RESEARCH ON THE BEHAVIOUR OF GEOGRIDS IN STABILISATION APPLICATIONS

Erol Tutumluer[1], Hai Huang[2] & Xuecheng Bian[3]

Civil & Environmental Engineering, University of Illinois, Urbana, IL 61801, USA.
[1] (e-mail: tutumlue@illinois.edu)
[2] (e-mail: hhuang14@illinois.edu)
[3] (e-mail: bianxc@illinois.edu)

INTRODUCTION

Geogrids are the most popular type of geosynthetics used in the road construction industry for mechanical stabilisation and reinforcement purposes. Geogrids are commonly used over weak subgrade soils to provide a working platform for construction equipment. Often referred to as "subgrade restraint" design, such an application places a geogrid at the subgrade/aggregate cover interface to increase the bearing capacity or the support of construction equipment over a soft subgrade. Since the aggregate cover option requires large thicknesses for low subgrade strengths, the subgrade restraint use of geogrid reinforcement can therefore be quite beneficial by offering a reduced aggregate thickness alternative.

Geogrids can perform as tensile reinforcement for aggregate base courses in flexible or asphalt pavements. Adding a geogrid layer can mechanically stabilise aggregate particles and increase bearing capacity of a pavement structure by forcing the potential bearing capacity surface to develop along alternate, higher shear strength surfaces. The lateral restraint and/or membrane tension effects may also contribute to load carrying capacity as the wheel loads attempt to cause rutting in the pavement foundation layers, i.e., unbound aggregate base/subbase and subgrade soil.

Through the interlock between the geogrids and aggregate, geogrids are assumed to have higher friction and confining stresses than the smoother surfaced geotextiles. This is in part due to the additional bearing stresses created in the geogrid apertures as soil and aggregate particles provide the interlock in these openings. When placed in a granular base course, geogrids may restrain the lateral spreading of the granular base layer, and through interlocking, may develop a relatively "stiffer" layer surrounding the geogrid. Granular "base reinforcement" of geogrids could be crucial to ensuring their successful and beneficial application in low to moderate volume roads having thin hot-mix asphalt (HMA) surfaces and subgrade California Bearing Ratios (CBRs) between 3 to 8 percent. In addition to potentially reducing shear deformation in aggregates, the control of aggregate movement, especially in the upper part of the layer adjacent to the HMA, may also reduce HMA fatigue. Hence, a geogrid interlayer system can typically be used to reduce the overall thickness of a pavement system for a target design life or extend the design life of the pavement.

This paper highlights subgrade restraint and base reinforcement applications of geogrids in road infrastructure. The paper also describes recent research efforts in numerical modeling and field studies which helped identify and quantify the geogrid reinforcement mechanism in unbound aggregate layers of pavement systems. The primary geogrid reinforcement mechanism of improved aggregate interlock and its importance in preventing aggregate lateral movements is demonstrated in this paper by the use of an innovative image-aided Discrete Element Modeling (DEM) approach for different rectangular and triangular geogrids in a shear box DEM model. Finally, a recent field validated mechanistic model developed at the University of Illinois for geogrid base reinforced flexible pavements is given as an example to demonstrate how the concept of compaction induced residual stresses can be included in finite element analysis as an initial condition and how such an approach can effectively represent the contribution of geogrid reinforcement in the form of stiffened zone in mechanistic pavement analysis.

SUBGRADE RESTRAINT SOLUTIONS

Several design solutions based on the bearing capacity for soil strength have been developed to evaluate aggregate thickness for subgrade restraint with geosynthetics. However, only a few recent design approaches by Tingle & Webster (2003) and Giroud & Han (2004) take into account improved reinforcement benefits provided by geogrids over geotextiles by increasing the bearing capacity factor N_c in the equation and, in the case of the Giroud & Han (2004) approach, including a consideration for aperture stability modulus in the solution. In addition, a geosynthetics design procedure was also developed for thin asphalt roads on soft subgrade soils by the Dutch agency CROW (van Gurp & van Leest 2002). According to their approach, the amount of thickness reduction often depends on the type and strength/stiffness characteristics of the geosynthetics, aggregate, and the subgrade soil combination with geogrids providing better reinforcement benefits over geotextiles.

Based on recent research at the University of Illinois, aggregate cover thicknesses were found to depend on the type and strength/stiffness characteristics of the geosynthetic, aggregate, and the subgrade soil strength, Tutumluer & Kwon (2006). Much higher base course reductions from the unreinforced cases and therefore benefits were observed when using geogrids instead of geotextiles. The findings were compiled to establish thickness reduction guidelines for Illinois Department of Transportation (IDOT) in their Subgrade Stability Manual, IDOT (2005).

Note that not all types and/or brands of geogrids have the same engineering properties, which makes the performance and, consequently, the specifications of geogrids product specific. For this reason many transportation agencies do not have generic specifications that could be applied to all geogrid products used for subgrade restraint.

Further, both the Illinois DOT guidelines and CROW methodologies only allow a maximum reduction of 150 mm from the unreinforced thickness for a more conservative use of geogrids in the subgrade restraint application. All these limitations stem from a lack of understanding of the main mechanism by which geogrids reinforce and how this mechanism needs to be incorporated into a mechanistic based analysis procedure.

REINFORCEMENT MECHANISM THROUGH AGGREGATE INTERLOCK

The mechanical interlock is vital for the performance of any geogrid in mechanical stabilisation and pavement reinforcement. It is a typical property of geogrids, occurring when well graded granular fill is compacted on top of a geogrid, letting the coarser particles partially project through the geogrid's apertures to lock them into place. The mechanical interlock and the resulting lateral restraint of the granular layer assembly explains the performance provided by extruded geogrids compared to geotextiles and other geogrids, even with comparable values of some index properties such as modulus or ultimate tensile strength as demonstrated by a US Army Corp of Engineers study, Webster (1992) and other research by Berg et al. (2000).

On the interlock between the geogrid and aggregate particles, the study by Jewell et al. (1984) identified early on the important mechanisms of soil and geogrid interactions through the use of large shear box testing. Seven granular soils reinforced with a biaxial geogrid with an aperture width 17.3 mm were tested. The peak direct shear forces and the sliding resistances measured for the various soil gradations adopted indicated that the relative size of the aggregate particle and its gradation compared to the grid aperture had an influence on the size of the rupture zone. The research findings of Jewell et al. (1984) therefore laid down the foundation for understanding the fundamental mechanisms by which geogrids reinforce pavement systems by entertaining the idea of choosing the type of geogrid for the intended aggregate particle sizes and gradation.

Discrete element modeling (DEM) studies

The Discrete Element Method is one of the most realistic modeling techniques for simulating complex soil/aggregate geogrid interaction. This micro scale numerical simulation approach is fully capable of modeling the most realistic interaction of soil/aggregate particles and the geogrid by reproducing the actual geometry, assigning properly geogrids and soil properties and accounting for the aggregate particle size distribution and shape. In this methodology, multiple interacting bodies undergoing large dynamic motions can be modeled by modeling the individual particles or elements and computing their motion, and the overall behavior of the assembly. Force displacement laws for different element bonding conditions and the law of motion govern the movement and contacts of each element within the assembly of elements.

Recent work by the ITASCA Group in Germany and the University of Nottingham in the UK focused on investigating aggregate and geogrid interactions and modeling confinement effects using three-dimensional Particle Flow Code (PFC3D) DEM program, Konietzky et al. (2004) and McDowell et al. (2006) utilizing spherical discrete elements. The findings of DEM modeling studies covered the areas of interaction between geogrids and surrounding soil/aggregate in both pull-out and triaxial tests, load transfer mechanisms, deformations, particle rearrangements and more. The modeling simulations demonstrated the development of considerable horizontal residual stresses at vicinity of geogrid when applied loading is removed. The developed residual stresses could be directly linked to the increased confinement and stiffening achieved through the use of geogrid base reinforcement in flexible pavement systems. Konietzky et al. (2004) and McDowell et al. (2006) both indicated that a stiffened, i.e., higher modulus, zone and consequently an area of locked-in permanent residual stresses occurred approximately 10 cm above and below the geogrid, expected to vary depending on aggregate size and geogrid type.

Image-aided DEM methodology at the University of Illinois

An image aided DEM approach, which utilizes a DEM program BLOKS3D developed at the University of Illinois, Zhao et al. (2006), has been recently introduced to investigate effects of multi-scale aggregate morphological properties on performances of granular assemblies, Tutumluer et al. (2007). Imaging technology provides detailed measurements of aggregate shape, texture and angularity properties and has been successfully used in the last two decades for quantifying aggregate morphology. Among the various particle morphological indices, the flat and elongated (F&E) ratio, the angularity index (AI), and the surface texture (ST) index, all developed using University of Illinois Aggregate Image Analyzer (UIAIA), are key indices, Tutumluer et al. (2000), Rao et al. (2002) and Pan & Tutumluer (2007). The UIAIA system features taking images of an individual aggregate particle from three orthogonal views to quantify imaging based F&E ratio, AI, and ST morphological indices. The image-aided DEM approach then recreates the three-dimensional aggregate shapes as individual DEM elements based on the UIAIA processed top, front, and side views. This process can be easily performed using available computer aided design software and by changing the shapes of the top, front, and side aggregate 2-D images to establish representative elements with different shape properties, such as cubical, flat, flat and elongated, angular or rounded, in order to investigate effects of aggregate shape on the granular assembly strength.

Preliminary research efforts to investigate aggregate and geogrid interactions using the image-aided DEM methodology considered simulating direct shear (shear box) testing as the choice since the test procedure is simple, reliable and widely used for particulate medium strength testing. In the shear box test, aggregate particles are pushed against each other to cause frictional resistance through aggregate interlock followed by aggregate sliding, rolling and even crushing. Therefore, interactions of individual particles and their hardness, shape, texture and angularity play significant roles in contributing to the granular assembly strength and the interlock provided by the geogrid reinforcement.

For the shear box direct shear strength test DEM simulations, 3037 aggregate particles were first processed through the UIAIA and then representative DEM element shapes were created for an accurate modeling of the average shape properties in the granular assembly. In this particular case, all coarse aggregate particles were uniformly graded with an average size of 25 mm, which resulted in a ratio of minimum geogrid edge to particle size between 3 to 4 for both triangular and rectangular (or square) geogrid geometries studied, Fig. 1. This was in accordance with the suggested geogrid aperture and aggregate particle size combinations by Jewell et al. (1984) to achieve good aggregate interlock. Figure 1 shows the comparisons from two 2-D images between an actual aggregate particle and the corresponding DEM representative element. The angularity (AI) of the particles ranged from 390 to 630 (rounded to angular) and cubical, rough textured particles with an F&E ratio range of 1 to 1.3 were mainly used in the DEM simulations, Tutumluer et al. (2000) and Rao et al. (2002).

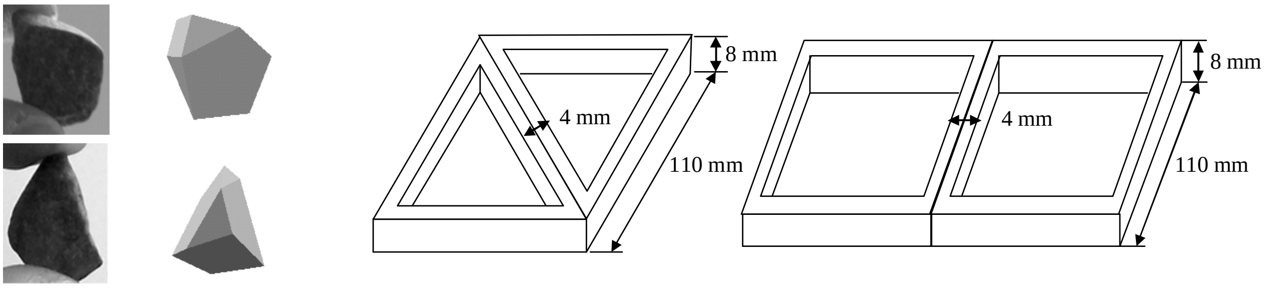


Figure 1. Discrete element representations of aggregate particles and geogrids with triangular and rectangular openings generated

The lower box of the shear box DEM model, with dimensions 35.6 cm x 30.5 cm by 15.2 cm in height, was generated first; aggregate particles were then dropped in layers to completely fill the simulated shear box by using rigid blocks and the force contact equilibrium was established. On the top of the lower box, the geogrid was placed with either rectangular or triangular openings and fixed to the lower box, Fig 2. The upper shear box, with dimensions 30.5 cm x 30.5 cm by 7.6 cm in height, was next generated and filled similarly with aggregate particles followed by the placement of normal loading plate on top of the particles. Aggregate samples reinforced with geogrid in the middle were then sheared at a constant speed of 0.0002 m/second. Two normal forces, 10 kN and 20 kN, were applied on the upper box to cover typical road infrastructure normal load stress regimes. The generated particle contact forces and the shear reaction forces were recorded and graphed against shear displacements.

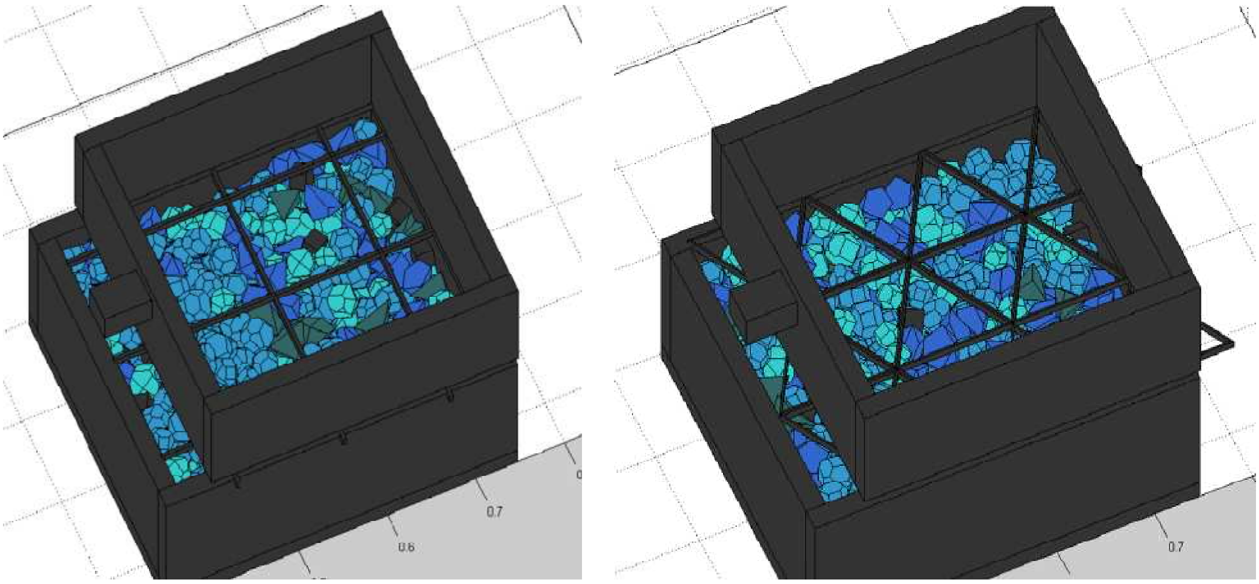


Figure 2. Shear box DEM model; aggregate particles in the lower box with geogrids having rectangular or triangular openings on top

Figure 3 shows the shear forces predicted for geogrids with both the rectangular (or square) and triangular openings used to reinforce the horizontal shear plane under the applied 10 kN and 20 kN normal forces. As the applied normal force increased, the shear force also increased primarily influenced by the increased confinement. The increase in the peak shear stress, i.e., strength, was somewhat higher in the case of the rectangular geogrid. However, under both 10 kN and 20 kN normal loads, the highest shear strengths were achieved with the geogrid with triangular openings. An investigation of the aggregate interlock achieved with both geogrid geometries was undertaken by collecting individual shear deformation data obtained from all 3307 aggregate particles (or discrete elements) used in the DEM simulations. Figure 3 also shows average horizontal displacements of particles along the shearing direction and below the geogrid position, hardly any movement was observed.

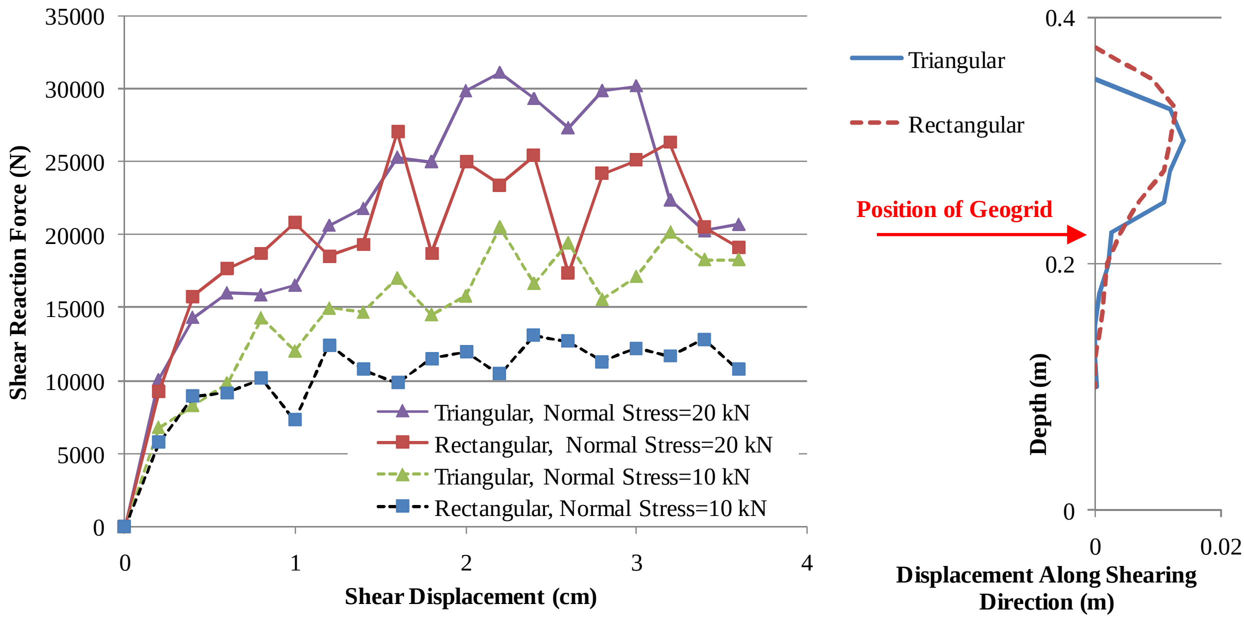


Figure 3. Predicted shear reaction forces and average aggregate displacements from the shear box DEM model

To further visualize the effect of geogrid type, i.e., rectangular or triangular openings, on mobilizing the shear strength, Fig. 4 shows the contact force vector plots obtained from the shear box DEM simulations under an applied normal force of 20 kN. The top horizontal arrow shows the shearing direction for each geogrid case. All contact forces are shown for the same time step when the first peak forces were recorded in the shear box DEM simulations. It is interesting to note that in the case of triangular openings with the highest shear strengths achieved, there exist much fewer force contact vectors of any significant magnitude in the lower box, Fig. 4. This may well be due to the fact that the contact forces are concentrated along the geogrid shown in horizontal dashed line, which is an indication of improved aggregate interlock. No doubt future research, using the hereby introduced image-aided DEM model, will need to consider in greater detail individual effects aggregate particle size, shape, texture and angularity, compaction procedure, etc. in relation to different geogrid types, aperture sizes and properties.

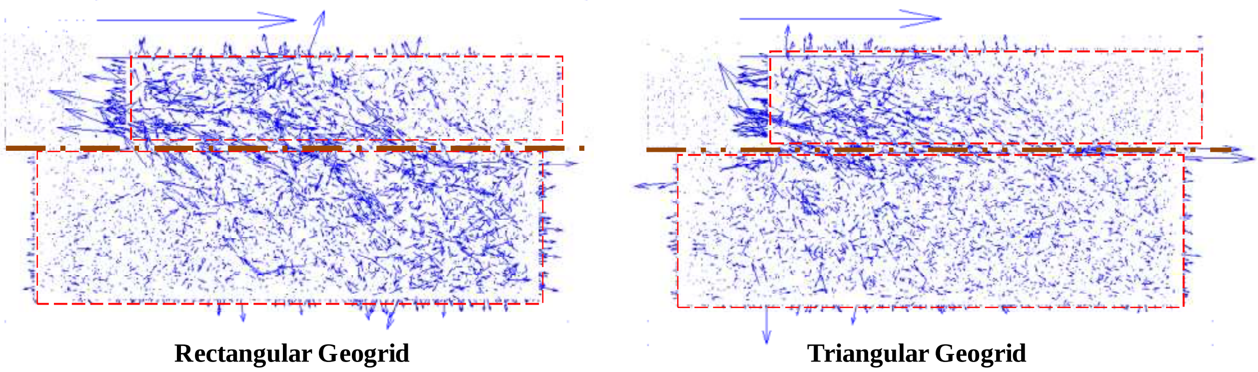


Figure 4. Contact forces predicted in shear box DEM simulations (normal force = 20 kN)

VALIDATED MECHANISTIC MODEL FOR GEOGRID BASE REINFORCEMENT

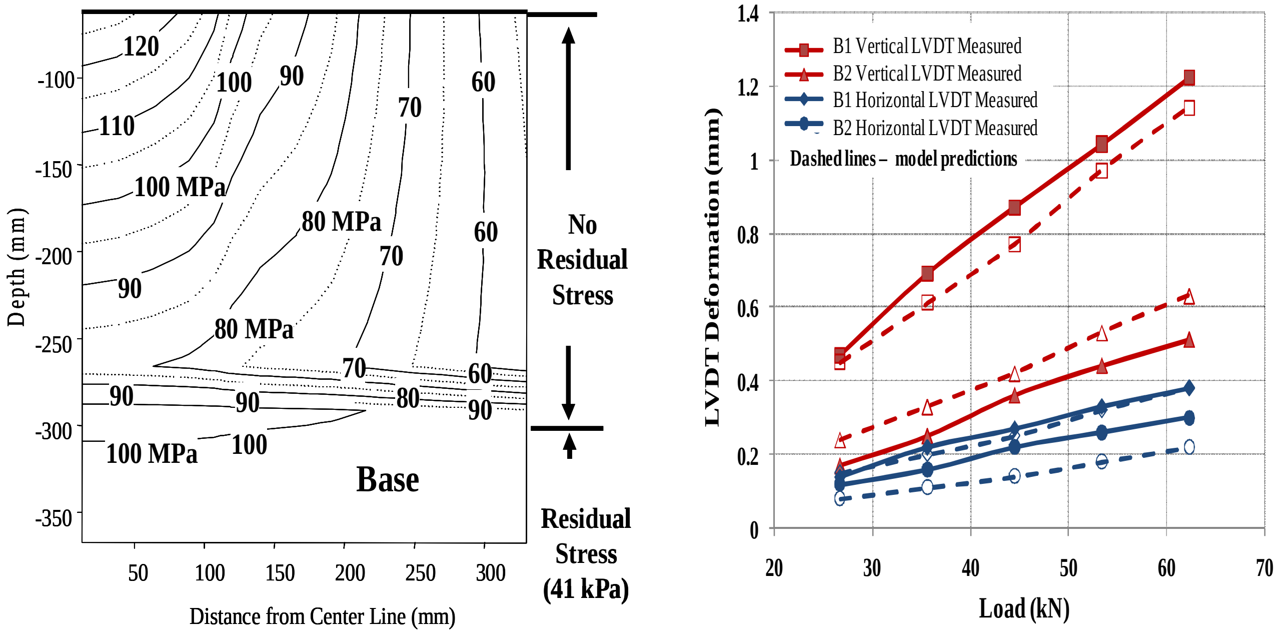
In the Mechanistic-Empirical (M-E) pavement design methodology, pavement performance is no longer linked only to pavement thicknesses and loading conditions. Failure is instead linked to a critical pavement response, such as shear stress in the upper part of the subgrade, which can be responsible for subgrade pavement rutting failure. Proper modeling of pavement materials and the reinforcement mechanism is essential to obtain accurate response prediction under applied wheel loading. The effectiveness of geogrid in the base reinforcement application can then be quantified by means of a "Response Benefit," that is, the reduction of such a critical pavement response due to grid.

To help quantify the effectiveness of geogrid in base reinforcement, a finite element (FE) program was developed at the University of Illinois to properly analyze geogrid-reinforced flexible pavements considering nonlinear, stress-dependent behavior of unbound aggregate base and subgrade layers (Kwon et al. 2005). The FE model takes into account the directional dependency of load-induced stiffening (anisotropic modulus properties) of the granular base materials and the compaction and preloading induced residual stresses in the base course. The aggregate-geogrid interlock mechanism from the DEM findings has been linked to the continuum analysis technique to improve the FE based analysis methodology (Kwon et al. 2009).

Attempts were made to validate the mechanistic FE model results using pavement responses to accelerated loading from full-scale pavement testing. Testing conducted at the University of Illinois focused on evaluating the effectiveness of geogrids on the response and performance of low-volume flexible pavements constructed on low subgrade loading capacity (i.e., CBR < 4 percent). Nine instrumented pavement sections were designed and constructed to measure pavement responses, monitor pavement performance, and quantify the effectiveness of geogrid-reinforced flexible pavements, Al-Qadi et al. (2008). The variables considered in the study included HMA (76- and 127-mm thick), granular base layer thickness (203, 305, and 457 mm) and the type and location of geogrid within the granular base course. Most of the reinforced sections had the geogrid placed at the base-subgrade interface, except for the thicker sections with 457-mm aggregate base, which also had geogrid placed in the upper portions of the base layer. The sections were heavily instrumented with pressure cells, linear variable differential transformers (LVDT's), and strain gauges to measure the pavement response to moving wheel load during testing, and with thermocouples, time domain reflectometer (TDR), and piezometers to capture environmental changes during testing.

Testing was conducted using the mobile Accelerated Testing Loading ASsembly (ATLAS) for response and trafficking data collection. In general, analyses of measured responses indicated that the unreinforced control sections had higher tensile strains measured at the bottom of the HMA, higher vertical pressure and resilient deformation at the top of the subgrade, and significantly greater lateral deformations in the aggregate base layer; especially in the direction of traffic, compared to the geogrid reinforced sections. This observation was further validated by the measured surface rutting. It was evident that the aggregate-geogrid interlock decreased lateral strain in the aggregate layer and decreased the vertical deformation of the pavement surface. At the end of trafficking, the unreinforced pavement sections exhibited more pronounced pavement distresses including greater surface rutting due to subgrade shear failure as well as aggregate lateral movement. The effectiveness of geogrid in confining the aggregate was evident when the geogrid was placed within the upper part of the thicker base layer, Al-Qadi et al. (2008).

The mechanistic model validation efforts involved comparing the outcome of the FE model to the field data obtained from the full-scale tests. It was evident that when base course anisotropy and compaction-induced residual stresses were considered in the analyses, the main trends in response behavior were in better agreement with that measured in the field. Figure 5a shows contour plots of predicted modulus distributions in the entire base of the B1 geogrid reinforced section with up to 41-kPa residual stresses assigned in the bottom of the base layer. This caused approximately 40% increase in the modulus around the geogrid reinforcement when compared to the unreinforced B2 section with the same geometry and material input properties, which is in agreement with the DEM results of Konietzky et al. (2004) and McDowell et al. (2006). The benefits of including geogrids in the pavement system could be successfully modeled by considering residual stress concentrations assigned in the geogrid-aggregate vicinity. This resulted in lower pavement responses predicted in the geogrid reinforced sections and the predictions were in good agreement with the measured responses from the full scale tests, Fig. 5b.



(a) Base modulus contours for B2 reinforced section (b) Top of subgrade deformations with wheel loads

Figure 5. Mechanistic model predictions of University of Illinois full-scale pavement test sections – unreinforced (B1) and geogrid reinforced (B2) pavement sections with 30.5-cm thick aggregate base

CONCLUSIONS

Geogrids provide improved aggregate interlock in stabilising road infrastructure through subgrade restraint and base reinforcement applications. Recent numerical modeling research using the Discrete Element Modeling (DEM) approach and field studies of geogrid base reinforced pavement systems have adequately identified improved pavement response and performance when geogrid is incorporated in low volume roads. The findings suggest the development of a “stiffened” zone around the geogrid indicating aggregate interlock as the primary reinforcing mechanism.

As demonstrated in this paper by the use of an innovative image-aided DEM shear box model for geogrids with rectangular and triangular openings, the “stiffened” zone could be due to restraining the lateral movement of the aggregates. Future DEM research should undoubtedly focus on investigating how this “stiffened” zone can be quantified, predicted, or even engineered for a given set of pavement geometry, geogrid, and granular base aggregate properties (including proper imaging based characterization of aggregate shape, texture and angularity), and compaction procedures. Once properly quantified, the increases in stiffness around the geogrid reinforcement can be properly incorporated into mechanistic response analysis, which involves generating finite element continuum solutions of pavement systems and assigning horizontal residual stresses around geogrid as an initial condition.

ACKNOWLEDGEMENTS

The authors would like to acknowledge significant research contributions of Dr. Jayhyun Kwon of Tensar International Corp., Professor Imad Al-Qadi of the University of Illinois at Urbana-Champaign and Professor Samer Dessouky of University of Texas at San Antonio.

REFERENCES

Al-Qadi, I.L., Dessouky, S., Kwon, J., & Tutumluer, E. 2008. Geogrid in flexible pavements: validated mechanism. Transportation Research Record No. 2045, TRB, National Research Council, Washington, D.C., 102-109.

Berg, R.R., Christopher, B.R. & Perkins, S.W. 2000. Geosynthetic reinforcement of the aggregate base/subbase courses of pavement structures. GMA White Paper II, Geosynthetics Materials Association, Roseville, MN, USA.

Giroud, J.P. & Han, J. 2004. Design method for geogrid-reinforced unpaved roads. Journal of Geotechnical and Geoenvironmental Engineering, ASCE, Vol. 130, No. 8, August, 775-786.

IDOT, 2005. Subgrade stability manual. IDOT Bureau of Bridges & Structures, Springfield, Illinois, May, 34 pages.

Jewell, R.A., Milligan, G.W.E., Sarsby, R.W. & Dubois, D. 1984. Interaction between soil and geogrids. Proceedings Symposium on Polymer Grid Reinforcement in Civil Engineering, London, U.K., 19-29.

Konietzky, H., te Kamp, L., Gröger, T. & Jenner, C. 2004. Use of DEM to model the interlocking effect of geogrids under static and cyclic loading. Numerical Modeling in Micromechanics via Particle Methods: Shimizu, Y., Hart, R. & Cundall, P. (Eds.), A.A. Balkema, Rotterdam, 3-12.

Kwon, J., Tutumluer, E. & Kim, M. 2005. Development of a mechanistic model for geosynthetic-reinforced flexible pavements. Geosynthetics International, Vol. 12, No. 6, 310-320.

Kwon, J., Tutumluer, E., & Al-Qadi, I.L. 2009. A validated mechanistic model for geogrid base reinforced flexible pavements. Accepted for publication in ASCE Journal of Transportation.

McDowell, G.R., Harireche, O., Konietzky, H., Brown, S.F. & Thom, N.H. 2006. Discrete element modelling of geogrid-reinforced aggregates. Proceedings Institution of Civil Engineers, Geotechnical Engineering 159, 35-48.

Pan, T. & Tutumluer, E. 2007. Quantification of coarse aggregate surface texture using image analysis. ASTM Journal of Testing and Evaluation, Volume 35, Issue 2, March.

Rao, C., Tutumluer, E. & Kim, I.T. 2002. Quantification of coarse aggregate angularity based on image analysis. Transportation Research Record No. 1787, TRB, National Research Council, Washington, D.C., 117-124.

Tingle, J.S. & Webster, S.L. 2003. Corps of Engineers design of geosynthetic-reinforced unpaved roads. Transportation Research Record No. 1849, TRB, National Research Council, Washington DC, 193-201.

Tutumluer, E. & Kwon, J. 2006. Evaluation of geosynthetics use for pavement subgrade restraint and working platform construction. ASCE Geotechnical Practice Publication No. 3: Geotechnical Applications for Transportation Infrastructure, Hani Titi (Ed.), ISBN: 0-7844-0821-1, 96-107.

Tutumluer, E., Huang, H., Hashash, Y.M.A. & Ghaboussi, J. 2007. Discrete element modeling of railroad ballast settlement. Proceedings 2007 AREMA Annual Conference, Chicago, Illinois, September 9-12.

Tutumluer, E., Rao, C., & Stefanski, J.A. 2000. Video image analysis of aggregates. Final Report, FHWA-IL-UI-278, Civil Engineering Studies UILU-ENG-2000-2015, University of Illinois Urbana-Champaign, Urbana, Illinois.

van Gurp, C.A.P.M. & van Leest, A.J. 2002. Thin asphalt pavements on soft soil. Proceedings 9th International Conference on Asphalt Pavements, ISAP, Copenhagen, Denmark, 1-18.

Webster, S.L. 1992. Geogrid reinforced base courses for flexible pavements for light aircraft. Literature Review and Test Section Design, Technical Report GL-92-6, USAE Waterways Experiment Station, Vicksburg, MS, USA.

Zhao, D., Nezami, E.G., Hashash, Y.M.A & Ghaboussi, J. 2006. Three-dimensional discrete element simulation for granular materials. Journal of Engineering Computations, Emerald Group Publishing Ltd., 23, 7, 749-770.