td><td>8-noded solid</td><td>76</td><td>2,758</td><td>0.35</td><td colspan="4">Isotropic and Linear Elastic</td></tr>
<tr><td>Base</td><td>8-noded solid</td><td>254</td><td>207 or 124</td><td>v= 0.4
h= 0.1</td><td colspan="4">Nonlinear analysis with resilient modulus = f( ): $M_R=K_1(\theta/p_o)^{K_2}(\sigma_d/p_o)^{K_3}$</td></tr>
<tr><td rowspan="4">Subgrade</td><td rowspan="4">8-noded solid</td><td rowspan="4">-</td><td rowspan="4">28</td><td rowspan="4">0.45</td><td colspan="4">Nonlinear: Bilinear or Arithmetic Model</td></tr>
<tr><td>E_{Ri} (kPa)</td><td>di (kPa)</td><td>K_3</td><td>K_4</td></tr>
<tr><td>41,369</td><td>41</td><td>1,000</td><td>200</td></tr>
<tr><td colspan="4">or Isotropic and Linear Elastic</td></tr>
<tr><td>Geogrid (at base-subgrade Interface)</td><td>3-noded membrane</td><td>1.27</td><td>5,516</td><td>0.1</td><td colspan="4">Isotropic and Linear Elastic</td></tr>
</table>

INTERFACE MODELING RESULTS FOR GEOGRID-REINFORCED PAVEMENT SYSTEM

Table 2 lists the interface properties used for the two different interface modeling approaches studied; the mechanistic FE model developed in this study and also the commercial ABAQUS™ FE program contact model. The soil/aggregate-geogrid interface in the developed mechanistic model was represented by the membrane element and the neighboring 6-node interface elements. The normal and shear springs placed between continuum and membrane elements provided relative movements depending upon the spring stiffnesses (k_s and k_n). The normal interface springs were assigned a high value of k_n=2,442.6 × 10^6 kPa/m to maintain continuity and prevent overlapping or punching-through the neighboring elements. The base and subgrade soil layers were assigned constant moduli of 207 and 28 MPa, respectively. Various levels of interface bonding conditions were studied by varying the shear stiffness, k_s, in the interface element.

Table 2. Interface properties in the mechanistic model and ABAQUS™ FE analyses

<table>
<tr><th rowspan="2">Interface Element</th><th colspan="2">Developed Mechanistic Model</th><th colspan="2">ABAQUS™</th><th rowspan="2">Friction angle Ø</th></tr>
<tr><th>k_n (10^6 kPa/m)</th><th>k_s (10^6 kPa/m)</th><th>E_{slip} (mm)</th><th>Friction coefficient, μ</th></tr>
<tr><td>6-node spring interface</td><td>2,442.6</td><td>1.4 / 4.1 / 16.3 / 135.7 / 2,714</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Interface Contact Model (ABAQUS™)</td><td>-</td><td>-</td><td>0.25</td><td>1</td><td>45°</td></tr>
</table>

Interface relative displacements typically decreased as the shear stiffness k_s assigned to each interface increased. The highest value of k_s(=2,714 × 10^6 kPa/m) corresponded to the perfect bonding condition. The maximum relative displacements varied from 25 × 10^{-6} to 4,140 × 10^{-6} mm in the top and bottom interfaces, which were assigned equal shear stiffnesses in this analysis. Such small magnitude relative displacements predicted, therefore, indicated no large movement or slip condition of the geogrid was taking place at the base-subgrade interface. The shear stresses developed at the top and bottom interfaces are shown in Figure 2. A clear increase in shear resistance is observed at both interfaces with increasing shear stiffnesses. For k_s greater than 135.7 ×

10^6 kPa/m, a shear resistance buildup was observed in the top interface in the opposite direction. This is indicated with the negative values of the shear stresses reported in Figure 2 at the geogrid-base interface, whereas, positive values are observed at the geogrid-subgrade interface.

In the ABAQUS™ axisymmetric FE model, the three-noded axisymmetric membrane (MAX2) was used to model geogrid reinforcements. The ABAQUS™ contact model was assigned various bonding conditions to represent the frictional resistance at the soil/aggregate-geogrid interfaces. The friction coefficient $\mu(= \tan\phi)$ and elastic slip E_{slip} were the required inputs to ABAQUS™ contact model. The main goal was to validate the developed mechanistic model interface behavior and to determine a set of input properties for each analysis to yield similar pavement responses. The developed mechanistic FE model pavement response predictions were therefore compared to ABAQUS™ FE analysis results. The prediction results showed good agreement between the mechanistic FE model and the ABAQUS™ solutions when the shear stiffness k_s was taken as 4.1×10^6KPa/m (15,000 pci) in the 6-noded interface elements corresponding to ABAQUS™ contact model inputs of $\mu = 1$ and $E_{slip} = 0.25$ mm.

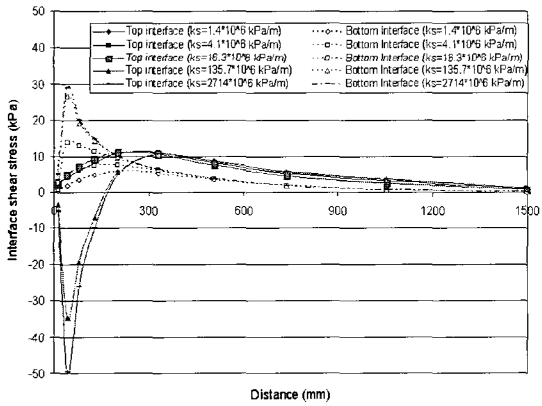

Figure 2. Predicted interface shear stresses for various interface bonding conditions

The critical pavement responses are those that relate to the pavement failure distresses in the context of M-E pavement design. How the base/subgrade-geogrid interface shear friction conditions would impact the predicted pavement responses was studied next for the surface deflections, asphalt tensile strains responsible for fatigue cracking, and the vertical subgrade strains responsible for subgrade rutting eventually causing wheel path pavement surface ruts. Table 3 shows very good agreement in the critical pavement responses predicted at the centerline of circular wheel loading from the mechanistic FE model developed in this study and the ABAQUS™ linear elastic runs considering three different interface bonding conditions: (1) unreinforced, (2) perfect bonding of the geogrid, and (3) partial bonding of the geogrid by the use of interface elements.

Table 3. Comparison of predicted pavement responses from linear analysis at the centerline of loading

Pavement Responses	UNREINFORCED		PERFECT BONDING		WITH INTERFACE ELEMENTS	
	ABAQUS™	Mechanistic FE model	ABAQUS™	Mechanistic FE model	ABAQUS™ (interface E_{slip}=0.25mm, μ=1)	Mechanistic FE model ($k_s = 4.1 \times 10^6$kPa/m)
δ (mm) surface	0.884	0.884	0.859	0.861	0.861	0.861
$\varepsilon_r (\mu\varepsilon)$ bottom of AC	-275 (*tension*)	-274	-271	-271	-271	-271
$\varepsilon_v (\mu\varepsilon)$ top of subgrade	658	631	595	593	595	592
σ_v(kPa) top of subgrade	21.7	19.9	20.1	20.3	20.1	20.0

EFFECT OF UNBOUND AGGREGATE QUALITY ON PAVEMENT PERFORMANCE

Evaluation of nonlinear anisotropic properties

Several studies have proven that the higher values of modular ratios are obtained when aggregate particles have well-gradation, less elongation, more angularity and rougher surface texture [18-22]. The level of anisotropy is defined as the ratio of the horizontal modulus to the vertical modulus. The anisotropic levels of aggregate base could be approximated from regression analyses based on nonlinear material model parameters and physical properties from Equation (4) [15, 16].

$$\begin{Bmatrix} k4/k1 \\ k7/k1 \\ k5-k2 \\ k6-k3 \\ k8-k2 \\ k9-k3 \end{Bmatrix} = \begin{bmatrix} -0.781 \\ 0.312 \\ 1.22 \\ -1.82 \\ -0.19 \\ 0.061 \end{bmatrix} + \begin{bmatrix} -0.000051 & -0.145 & -0.980 & 0.0118 & -0.122 & -0.605 & 0.317 & 0.00151 & 0.00783 & 0.233 \\ 0.0000004 & -0.047 & -0.437 & 0.00047 & -0.0197 & -0.0484 & 0.0095 & 0.000105 & 0.000674 & 0.00202 \\ -0.000007 & 0.222 & 1.72 & -0.0177 & 0.142 & 0.486 & -0.267 & -0.00117 & -0.00622 & -0.176 \\ -0.000046 & -0.172 & -0.982 & 0.0068 & -0.116 & -0.634 & -0.339 & 0.00168 & 0.00871 & 0.218 \\ -0.000031 & -0.031 & 1.19 & -0.00108 & 0.0315 & -0.02 & 0.0428 & 0.000102 & 0.00007 & 0.0066 \\ 0.000013 & 0.160 & -0.695 & 0.00488 & -0.0121 & 0.046 & -0.0349 & -0.0131 & -0.00049 & -0.0262 \end{bmatrix} \begin{Bmatrix} k_1 \\ k_2 \\ k_3 \\ g_a \\ g_n \\ f_a \\ f_n \\ a_a \\ t_a \\ t_n \end{Bmatrix} \quad (4)$$

Where g_a is a fitting parameter corresponding to the initial break in the grain-size curve, g_n is a fitting parameter corresponding to the maximum slope of the grain-size curve, f_a is a fitting parameter corresponding to the initial break in the angularity curve, f_n is a fitting parameter corresponding to the maximum slope of the angularity curve, a_a is a fitting parameter corresponding to the initial break in the angularity index curve, t_a is a fitting parameter corresponding to the initial break in the texture index curve, t_n is a fitting parameter corresponding to the maximum slope of the texture index curve, and k_i are the coefficient of the nonlinear anisotropic model [16].

The reduction in g_a and g_n indicate that the gradation moves towards a well gradation. Higher resilient modulus can be obtained for well graded materials than open graded materials. The increase of form index, f_a and f_n, means that the percentage of particles which have less elongated form. An increase in aa and t_a indicate aggregate have more angular and rough textured particles. Rough-textured and angular aggregates develop a strong and stiff mass by locking together and therefore, provide higher resilient modulus than smooth-textured, rounded particles.

A parametric study was conducted to investigate the effect of anisotropy on pavement responses [15, 16]. Four different aggregate physical properties were considered: (Case 1) well gradation; (Case 2) open gradation; (Case 3) high elongation; and (Case 4) smooth-textured, rounded aggregate particles. Table 4 lists calculated model parameters based on the given values of aggregate physical properties obtained from nonlinear regression analysis. Note that these parameters

Table 4. Aggregate properties and nonlinear anisotropic model parameters [15,16]

		Case 1	Case 2	Case 3	Case 4
Vertical resilient modulus $M_R=K_1(\theta/p_o)^{K_2}(\sigma_d/p_o)^{K_3}$	K_1(kPa)	13,102	13,102	13,102	13,102
	K_2	0.397	0.397	0.397	0.397
	K_3	0.204	0.204	0.204	0.204
Horizontal resilient modulus $M_R^H=K_4(\theta/p_o)^{K_5}(\sigma_d/p_o)^{K_6}$	K_4 (kPa)	9,683	7,635	4,806	12,255
	K_5	0.446	0.547	0.663	0.433
	K_6	-0.095	-0.188	-0.368	-0.172
Shear modulus $G_R=K_n(\theta/p_o)^{K_8}(\sigma_d/p_o)^{K_9}$	K_7 (kPa)	3,505	3,300	3,522	4,050
	K_8	0.580	0.606	0.537	0.551
	K_9	-0.066	-0.082	-0.035	-0.081
Grain size	g_a	11.997	***13.272***	11.997	11.997
	g_n	1.544	***2.416***	1.544	1.544
Form Index	f_a	6.9398	6.9398	***6.8045***	6.9398
	f_n	7.5816	7.5816	***6.5241***	7.5816
Angularity and texture	a_a	622.1465	622.1465	622.1465	***165.0481***
	t_a	229.6287	229.6287	229.6287	***242.9550***
	t_n	4.3603	4.3603	4.3603	***7.0000***

were given by Kim et al. [15, 16] in their models based on stress normalizations with atmospheric pressure instead of unit pressure shown in Table 4.

Finite element analysis results

The developed mechanistic FE model was next employed to compare responses predicted from isotropic and cross-anisotropic characterizations of the granular base layer in an unreinforced and geogrid reinforced conventional flexible pavement. A cross-anisotropic material representation in the granular base layer was considered by assigning different resilient modulus properties in the horizontal and vertical directions. The model parameters used in the anisotropic modulus models, given in Table 4, were obtained from previous research studies [15, 16].

Table 5 lists unreinforced pavement responses predicted at the centerline of loading from the nonlinear elastic analyses considering the four different aggregate physical property cases: (1) well gradation; (2) open gradation; (3) high elongation; and (4) smooth-textured, rounded aggregate particles. The isotropic material representation in the granular base layer was also considered to compare critical pavement responses predicted from the isotropic and cross-anisotropic aggregate base characterizations. Note that for the isotropic case, the horizontal moduli are exactly the same with the vertical moduli. However, the same is not true for the anisotropic case. For aggregate layers, cross-anisotropic characterization typically results in lower horizontal modulus than the vertical. In general, the predicted pavement responses were much higher when cross-anisotropy was considered.

A comparison of the effect of the levels of anisotropy, presented in Table 5, indicates higher vertical strains/stresses on top of the subgrade as predicted from Case 3 with elongated shaped aggregate particles. For example, the percent increases of pavement responses from isotropic material characterization to anisotropic material characterization are much higher in Case 3, up to 66% for subgrade vertical strains. The aggregate physical properties can, therefore, have a substantial influence on the level of anisotropy and affect predicted pavement responses, which make it critical to consider in pavement analysis.

The predicted pavement responses are compared in Table 6 for evaluating how geogrids can be more beneficial depending on the different aggregate materials and qualities used in the pavement construction. Different from the varying percentages of increase shown in Table 5 for the anisotropic predictions in comparison to isotropic ones, similar critical responses were typically predicted in Table 6 with the different level of anisotropies known to exist among the four cases. For example, in Table 5, the percent increases for case 1 and 3 are 40 % and 66 %, respectively, as predicted for the vertical subgrade strains. However, considering the analysis of unreinforced sections given in

Table 5. Comparison of predicted pavement responses (*Unreinforced sections*)

Pavement responses	Nonlinear Analysis Results (% increase from results with *isotropic* base)				
	Isotropic Base	Anisotropic Base			
		Case 1	Case 2	Case 3	Case 4
δ_v (mm) surface	0.978	1.107 (13 %)	1.120 (15 %)	1.133 ***(16 %)***	1.110 (14 %)
$\varepsilon_R(\mu\varepsilon)$ bottom of AC	-341	-419 (23 %)	-428 (25 %)	-439 ***(28 %)***	-425 (25 %)
ε_r $(\mu\varepsilon)$ top of subgrade	1,204	1,683 (40 %)	1,744 (45 %)	1,998 ***(66 %)***	1,732 (44 %)
σ_v(kPa) top of subgrade	35.4	52.8 (49 %)	54.2 (53 %)	55.1 ***(56 %)***	53.7 (52 %)

Note : Negative for Tensile and Positive for Compressive

Table 6, the percent increases for case 1 and 3 are 24 % and 32 %, respectively, as predicted for the vertical subgrade strain. The use of geogrid reinforcement seems to successfully eliminate the negative conditions that may arise due to the use of poor quality aggregates in pavement base/subbase construction.

Predicted percent decreases in pavement responses when going from the unreinforced section to geogrid reinforced section are listed in Table 7. The percent decreases of pavement responses from unreinforced to reinforced section are much higher in the anisotropic analyses, which are primarily considered in Table 7. The vertical subgrade strains are successfully reduced with the use of geogrid reinforcement for up to 44% of the original strain levels in the unreinforced pavement sections (Case3). These results indicate the most significant technical advantage or benefit thus far provided with the use of geogrid reinforcement. Considering that subgrade vertical strains are often used in subgrade rutting predictions through distress models or transfer functions, geogrid reinforcement are indeed beneficial within the context of M-E design.

Table 6. Comparison of predicted pavement responses (Reinforced sections)

Pavement responses	Nonlinear Analysis Results (% increase from results with *isotropic* base)				
	Isotropic Base	Anisotropic Base			
		Case 1	Case 2	Case 3	Case 4
δ_v (mm) surface	0.937	1.064 (14%)	1.080 (15%)	1.082 *(15%)*	1.069 (14%)
$\varepsilon_R(\mu\varepsilon)$ bottom of AC	-334	-409 (23%)	-417 (25%)	-424 *(27%)*	-415 (24%)
ε_r $(\mu\varepsilon)$ top of subgrade	842	1,046 (24%)	1,064 (26%)	1,113 *(32%)*	1,066 (27%)
σ_v(kPa) top of subgrade	33.8	49.1 (45%)	50.4 *(49%)*	50.2 (49%)	49.9 (48%)

Note : Negative for Tensile and Positive for Compressive

Table 7. Comparison of predicted pavement responses

Pavement responses	Nonlinear Analysis Results (% decrease from Unreinforced)							
	Case 1		Case 2		Case 3		Case 4	
	Unreinf	Reinf	Unreinf	Reinf	Unreinf	Reinf	Unreinf	Reinf
δ_v (mm) surface	1.107	1.064 (3.9%)	1,120	1.080 (3.6%)	1.133	1.082 *(4.5%)*	1,110	1.069 (3.7%)
$\varepsilon_R(\mu\varepsilon)$ bottom of AC	-419	-409 (2.4%)	-428	-417 (2.5%)	-439	-424 *(3.4%)*	-42.5	-415 (2.5%)
ε_r $(\mu\varepsilon)$ top of subgrade	1,683	1,046 (37.8%)	1.744	1,064 (39%)	1,998	1,113 *(44.3%)*	1,732	1,066 (38.7%)
σ_v(kPa) top of subgrade	52.8	49.1 (7.1%)	54.2	50.4 (7.0%)	55.1	50.2 *(8.8%)*	53.7	49.9 (7.1%)

SUMMARY AND CONCLUSIONS

An axisymmetric finite element model was developed to mechanistically solve for the layered pavement responses due to traffic loading and investigate the structural benefit provided by geogrid base reinforcement in flexible pavement design. The mechanistic model approximates the wheel load by a circular uniform load and computes pavement elastic responses from axisymmetric stress analysis with continuum elements used to represent pavement layers, membrane elements to model the geogrid, and interface spring elements to model the soil/aggregate-geogrid interfaces.

An investigation of the geogrid reinforcement mechanism was undertaken by varying the shear stiffnesses in the interface elements to specify various levels of interface bonding, i.e., perfect bonding, partial bonding with geogrid and no geogrid (unreinforced) for the linear and nonlinear analyses that considered both isotropic and anisotropic base course characterizations. As the spring shear stiffness k_s of the no thickness interface elements increased, predicted pavement responses of the partial bonding cases approached to predicted pavement responses of the perfect bonding case. Good agreement was achieved between the mechanistic model and the ABAQUS™ predictions when interface elements were assigned a spring shear stiffness k_s of 4.1×10^6kPa/m and the ABAQUS™ interface contact model was assumed an elastic slip of 0.25 mm and friction coefficient of μ=1.

An investigation of the effect of aggregate quality on pavement performance was undertaken by varying aggregate gradation and physical shape properties to specify various levels of anisotropy in the granular base layer. The cases with and without geogrid (unreinforced) were considered in the nonlinear analysis with both isotropic and anisotropic base course characterizations. The results of the numerical study demonstrated that the aggregate gradation and physical shape properties have a substantial influence on the predicted pavement responses. Analysis results indicated that the performance of pavement structures can be enhanced by inclusion of geogrids, because geogrid reinforced sections commonly yield reduced critical pavement responses. The findings also indicated that the benefits of using geogrid reinforcement increased when cross-anisotropy of the unbound granular layers were considered properly in the analyses. Further, geogrid reinforcement helped successfully eliminate differences in the predicted pavement responses due to the different qualities of unbound aggregate materials used in pavement construction.

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