Effectiveness of Double-Layer HDPE Geocell System to Reinforce Reclaimed Asphalt Pavement (RAP)-Base Layer

Md. Ashrafuzzaman Khan, Nripojyoti Biswas, Aritra Banerjee, Surya Sarat Chandra Congress, and Anand J. Puppala

Abstract Geocell has been used for reinforcing foundation soil, stabilizing slopes, construction of retaining walls, and unpaved roads, but limited information is available about the construction of structural/flexible pavement with geocell. It can provide additional confinement for the infill material, which allows the use of recycled material in the base layer. Reclaimed asphalt pavement (RAP) often has adequate stiffness in terms of modulus of resilience, but excessive permanent deformation under repeated loading restricts the use of 100% RAP in the pavement. Though some studies are available regarding the use of geocell with RAP for unpaved roads, there are no established methods or guidelines available for the design and construction of geocell-reinforced structural pavement, especially with multi-layer geocell system. The main objective of this study is to design and construct a pavement section with a double-layer geocell system with RAP and monitor its field performance. A two-lane two-way road in Venus, Texas, which was suffering from cracking and rutting problems, was selected for the construction of the test section using geocell filled with RAP material. Earth pressure cells and shape array sensors were also installed to monitor the performance of the test section. Results obtained from the field show that the use of geocell can reduce the average vertical stress at the bottom of the reinforced base layer by 48%. Performance of the double-layer HDPE geocell system

Md. A. Khan · N. Biswas · S. S. C. Congress · A. J. Puppala (✉)
Texas A&M University, College Station, TX, USA
e-mail: anandp@tamu.edu

Md. A. Khan
e-mail: mak2019@tamu.edu

N. Biswas
e-mail: nripojyoti.biswas@tamu.edu

S. S. C. Congress
e-mail: congress@tamu.edu

A. Banerjee
University of Delaware, Newark, Delaware, USA
e-mail: aritra@udel.edu

E. Tutumluer et al. (eds.), *Advances in Transportation Geotechnics IV*, Lecture Notes in Civil Engineering 164, https://doi.org/10.1007/978-3-030-77230-7_45

incorporated in the flexible pavement bases with RAP material was found to be satisfactory with no significant deformation or cracking recorded during the first year of monitoring.

Keywords Geocell · RAP · Flexible pavement · Base reinforcement

1 Introduction

High plasticity expansive subgrade is one of the major reasons for pavement failures [1, 2]. Most of the low to medium volume roads, constructed over expansive subgrade, suffer from rutting, longitudinal cracking, shoulder dropping, and other types of depressions which are closely associated with the seasonal movements of subgrade soil [3–8]. Mitigation methods for such problems are available in the literature, which can be grouped into three categories: (1) mechanical/chemical stabilization of base and/or soil, (2) geogrid reinforcement, and moisture control barriers [9]. Several researchers concluded that stabilization increases soil stiffness, reduces swelling, and decreases the permeability of the soil [5, 10, 11]. However, excavating subgrade soil and mixing it with lime may not be a feasible option for highly trafficked areas [4]. Treating with cement may increase the layer stiffness but also increases the brittleness of the layer, which might lead to the block/longitudinal cracking [12]. Planar geosynthetics (i.e., geogrid) can be used in the base layer of the pavement to mitigate the problems associated with pavement rutting and fatigue cracking [13–15]. The planar geosynthetics layer can provide two-dimensional reinforcement, which can enhance the bearing capacity of the pavement layer; however, the excessive permanent deformation of the inferior type base material (i.e., RAP) does not allow the usage of such reinforcement without additional lateral support. Federal highway administration (FHWA) and other state agencies (DOTs) are encouraging the use of recycled material for the construction of pavement [2]. Utilization of recycled material can be a sustainable solution for the rehabilitation of existing road networks, and a special type of three-dimensional (3D) confinement is required to control the permanent deformation of such material [16, 17]. This kind of 3D confinement is commercially known as geocell, which is a honeycomb type structure, made from high-density polyethylene (HDPE) or novel polymeric alloy (NPA). The flexibility and elastic modulus for the NPA geocell are higher at elevated temperature; however, the performance of NPA and HDPE geocell at a lower temperature is almost similar [18]. Several laboratory studies indicated that the inclusion of geocell could significantly control the permanent deformation of the RAP-base layer [19–21]. Strength and stiffness of the geocell-reinforced RAP base (GRRB) layers were also back-calculated from the large-scale repeated load tests conducted by George et al. [22, 23]. The studies showed that the resilient moduli for the GRRB layers were 3–4 times higher than the average modulus obtained from the unreinforced RAP-base layer. Though the laboratory investigation of the GRRB layer showed significant improvement, but very few field studies are documented which hindered the use of such reinforced layer by the federal or state agencies [24]. Texas DOT (TxDOT) acknowledged the effectiveness of geocell for pavement reinforcement; however, no such use of geocell has been yet documented in the state of Texas [25]. Most of the case studies available on geocell-reinforced paved or unpaved road sections were constructed as a single-layer system [24, 26, 27]. Depending on the traffic and material configurations, thickness of base layer may vary; consequently, geocell of various thicknesses is required. However, the geocells are commercially available with variable heights but proper compaction of the infill materials is very difficult to achieve with higher lift thickness. Instead of a single-thick layer, double-thin layers of equivalent thicknesses may provide better compaction and enhance the performance of the flexible pavement. In this study, a distressed section of a pavement was replaced with double layer of GRRB to mitigate the issues, which are associated with the seasonal movements of the expansive subgrade.

2 Existing Road Section

The test section was constructed in the eastbound lane of a pavement, located in the North Texas region, and the current average annual daily traffic is less than 1500. This road was previously constructed over an untreated expansive subgrade; consequently, it suffered from distresses in the form of rutting, longitudinal cracking, and shoulder dropping. The pavement was rehabilitated by applying overlays; however, the longitudinal cracks reappeared within a year. This is a two-lane, two-way highway having a lane width of 11 ft (3.4 m), and width of the shoulder was 2.25 ft (0.7 m). The existing base layer of the road had a depth of 10 in. (0.25 m), which was revealed during the excavation of the existing road section. The total thickness of the surface layer varied from 2 to 4 in. (5–10 cm) due to the application of overlays over time.

3 The Objective of the Study

One of the main objectives of this construction project was to provide a sustainable solution for the existing pavement, which experienced distresses related to environmental loading. The application of RAP was considered as a sustainable solution, which can significantly reduce the landfill waste and depletion of the natural aggregate [28]. A 10 in. (25 cm) thick reinforced base layer was required for the road section, which is difficult and/or inefficient to construct with a single-layer system, and hence, double-layer geocell system was adopted. The objective of this current study is to evaluate the performance of the newly constructed test section with double-layer GRRBs.

4 Materials

Soil samples were collected from the subgrade level during the initial phase of the project. Subgrade was classified as high plasticity clay (CH) according to the unified soil classification system with a liquid limit of 58% and a plasticity index of 31. Based on ASTM D698, maximum dry density and optimum moisture content of the soil were determined as 14.1 kN/m^3 and 23.5%, respectively. The average swelling potential of 8.5% was determined from the ASTM 4546-method B. Resilient modulus of the soil at different confining pressures was also determined based on AASHTO T307 method. The subgrade modulus of 9 ksi (62 MPa) was used for the pavement analysis. The previous researchers [22] reported that the average resilient modulus for a 4 in. (10 cm) thick GRRB layer is around 43.5 ksi (300 MPa), and the modulus of the unreinforced recycled asphalt pavement was 30 ksi (206 Mpa). The height of the geocell used in the current study was also 4 in. (10 cm), which was made from HDPE sheets with a tensile strength of 1370 lb/ft (20 kN/m) and a secant elastic modulus of 48.6 ksi (355 MPa) at 2% strain. According to the data provided by the manufacturer, seam peel strength was 320 lb (1.42 kN), and the nominal expanded cell size was 12.6 in. × 11.3 in. (32.0 × 28.7 cm). A nonwoven geotextile was used in between the subgrade and base layer as a separator, meeting the criteria of the TxDOT DMS 6200 type.

5 Pavement Analysis

Most of the state agencies, including TxDOT, follow the linear elastic approach (LEA) for the static analysis of the multi-layered pavement structure. The horizontal strains at the bottom of the surface layer and vertical compressive strains at the top of the subgrade layer are considered for the determination of the fatigue and rutting life of the flexible pavement, respectively. The equivalent composite approach (ECA) considering the vertical strain on top of the subgrade layer has been considered for the pavement analysis in the current study. The ECA can be an effective solution to incorporate the geocells in a two-dimensional framework [29]. Numerous studies can be found where ECA has been adopted to model the geocell [30–33]. In this approach, improved strength and stiffness parameters of the reinforced layer are used, which can be either determined from the laboratory investigation or empirical correlation available in the literature. Results obtained from the ECA are presented in Fig. 1.

George et al. [22] conducted repeated load tests on 4 in. (10 cm) thick single GRRB layer in a laboratory setup to back-calculate the stiffness of the composite layer. The material set used for the laboratory investigation was similar to the material set used for the construction work in the present study. Hence, the equivalent strength and stiffness properties (also shown in Fig. 1) were used for the current pavement analysis with LEA. The rutting life of the flexible pavement was determined with the shell

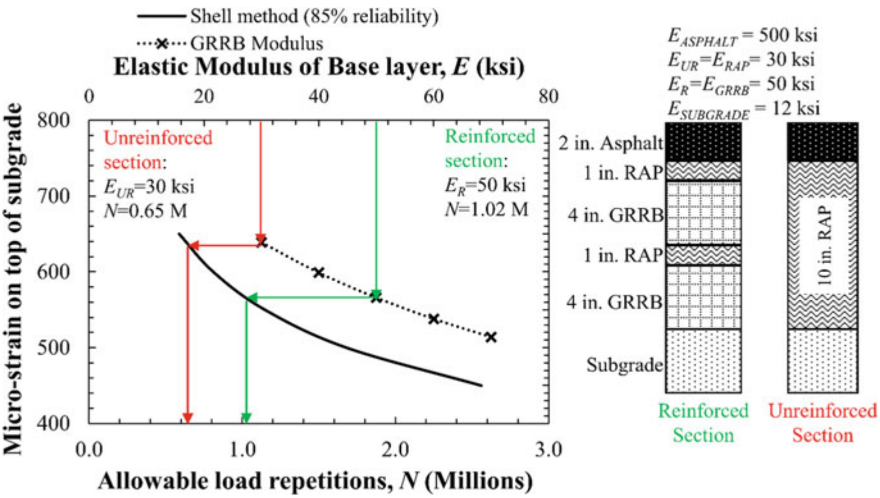

Fig. 1 Pavement analysis based on equivalent composite approach

method with 95% reliability [34]. A uniform circular load of radius 3 in. (7.5 cm) and a magnitude of 100 psi (680 kPa) was applied on the top of the pavement surface to generate the stress–strain profile. However, only the vertical compressive strain, acting on top of the subgrade layer, was used for rutting life analysis. The inclusion of geocell increased the elastic modulus of the base layer from 30 ksi (206 MPa) to 50 ksi (345 MPa), which can increase the pavement rutting life from 0.65 million to 1.02 million load repetitions.

6 Construction of Test Section

The test section was constructed within the eastbound lane, covering a total area of 120 × 15 ft (36.6 × 4.6 m). The existing road section was milled up to a depth of the subgrade level with the help of an RX-600e type cold planar machine. Construction sequence and instrumentation of the test section are discussed in the following sections.

6.1 Construction Sequence

Preparation of Roadbed:

Before the construction of the GRRB layers, a smoother pavement bed surface was achieved with the help of a bobcat with a loader head. A pneumatic-type roller was used to achieve proper compaction.

Placement of Geotextile:

A nonwoven-type geotextile (see Fig. 2a) with a roll width of 15 ft (4.6 m) was used as a separation layer between the subgrade and bottom GRRB layer. Application of geotextile will also prevent the migration of finer particles of subgrade into the base layer and intrusion of base aggregate into the subgrade layer.

Construction of GRRB layers:

The number of geocell panels required for covering the width of the test section was determined by dividing the width of the test Sect. (15 ft or 4.6 m) with the optimum width of the geocell panel after expansion (7.5 ft or 2.3 m). Before the placement of the geocell panel (Fig. 2b) on top of the geotextile, two adjacent geocell panels were tied with each other using commercially available plastic zip ties. Four sets of geocell panels ($2 \times 4 = 8$ panels) were required to construct one single layer of reinforcement, which covered the total area of the test section. After the placement of geocells, RAP materials were dumped (Fig. 2c) with the help of loading trucks. After the placement of the RAP layer, the motor grader was used to scrap and maintain a level surface before compacting the GRRB layer with pneumatic-type roller, shown in Fig. 2d. A cover layer, on top of the geocell, was required to protect the geocell

Fig. 2 Construction sequence: **a** placement of geotextile, **b** placement of first geocell layer, **c** placement of RAP, **d** compaction of GRRB layer, **e** placement of second geocell layer, and **f** final surface layer

from the construction equipment. Consequently, a minimum cover thickness of 1 in. (2.5 cm) was maintained throughout the test section. The second layer of GRRB (Fig. 2e) was constructed following the same technique described above, and the second cover layer was required in between the asphalt and second GRRB layers.

Construction of Top Asphalt Layer

A temporary surface layer with flex base material was used for a week before the application of the final asphalt layer. The test section was opened to traffic during this period, which also helped to compact the base layer. Before the construction of the final layer, i.e., top asphalt layer (Fig. 2f), the top of the base layer was further compacted with a pneumatic roller and coated with a seal coat.

6.2 *Instrumentation*

Pressure and deformation sensors (Fig. 3) were installed before the placement of the geotextile layer. Shape array accelerometer (SAA) was enclosed in a 2 in. (5 cm) diameter PVC casing, installed during the construction, and placed on top of the subgrade level. Earth pressure cells (EPCs) were also installed on top of the subgrade level to measure the vertical compressive stress under each wheel path. The control Sect. (15 × 1 ft) is located adjacent to the reinforced section, which was constructed before the construction of the reinforced section. The thickness of the unreinforced RAP-base layer was 10 in. (25 cm), and the SAA sensors run across this control section.

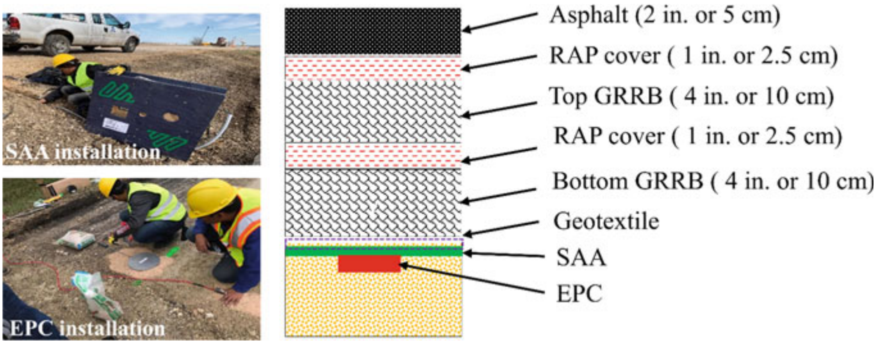

Fig. 3 Instrumentation of the test section

7 Results of Performance Monitoring

The newly constructed test section was opened to traffic from December 15th, 2018, and since then, vertical deformations and vertical stresses data have been collected on a bi-weekly basis. In addition to the sensor data, the performance of the road section was also monitored visually for any depressions or cracking on top of the pavement surface. Stresses and deformation observed from the field are discussed in the following sections.

7.1 Stress Analysis

Vertical stresses obtained from the pavement analyses were compared with the observed stresses from the EPCs installed just under the bottom of the reinforced base layer. The static load of 100 psi (680 kPa) was considered on top of the pavement surface through a 6 in. diameter loading plate to obtain the vertical stresses at various depths based on LEA. The average vertical stress obtained from the EPCs was 3.5 psi (24.1 kPa); however, the average vertical stress obtained from the LEA approach was 6.7 psi (46.2 kPa). The maximum vertical stresses observed in the field were lower compared to the vertical stresses obtained from the theory due to the dynamic nature of loading in the field. The longitudinal strain decreases as the speed of the vehicle increases, which is one of the reasons for getting lower vertical stresses in the field compared to the analytical solution [35]. Comparison of field results with analytical approach shows a 48% reduction in vertical stress; however, field study on geocell-reinforced gravel base layer showed a reduction of 28% in the vertical stress on top of subgrade layer [24]. Experimental results on geocell-reinforced RAP also showed that the inclusion of geocell could increase the stress distribution angle from 19° to 25° [36]. The increase of stress distribution angle indicates the reduction of stresses due to the inclusion of geocell.

7.2 Deformation Analysis

The results obtained from the SAAs provided the actual shape of the sensor array containing *x*, *y*, and *z* coordinates with time. These data were further analyzed to get the deformation values under the right and left wheel path locations, as shown in Fig. 4. Results obtained from the control section were also compared with the reinforced section. The deformation of the subgrade soil also depends on the fluctuation of moisture level. However, moisture sensors were not installed, but rainfall data collected from the nearby weather station were used (shown in Fig. 4) to understand the possible intrusion of moisture into the subgrade soil. Cumulative rainfall data for the two-week period are presented here, which may explain the trend of

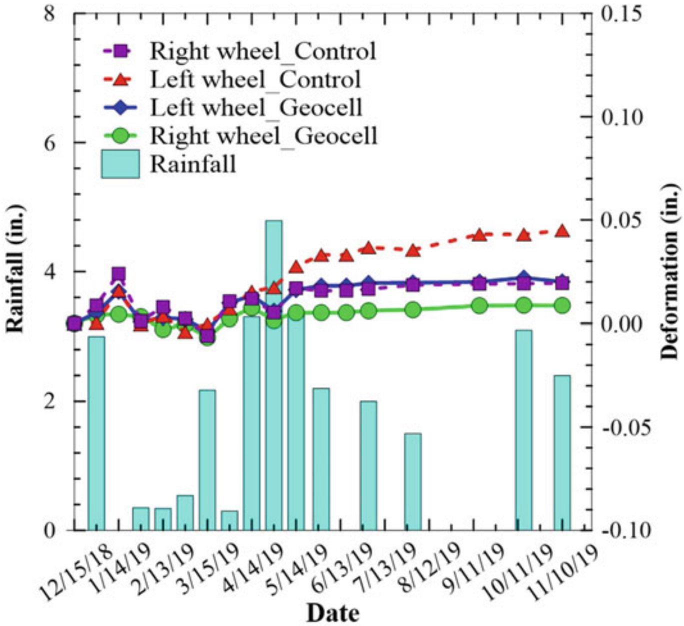

Fig. 4 Subgrade deformation obtained from shape array accelerometer (SAA)

subgrade movement. Positive values of deformation indicate heaving and negative values indicate a settlement. During the months of April and May 2019, a sudden increase in heaving can be attributed to higher rainfall. Average heaving observed after the long wetting period was 0.05 in. (0.11 cm) for the control section, whereas maximum heaving observed under the reinforced section was only 0.03 in. (0.07 cm). The inclusion of geocell can increase the stress distribution angle, which helps to distribute the swelling pressure over a larger area and reduce the subgrade movement [20, 26, 37]. This field study indicates that the average reduction in heaving due to the inclusion of geocell was 36%, which is also supported by the experimental observation by previous researchers, who reported that the inclusion of geocell in the base layer could reduce the heaving of expansive soil by 29% [38].

During the current monitoring period, no surficial cracks or depressions were found on the top surface of the reinforced section; however, the maximum visible depression of 0.5 in. (1.25 cm) was observed on top of the control section. A 10 in. (25 cm) thick unreinforced RAP base layer undergone a large amount of permanent deformation, which was the main reason for the surface depression. In contrast, geocells, within the reinforced section, restrained the lateral movement of the infill material [20, 39], which eventually controlled the vertical permanent deformation of the GRRB layers.

8 Conclusions

In this study, a double-GRRB layer was constructed, and the performance was further evaluated, based on field monitoring. The field results obtained from this initial monitoring period indicated that the inclusion of geocell in the base layer could control the heaving of subgrade and reduce the permanent deformation of the inferior base material. The following conclusions can be drawn from this study.

- Double-layer geocell can be a feasible solution where a thicker base layer is required for highly trafficked roads
- Total time required for rehabilitation work is much less than other types of subgrade stabilization techniques, such as chemical stabilization, and the road section was opened to traffic, immediately after construction
- GRRB has the potential to reduce the vertical stresses on the subgrade layer up to 48%
- GRRB has the potential to reduce the heaving of subgrade soil by 36%

This study only presents the short-term performances of the double-layer GRRB, constructed within a flexible pavement section; however, long-term field studies are required to understand the efficiency of the geocell reinforcement to develop guidelines for future design and construction.

Acknowledgements This research was funded by Texas Department of Transportation (TxDOT)—Fort Worth district (Mr. Richard Williammee, P.E. and Mr. Paul Spraggins, P.E.) and NSF Industry-University Cooperative Research Center (I/UCRC) program funded 'Center for Integration of Composites into Infrastructure (CICI)' site at TAMU (NSF PD: Dr. Prakash Balan; Award #2017796). The authors would like to thank their support. The authors also like to express sincere gratitude to the Geo Products, LLC, for providing Envirogrid geocells for the research. The authors would further like to express their sincere gratitude to the TxDOT construction crew, Dr. Sayantan Chakraborty and other members of UTA- SARCI group for their help during the construction phase.

References

1. Puppala AJ, Intharachicagocsombat N, Qasim SR (2004) The effects of using compost as a preventive measure to mitigate shoulder cracking : laboratory and field studies. Arlington
2. Das JT, Banerjee A, Puppala AJ, Chakraborty S (2019) Sustainability and resilience in pavement infrastructure: a unified assessment framework. Environ Geotech 1–13. https://doi.org/10.1680/jenge.19.00035
3. Banerjee A, Puppala AJ, Hoyos LR, Likos WJ, Patil UD (2019) Resilient modulus of expansive soils at high suction using vapor pressure control. Geotech Test J 43:1–17
4. Dessouky SH, Oh J, Ilias M, Lee SI, Park D (2015) Investigation of various pavement repairs in low-volume roads over expansive soil. J Perform Constr Facil 29:04014146(1–9). https://doi.org/10.1061/(ASCE)CF.1943-5509.0000623
5. Puppala AJ, Musenda C (2000) Effects of fiber reinforcement on strength and volume change in expansive soils. Transp Res Rec 1736:134–140. https://doi.org/10.3141/1736-17

6. Banerjee A (2017) Response of unsaturated soils under monotonic and dynamic loading over moderate suction states. https://rc.library.uta.edu/uta-ir/handle/10106/26940
7. Puppala AJ, Congress SSC, Banerjee A (2019) Research advancements in expansive soil characterization, stabilization and geoinfrastructure monitoring. In: Latha GM (ed) Frontiers in geotechnical engineering. Springer, Singapore, pp 15–29
8. Khan MA, Hossain MS, Khan MS, Samir S, Aramoon A(2017) Impact of wet-dry cycles on the shear strength of high plastic clay based on direct shear testing. In: Geotechnical Special Publication. American Society of Civil Engineers (ASCE), pp 615–622
9. Zornberg JG, Gupta R (2009) Reinforcement of pavements over expansive clay subgrades. In: Proceedings 17th International conference soil mechanics geotechnology engineering academy practical geotecholgy engineering. vol 1. pp 765–768. https://doi.org/10.3233/978-1-60750-031-5-765
10. Freeman TJ, Little DN (2002) Maintenance strategies for pavements with chemically stabilized layers
11. Puppala AJ, Hoyos LR, Potturi AK (2011) Resilient moduli response of moderately cement-treated reclaimed asphalt pavement aggregates. J Mater Civ Eng 23:990–998. https://doi.org/10.1061/(asce)mt.1943-5533.0000268
12. Chen DH, Hong F, Zhou F (2011) Premature cracking from cement-treated base and treatment to mitigate its effect. J Perform Constr Facil 25:113–120. https://doi.org/10.1061/(ASCE)CF.1943-5509.0000140
13. Imjai T, Pilakoutas K, Guadagnini M (2019) Performance of geosynthetic-reinforced flexible pavements in full-scale field trials. Geotext Geomembranes 47:217–229. https://doi.org/10.1016/j.geotexmem.2018.12.012
14. Vennapusa PKR, White DJ, Wayne MH, Kwon J, Galindo A, García L (2018) In situ performance verification of geogrid-stabilized aggregate layer: route-39 El Carbón-Bonito oriental, honduras case study. Int J Pavement Eng 8436:1–12. https://doi.org/10.1080/10298436.2018.1442576
15. White DJ, Vennapusa PKR (2017) In situ resilient modulus for geogrid-stabilized aggregate layer: a case study using automated plate load testing. Transp Geotech 11:120–132. https://doi.org/10.1016/j.trgeo.2017.06.001
16. Khan MA, Biswas N, Banerjee A, Puppala AJ (2020) Performance of Geocell-Reinforced Recycled Asphalt Pavement (RAP) bases in flexible pavements built on expansive soils. Geo-Congress 2020, American Society of Civil Engineers, Reston, VA, 488–497. https://doi.org/10.1061/9780784482810.051
17. Khan MA, Biswas N, Banerjee A, Puppala AJ (2020) Field performance of geocell reinforced recycled asphalt pavement base layer. Transp Res Rec J Transp Res Board 2674:69–80. https://doi.org/10.1177/0361198120908861
18. Pokharel SK, Han J, Parsons RL, Qian Y, Leshchinsky D, Halahmi I (2009) Experimental study on bearing capacity of geocell-reinforced bases. In: Bearing capacity of roads, railways and airfields—proceedings of the 8th international conference on the bearing capacity of roads, railways and airfields. pp 1159–1166
19. Han J, Pokharel SK, Yang X, Manandhar C, Leshchinsky D, Halahmi I, Parsons RL (2011) Performance of geocell-reinforced rap bases over weak subgrade under full-scale moving wheel loads. J Mater Civ Eng 23:1525–1534. https://doi.org/10.1111/vop.12354
20. Thakur JK, Han J, Parsons RL (2016) Factors influencing deformations of geocell-reinforced recycled asphalt pavement bases under cyclic loading. 29:04016240(1–12). https://doi.org/10.1061/(ASCE)MT.1943-5533.0001760
21. Thakur JK, Han J (2015) Recent development of recycled asphalt pavement (rap) bases treated for roadway applications. Transp Infrastruct Geotechnol 2:68–86. https://doi.org/10.1007/s40515-015-0018-7
22. George AM, Banerjee A, Puppala AJ, Saladhi M (2019) Performance evaluation of geocell-reinforced reclaimed asphalt pavement (RAP) bases in flexible pavements. Int J Pavement Eng 1–11. https://doi.org/10.1080/10298436.2019.1587437

23. George AM, Banerjee A, Taylor T, Puppala AJ (2019) Large-scale experimental studies to evaluate the resilient modulus of geocell-reinforced reclaimed asphalt pavement bases. In: Geosynthetics conference 2019, Houston, Texas
24. Kief O, Rajagopal K (2019) Three dimensional cellular confinement system contribution to structural pavement reinforcement. In: Geosynthetics India. pp 1–12
25. TxDOT Pavement Manual: Pavement Manual (2019) Austin
26. Kief O, Schary Y, Pokharel SK (2015) High-modulus geocells for sustainable highway infrastructure. Indian Geotech J 45:389–400. https://doi.org/10.1007/s40098-014-0129-z
27. Rajagopal K, Veeragavan A, Chandramouli S (2012) Studies on geocell reinforced road pavement structures. In: GA 2012-5th Asian regional conference on geosynthetics: geosynthetics for sustainable adaptation to climate change. pp 497–502
28. George AM, Banerjee A, Puppala AJ, Praticò F (2019) An integrated LCA-LCCA framework for the selection of sustainable pavement design. In: Transportation research board, 98th annual meeting. Washington, D.C.
29. Hegde A (2017) Geocell reinforced foundation beds-past findings, present trends and future prospects: a state-of-the-art review. Constr Build Mater 154:658–674. https://doi.org/10.1016/j.conbuildmat.2017.07.230
30. Hegde A, Sitharam TG (2015) Experimental and analytical studies on soft clay beds reinforced with bamboo cells and geocells. Int J Geosynth Gr Eng 1:13. https://doi.org/10.1007/s40891-015-0015-5
31. Latha GM, Rajagopal K, Krishnaswamy NR (2001) Measurement of strains in geocells supporting an embankment. Geosynth Conf 2001:387–398
32. Mehdipour I, Ghazavi M, Ziaie R (2013) Numerical study on stability analysis of geocell reinforced slopes by considering the bending effect. Geotext Geomembranes 37:23–34. https://doi.org/10.1016/j.geotexmem.2013.01.001
33. Dash SK, Sireesh S, Sitharam TG (2003) Behaviour of geocell-reinforced sand beds under circular footing. Proc Inst Civ Eng-Gr Improv 7:111–115. https://doi.org/10.1680/grim.2003.7.3.111
34. Huang YH (2004) Pavement analysis and design. Pearson Prentice Hall
35. Al-qadi IL, Wang H (2009) Evaluation of pavement damage due to new tire design. Urbana-Champaign
36. Thakur JK (2013) Geocell-reinforced unpaved and paved roads with recycled asphalt pavement (rap) bases: experimental study and damage model development
37. Pokharel SK (2015) Validation of geocell design for unpaved roads. In: Geosynthetics. Portland, Oregon, pp 711–719
38. Tamim MM (2017) Evaluating the effectiveness of a hybrid geosynthetic reinforcement system to mitigate differential heave on flexible pavement due to expansive subgrades
39. Hegde A, Sitharam TG (2015) Joint strength and wall deformation characteristics of a single-cell geocell subjected to uniaxial compression. Int J Geomech 15:04014080. https://doi.org/10.1061/(ASCE)GM.1943-5622.0000433