August 2004
Volume 22, Number 6

Geocells: a 25-year perspective

Part 1: roadway applications

By Gregory N. Richardson, Ph.D., P.E.

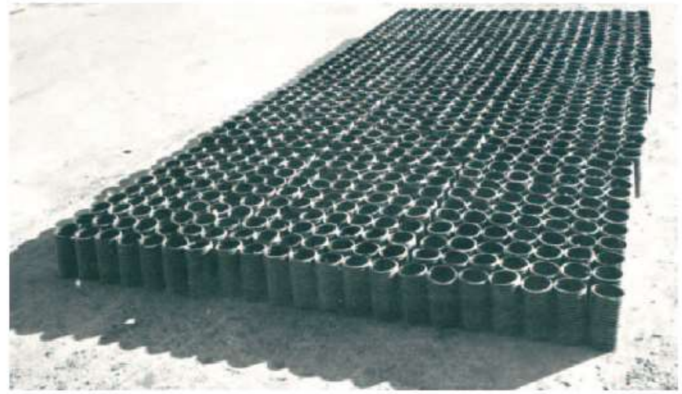

Photo 1. Corps of Engineers geocell test section, Vicksburg, 1977.

Commercial geocell	Flexural stiffness, EI (lb-in2)
GeoProducts – 3" Smooth	65,255
GeoProducts – 4" Smooth	58,003
GeoProducts – 4" Smooth	43,117
Presto – 3" Textured	23,976
Presto – 4" Textured & Perforated	34,096

Table 1. Geocell flexibility.

During the summer of 1977, I visited the Corps of Engineers Waterways Experiment Station at Vicksburg to discuss research that I was performing on the use of geotextiles to improve the performance of track support structures. Both the heat and humidity of a Mississippi August day and the Corps' innovative research on the use of what would become geocells left a lasting impression in my memory. Contained in the largest Quonset hut that I had ever seen was a roadway test section used for full-scale tests of alternative rapid deployment military roads for challenging weak subgrades. The search for a modern alternative to the steel mats made famous in both fronts during World War II was in full stride. The specific topic was focused on improving tactical bridge approach roads across soft ground (Webster 1977, 1979), but the fundamental nature of the research was self-evident even then.

A young (we all were) Steve Webster had the luxury in this test site to create a variety of challenging subgrades, construct a full-scale alternative military road, and then run cycles of actual military equipment over the road. As a young academic, I was flush with the thought of what optional research use I could find for an Army tank in North Carolina. Dove hunting took on a new meaning. The geocell test section I watched under construction was formed of thousands of short corrugated plastic pipe sections standing vertical on the native ground or a geotextile, see **Photo 1**. The pipe sections were mechanically attached together and then filled with sand. Given only a thin sand surfacing to bury the plastic pipes, the performance of the roadway under heavy traffic loading was amazing. The ability of the geocells to limit roadway displacements far exceeded the simple separator geotextiles that I had been investigating.

In the years since that steamy day in Vicksburg, I have been disappointed with the near absence of research papers on geocells in all of the geosynthetic national and international conferences. Even Koerner allocates only a handfull of pages in his textbook to this most interesting "geo" topic (Koerner 1996). With applications of geocells now encompassing roadway reinforcement, erosion control, retaining walls, and even emergency flood walls, a more applied review of geocells is overdue. This two-part series will focus on the basic theory behind geocell performance and its role in the initial application to roadways over poor subgrades. Part Two of this series will extend the application of geocells to erosion control and retaining walls. In all applications, an attempt is made to clearly identify the important physical properties of both the geocell manufactured component and the granular material used to fill the cells.

Photo 2. Today's geocell mats expand to form "honeycombs."

Today's geocell product

While Webster explored a wide range of potential geocell mats, today's commercial products are almost exclusively formed of 50-mil thick high-density polyethylene (HDPE) strips factory welded to form panels having a honeycomb structure. The panels are shipped collapsed but are quickly expanded and staked in place (**Photo 2**). The individual cells of the geocell panels are then filled with gravel or sand. The use of cohesive fills is physically impractical due to the inability to compact such soils in the small cells and lack of physical benefits for such soils. The individual cells have a height to diameter ratio in roadway applications of approximately one.

The HDPE geocells are available with the plastic sheets smooth or textured and with or without perforations. The role of these options is discussed in the technical discussions in this series. Additionally, a geotextile separator is typically placed beneath the geocell honeycomb on clayey subgrade to prevent pumping of subgrade fines into the geocell granular fill.

The role of confinement for granular subgrades

Webster's early research showed that the geocells provided an effective confinement of their contents when the height of the cell was equal to or greater than the diameter of the cell. This confinement may be thought of as similar to that provided by the bag in conventional sandbags. As load is applied to the confined granular material, its expansion perpendicular to the load is limited by the tensile strength of the bag. This creates a confining stress that increases the strength of the granular fill. This effect is shown in **Figure 1** using the Mohr's circle model (Hausemann 1976) that most civil engineers are familiar with. Here the stress σ'_r is the lateral

REINFORCED EARTH

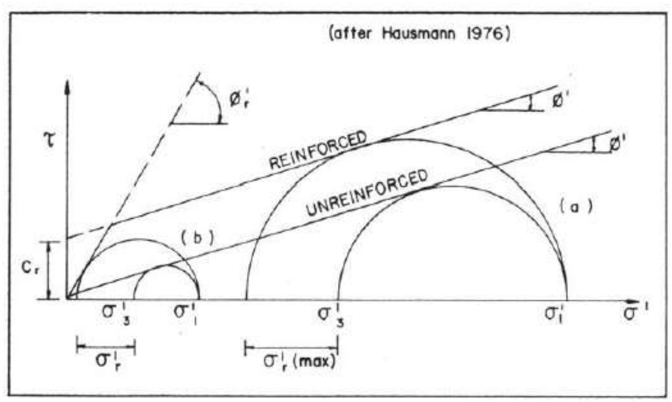

Figure 1. Composite Mohr envelope; reinforced earth.

stress taken by the reinforcement. This reduces the horizontal stress in the granular fill and produces the apparent cohesion. The lateral confinement of the geocell produces pseudo-cohesion strength in the granular fill that is critical to its performance. The amount of pseudo-cohesion developed is influenced by the stiffness of the geocell walls and the ability of the geocell to contain the granular fill. This pseudo-cohesion model has been successfully applied to all forms of soil reinforcement.

The role of the pseudo-cohesion in roadway applications can be clearly demonstrated using conventional bearing capacity analysis. The bearing capacity, Q_{ult}, of a soil having both cohesive and frictional strength subjected to a uniform circular loading (e.g., tire load) is given as follows:

$$Q_{ult} = 1.3\, c\, N_c + 0.6\, \gamma\, R\, N_\gamma$$

Where c is the cohesion of the soil, γ is the unit weight of the soil, R is the radius of the load, and N_c and N_γ are bearing capacity factors that are a function of the frictional strength of the subgrade. The first half of the equation represents the bearing capacity due to cohesion; the second half represents the bearing capacity due to the frictional strength of the subgrade.

The apparent cohesion from one commercial brand of geocells formed of 50 mil polyethylene is reported to be 3,000 psf (Presto 2003). Assuming conservative physical properties for the granular fill of γ = 100 psf and a friction angle of 30°, the bearing capacity for these 50 mil HDPE walled geocells subjected to a vehicle tire load would be approximately

$$Q_{ult} = 1.3x3000x32 + 0.6x100x1x7$$

$$Q_{ult} = 124{,}800 + 420 = 125{,}400 \text{ psf}$$

This simple example shows that commercial geocells would provide a 300-fold increase in the bearing capacity as compared to the layer of sand. This assumes that the thickness of the reinforced granular layer is greater than the radius of the applied wheel load.

Lacking a rigorous method for evaluation of the bearing capacity of a specific geocell and granular fill, the pseudo-cohesion must be based on laboratory testing. A design engineer must have a feel for the relative impact of geocell properties on actual performance.

Geocell rigidity for weak clay subgrade (CBR<2)

An alternative approach to quantifying the role of the geocell system in increasing the bearing capacity of roadways over weak clays is to account for the ability of the slab like stiffness of the

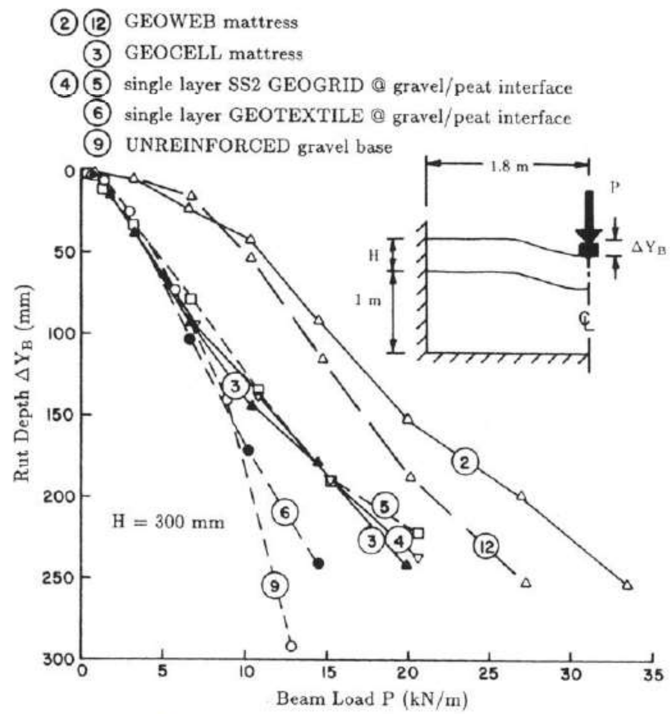

Figure 2. Comparison of reinforced and unreinforced tests with 300 mm of gravel base.

honeycomb structure of the geocell to spread out concentrated wheel loads. An excellent laboratory study that qualitatively examined this mechanism was performed by Richard Bathurst and Peter Jarrett at the Royal Military College of Canada in the 1980s (Bathurst 1981). **Figure 2** shows the deformation of the center of a various geocell/gravel systems constructed over one meter of compressible peat. The Presto GeoWeb® in **Figure 2** is similar to that shown in **Photo 2**. The geocellular system in **Figure 2** is actually more of a flexible honeycomb system formed from strips of geogrid joined with steel rod bodkin connections. Laboratory data shows that the geocell formed of the welded HDPE strips had significantly less deformation that the geocell formed of geogrids or the unreinforced gravel. This study qualitatively shows that the stiffness of the plastic honeycomb system is very important but does not provide guidance on quantifying this role.

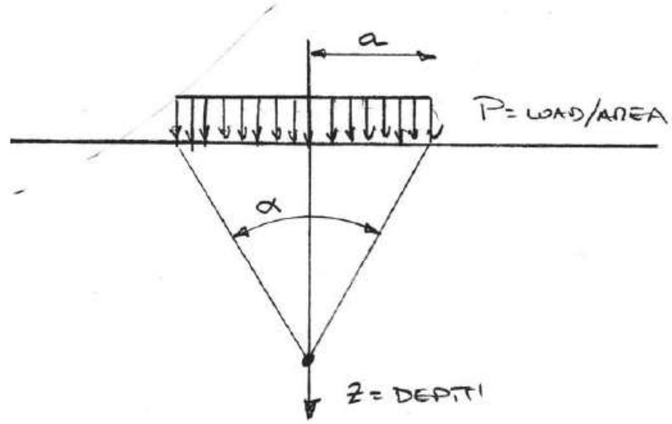

Figure 3. Variables for the calculation of vertical stress in subgrade.

The role of the stiffness of the plastic honeycomb system should be remembered when selecting geocell mats. Many of the available commercial geocell mats have a significant percentage of the side walls of the cells removed by perforation of the strips. These perforations greatly reduce the stiffness of the honeycomb structure. To illustrate this increased flexibility, "beams" of the flat as-shipped geocells were subjected to a central point load. **Table 1** shows the resulting decrease in the flexural stiffness of the geocell beams. For roadway applications, I see no advantage in using perforated or textured geocells, since the flexibility of the honeycomb is highly compromised. The drainage offered by the perforations is simply not needed in roadway applications.

An interesting analytical approach to bearing capacity based on cell rigidity estimates the amount of vertical stress that is transferred to the honeycomb cell structure. The load transferred to the cell structure is assumed to transfer laterally such that it does not influence the local bearing capacity. This approach requires testing such as performed by Barthurst and Jarrett to confirm sufficient rigidity in the cell structure to actually support the loading being transferred to it. The vertical stress at the top and bottom of an individual cell can be estimated for uniformly loaded line and circular loads centered over a single geocell using the following equations (Presto 2003):

Line load $$\sigma_z = \frac{P}{\pi}(\alpha + \sin\alpha)$$

Circular load $$\sigma_z = P\left[1 - \left\{\frac{1}{1 + (a/z)^2}\right\}^{3/2}\right]$$

The variables used in these equations are shown on **Figure 4**. The line load would be appropriate for tank/dozer tracks, while the circular load is good for rubber tires. Note also that these elastic equations do not account for the presence of the geocell honeycomb and are therefore quite approximate.

Having calculated the vertical stresses, σ_z, acting on a geocell, the horizontal stresses, σ_h, are simply taken as σ_z times the active earth pressure coefficient, K_a. The active earth pressure coefficient is related to the internal friction angle, ϕ,of the granular fill as follows:

$$K_a = \tan^2(45^\circ - \phi/2)$$

Figure 4 shows the assumed stress conditions acting on the single cell being evaluated. The average horizontal stress acting on the inside of the cell, σ_{havg} is assumed to be simply the average of the top and bottom horizontal stresses.

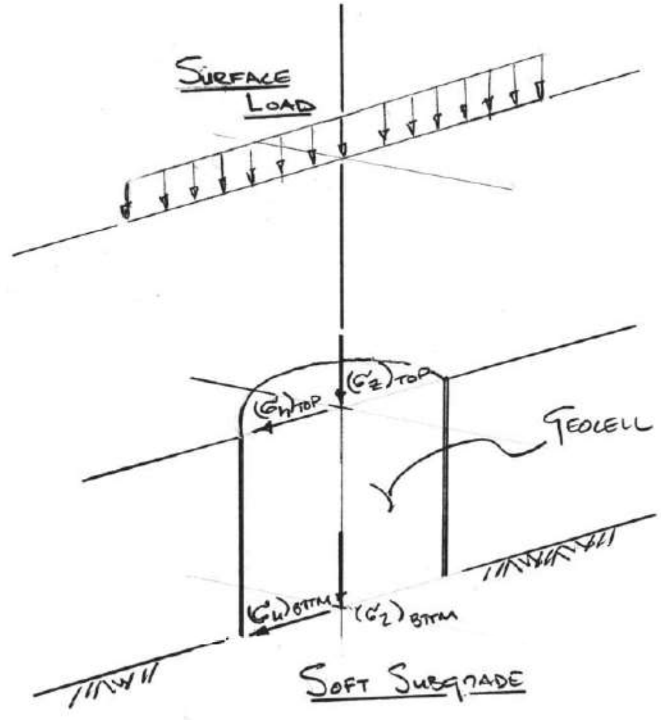

Figure 4. Assumed stress conditions acting on a single cell.

The load in the geocell being transferred to the geocell honeycomb system, $F_{transfer}$, is simply the one half the average horizontal stress times the interior surface area of a cell times the tangent of the interface friction, δ, between the granular fill and the interior walls of the geocell. This can be expressed as follows:

$$F_{transfer} = 1/2 \bullet (\pi DH) \bullet (\sigma_{havg}) \bullet (_{tan}\ \delta)$$

Note that the 1/2 factor conservatively accounts for the nonlinear distribution of the vertical stress with depth. This force is assumed to be transferred laterally by the geocell honeycomb and is subtracted from the vertical stress previously calculated at the base of the geocell, (sz)base, as follows:

$$(\sigma_z)\text{corrected} = (\sigma_z)\text{base} - (F_{transfer}/(\pi D^2/4))$$

The allowable stress on the geotextile underlying the geocell is assumed to equal 2.8 times the cohesive strength, c, of the subgrade. This is based on early recommendations by the U.S. Forest Service (Steward 1977) for geotextile stabilized haul roads designed for high traffic counts and light rutting. If the corrected vertical stress acting on the geotextile, (σ_z)corrected, is greater than 2.8c, then the thickness of the granular cover over the geogrid must be increased and the evaluation repeated.

Granular Material	Geocell Wall	Published* r = d/f	Measured** r = d/f
Coarse Sand/Gravel	Smooth	0.71	0.71
	Textured	0.88	0.83
	Smooth-Perforated	-	0.85
	Textured -Perforated	0.90	0.89
#40 Silica Sand	Smooth	0.78	0.68
	Textured	0.90	0.87
	Smooth-Perforated	-	0.87
	Textured -Perforated	0.90	0.93
Crushed Stone	Smooth	0.72	
	Textured	0.72	
	Smooth-Perforated	-	
	Textured -Perforated	0.83	
* = Hausemann 1976. ** = Steward 1977.			

Table 2. Peak interface friction angle ratio, r.

The force being transferred to the geocell system is dependent on the interface friction of the granular fill to the HDPE walls of the geocell. This is commonly referenced in terms of the ratio, r, of the interface friction angle to the internal friction angle of the granular fill. Typical published values for this interface friction ratio are compared in **Table 2** to those obtained specifically for this article. The performance of the geocells formed of textured HDPE sheet and those having perforations are essentially identical for most granular materials. Ironically, the perforations were introduced to allow drainage of geocell mats used on slopes for erosion control and not to improve bearing capacity applications. For typical bearing capacity applications, the perforations are not required for drainage and detrimentally impact the stiffness of the geocell. This will be discussed later.

As an example calculation, lets look at the problem shown on **Figure 5**. The vertical stress on the top of the geocell can be calculated as

$$(\sigma_z)_{top=90} \left[1\text{-}\left\{ \frac{1}{1 + (4.6/4)^2} \right\}^{1.5} \right] = 64.6 \text{ psi}$$

In a similar manner, the vertical stress on the bottom of the geocell is calculated to be 16.7 psi. The average horizontal stress acting on the geocell, σ_{havg}, is then calculated to be 9.7 psi. The total shear force transferred to the geocell, $F_{transfer}$, is equal to

$$F_{transfer} = ½ \bullet (\pi 8 \text{ x } 8) \bullet (9.7) \bullet (\tan 30.4) = 572 \text{ lb.}$$

The resulting vertical stress acting on the subgrade, (sz)corrected, is then calculated to be

$$(\sigma_z)\text{corrected} = 16.7 - (572/(\pi 8^2/4)) = 5.4 \text{ psi}$$

Given the allowable contact stress of 2.8 x 2.1 psi = 5.9 psi, the geocell design meets bearing capacity requirements.

Note that this design method is approximate and assumes that the structure of the geocell honeycomb is adequate to transfer the load laterally. Obviously this may not be true if the thickness of the plastic forming the cells is significantly reduced, if the welds holding the cells together are inadequate, or if the modulus of the plastic is significantly reduced. Since no calculations are performed for this honeycomb stiffness, the designer must cautiously accept manufacturer's recommendations. For bearing capacity applications, I would recommend avoiding geocells formed with perforations or texturing.

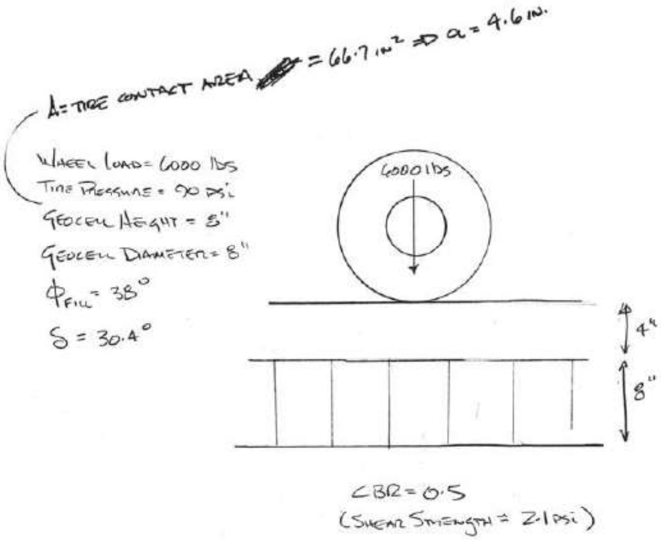

Figure 5. Peak interface friction angle ration, r.

Geocell specifications

Personally, I find evaluating specifications for commercial geocell products more difficult than reviewing the design concepts. Fortunately, all the commercial geocell products that the author reviewed are under license to the Army Corps of Engineers and shared many fundamental properties. Based on the design concepts previously reviewed, it is apparent that a geocell system for roadway applications must provide the following:

- A system stiffness that ensures applied loads are distributed laterally by the honeycomb structure
- Adequate frictional bond to the enclosed granular fill to ensure that either confinement or load transfer occurs
- Sufficient robustness that the HDPE used to form the geocell will survive both installation and service

As with all commercial products, the designer should understand the applicability of each specification requirement to the function being required of the product. The following discussion relates only to the roadway application of geocells.

System stiffness requirements

The work by Bathurst and Jarrett showed that geocells of the proper size and formed of welded smooth 50 mil thick HDPE sheet could provide adequate stiffness to distribute applied loads laterally. The geocells formed of geogrids did not perform as well. Four factors can have significant influence on the stiffness of the geocell honeycomb: weld strength, height-to-diameter ratio of the individual cells, panel thickness, and perforations to the sheet. Weld strength requirements for geocells are based on Corps of Engineers research (U.S. Army Corps) as summarized on **Table 3**. All commercial geocell products reviewed appeared to use and meet these requirements.

For roadway applications, the depth-to-diameter ratio of the individual cell should be approximately one. Commercial geocells are available in depths of 75 mm (3 in.), 100 mm (4 in.), 150 mm (6 in.), and 200

Strenth Property	Geocell Depth	Seam Peel Strength
Short-term Seam Strength	75 mm (3 in) 100 mm (4in) 150 mm (6in) 200 mm (8in)	1,060 N (240 lbf) 1,420 N (320 lbf) 2,130 N (480 lbf) 2,840 N (640 lbf)
Long-term Seam Strength	'Seam Hang Strength": a 100 mm welded joint must support a load of 72.5 kg (160 lbs) for 30 days minimum or a load of 72.5 kg (160 lbs) for 7 days minimum undergoing a temperature change from 23° C (74.5° F) ro 54° C (130° F) on 1 hour cycles.	

Table 3. Minimum geocell seam strength requirements.

Material Property	Test Method	Geogrid	GRI-GM13
Minimum Polymer Density	ASTM D1505	0.940 g/cm³	0.940 g/cm³
Minimum Carbon Black Content	ASTM D 1603	1.5%	2.0-3.0%
Environmental Stress Crack Resistance	ASTM D 1693	4,000 hr	200 hr

Table 4. Survivability physical properties of HDPE Geocells.

m (8 in.) with nominal areas of 289 cm^2 (44.8 $in.^2$), 460 mm^2 (71.3 $in.^2$) and 1.2 m^2 (187 $in.^2$). The depth-to-diameter ratio criteria would suggest that cost effective reinforcement would be obtained with 150 mm high cells having a nominal area of 289 cm^2 (H/D = 0.80) or 200 mm high cells having a nominal area of 460 mm^2 (H/D = 0.82).

The thickness of the HDPE forming the geocells is nominally 50 ± 3 mil. A factor that I have not seen addressed by direct research is the impact of texturing on this thickness. Typically we think of texturing as roughness added to the surface of a geomembrane so that the nominal thickness actually increases. However, the texturing in geocells is embossed into the sheet and results in a significant percentage of the sheet having a nominal thickness of only 31 mils by my measurement. Bending tests presented in **Table 3** indicated that the embossed texturing significantly reduces the stiffness of the geocell honeycomb.

Perforations are made in the strips forming geocells to allow lateral drainage when the system is installed on a slope or to improve the interface friction between the HDPE and granular fill. For roadway applications, lateral drainage is typically not a concern. Since excessive perforations could significantly reduce the stiffness of the geocell system (recall the poor performance of the geogrid formed geocells in the tests by Bathurst and Jarrett), the perforations should be only enough to improve the interface friction and not so many as to reduce the rigidity of the honeycomb system.

Frictional bond

Table 3 shows that the interface friction ratio (interface friction/internal friction angle of fill) between the geocell wall and the granular fill ranges from 0.71 for smooth to 0.9 for textured/perforated HDPE geocells. With the exception of crushed stone fill, the combination of texturing and perforations does not have merit. For smooth sheet, a minimal number of perforations dramatically increases the interface friction ratio. The number of perforations however must be limited to retain the strength of the geocell side wall.

Survivability

The key physical properties of the HDPE specified for commercial geocells are shown on **Table 4** with similar properties for HDPE liner material. Note that the geocell HDPE has greater stress crack resistance, which is needed since stone may be compacted direct on the HDPE in the geocell. Also, the liner HDPE has greater UV protection since it maybe exposed for extended periods of time in some applications. Conversely, the geocell HDPE is typically exposed to UV for only a short period of time during construction.

Summary

Geocells provide the most dramatic "geo" improvement in bearing capacity possible. For either sandy or weak clay subgrade, the performance is outstanding. Some 6.4 million $ft.^2$ (595,000 m^2) of geocells were used in the first Desert Storm to ensure mobility of the U.S. Army. Fortunately, they work as well in peacetime. This article has focused on the use of geocells in unpaved haul roads. Design procedures have also been developed by the Corps of Engineers to incorporate geocell systems in paved roadways. In such applications, the geocell honeycomb structure leads to a significant increase in the structural number, SN, of that layer. The readers are directed to the web sites of the manufacturers for guidelines on installation of geocells in roadway applications.

Rob Swan of SGI Testing Services performed the interface friction and bending tests of geocell products for the new data presented in this article. His ability to work out of the box is greatly appreciated.

Part Two of this series will examine the use of geocell systems in erosion control applications and in the construction of retaining walls. These "out-of-the-box" applications of geocells are now a principal use of these systems. GFR

References

Bathurst, R.J. and Jarrett, P.M. 1981. "Large-scale model tests of geocomposite mattresses over peat subgrades." Transportation Research Record 1188. Transportation Research Board, Washington, D.C.

Hausemann, M.R. 1976. "Strength of Reinforced Soil." Proceedings of 8th Australian Road Research Conference, vol.8.

Koerner, R.M. 1996. Designing with Geosynthetics. Prentice Hall, Engelwood Cliffs, N.J.

Presto Products Co. 2003. "The Geoweb." Load Support System Technical Overview. Presto Products Company, Appleton, Wis.

Steward, J.E., Williamson, R. and Mohney, J. 1977. Guidelines for use of Fabrics in Construction and Maintenance of Low-Volume Roads. USDA Forest Service, Portland, Ore.

US Army Corps of Engineers. Tech Report GL-86-19.

Webster, S.L. and Watkins, J.E. 1977. "Investigation of Construction Techniques for Tactical Bridge Ap proach Roads Across Soft Ground, Report S-77-1." Soils and Pavements Laboratory, U.S. Army Wa terways Experiment Station, Vicksburg, Miss.

Webster, S.L. 1979. "Investigation of Construction Concepts Across Soft Ground, Report S-79-20." Geo technical Laboratory, U.S. Army Waterways Experiment Station, Vicksburg, Miss.

Greg Richardson is president of G.N. Richardson & Associates, Raleigh, N.C.; www.gnra.com.