The Relevance of Geogrid Reinforcement in Flexible Road Pavement: A Review

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Abstract. This study reviews the available design methods for the use of geogrid in the unpaved road. Characterization and properties of geogrid for effective utilization in the pavement have been discussed briefly. The effective optimal location in the pavement, minimum number, interaction coefficient and tensile strength criteria of geogrid have been well explained in this study. This study also includes results of experimental work, small scale laboratory test, and field performance of geogrid reinforced flexible road pavement. Currently, there is no proper guideline available for the use of geogrid reinforcement in the flexible pavement. All the past application of geogrid in the pavement is mainly based on experience, field study, laboratory study, and few limited available guidelines. This study provides a detail description of previous findings and research gap for the use of future research.

Keywords: Geogrid, Reinforcement, Flexible Pavement, Rutting, Fatigue Cracking.

1 Introduction

Flexible road pavement consists of a different layer of bituminous and aggregate material. Due to the scarcity of natural aggregate material, there is a need to reduce down the demand for this natural aggregate. The solution for this challenge is to reduce the thickness of the pavement layer with effective use of geosynthetics without compromising on the performance of pavement against general failures such as rutting and fatigue cracking. Among all the available type of geosynthetics, Geogrid is mainly using for reinforcement purpose in the pavement due to its good reinforcing property. A reinforcement of geogrid is mainly due to the interlocking of aggregate, tension membrane effect, wider distribution of loads, etc.

1.1 Flexible Pavement

The pavement is a multi-layered structure. It is made up of compacted soil, unbound granular material (stone aggregates), asphalt mix or cement concrete (or other bound material) put as horizontal layers one above the other [1]. Two types of pavements are generally recognized as serving this purpose, namely flexible pavements, and rigid pavements. This study gives an overview of the application of Geogrids in flexible pavements.

1.2 Geogrid

Geogrid is a polymeric material consisting of connected parallel sets of intersecting ribs with apertures of sufficient size to allow strike-through of the surrounding soil, stone, or other geotechnical material [2]. Fig. 1 and 2 show the uniaxial and biaxial type of geogrids. It is a planar, polymeric product consisting of a mesh or net-like regular opening. A network of intersecting tensile-resistant elements called ribs, integrally connected at the junctions. The ribs are connected to each other either by extrusion, bonding or interlacing process. Resulting geogrids are called extruded geogrid, bonded geogrid and woven geogrid respectively. Extruded geogrids are classified as uniaxial or biaxial geogrids. Biaxial geogrids are used in pavement.

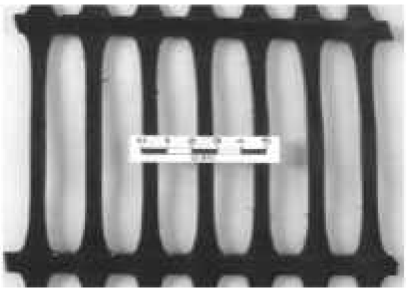

Fig. 1. Uniaxial Geogrid [3]

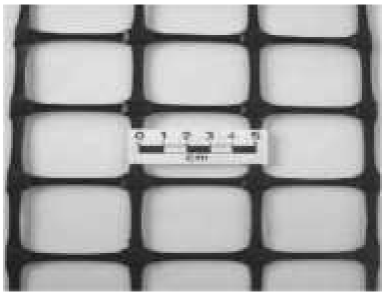

Fig. 2. Biaxial Geogrid [3]

1.3 Characterization of Geogrid

A comprehensive characterization of geogrid is crucial before its practice. The common geogrid characterization comprises the measurements of its aperture size, the thickness of rib and junctions, number of ribs per meter length, tensile strength, interfaces frictional strength, flexural stiffness, and aperture stability, etc. In addition, the information about unconventional chemical properties of geogrids such as carbon black content, resistance to ultraviolet rays and long term degradation is vital in the design of earth structures containing geogrid. Table 1 lists the typical physical, mechanical and chemical properties of the geogrids and the reference standard used in the determination for these properties are also mentioned.

2.0 Design Method for Geogrid Reinforced Unpaved Road

2.1 Giroud and Han Method

Giroud and Han [4,5] proposed equation (1) for the determination of aggregate thickness for the geogrid reinforced unpaved road. This method is based on the fact that base course thickness depends on bearing capacity of subgrade and stresses at the base-subgrade interface.

$$h = \frac{0.868 + \left(0.661 - 1.006 J^2\right)\left(\frac{r}{h}\right)^{1.5} \log N}{\left[1 + 0.204\,(Re - 1)\right]} + \left(\sqrt{\frac{\frac{P}{\pi r^2}}{\frac{s}{fs}\left[1 - 0.9 e^{-\left(\frac{r}{h}\right)^2}\right] Nc \cdot fc \cdot CBRsg}} - 1 \right) r \qquad (1)$$

Where h = required base course thickness (m), J = geogrid aperture stability modulus (m-N/degree), N = number of axle passes, P = wheel load (kN), r = radius of equivalent contact area (m), R_e = limit modulus ratio, s = allowable rut depth (mm), f_s = 0.075m, N_c = bearing capacity factor for 3.14 for unreinforced unpaved road and 5.71 for Geogrid reinforced unpaved road.

2.2 Leng and Gabr Method

Leng and Gabr [6] proposed a model which is highly realistic as they consider degradation in load distribution angle and an elastic modulus of base and subgrade layer along with the contribution of geogrids against repeated loading. The base layer thickness for geogrid reinforcement is given by equation (2).

$$h = \frac{a.(\ 1 + K2\ .\log N)}{\tan \alpha 1} \left(\sqrt{\frac{Pc}{mc\ .Nc.Cu}} - 1 \right) \qquad (2)$$

Where 'h' is the required base layer thickness (m); 'a' is the radius of the equivalent tire contact area (m); 'K_2' is the degradation constant of the stress distribution angle; 'N' is the number of axle passes; 'α_1' is an initial stress distribution angle; 'P_c' is the tire contact pressure (kN/m^2); 'm_c' is a mobilized bearing capacity ratio; 'N_c' is a bearing capacity factor and 'C_u' is the subgrade undrained shear strength. Reduction in thickness for geogrid reinforced base course layer is higher for Leng and Gabr method compared to that of Giroud and Han method.

Table 1. Typical Properties of Geogrid

Properties	Units	Test methods
Aperture size	mm	Calipers
Thickness of rib	mm	Calipers
Thickness of Junction	mm	ASTM D5199 [7]
Tensile strength	KN/m	ASTM D4595 [8] & ASTM D6637[9]
Junction strength efficiency	%	ASTM D7864 [10]
Carbon black content	%	ASTM D4218 [11]
Resistance to UV Degradation	%	ASTM D4355-05 [12]
Resistance to Long Term Degradation	%	EPA 9090 [13]
Flexural Stiffness/rigidity	mg-cm	ASTM 5732-01 [14]/ D1388 [15]
Aperture stability/ Torsional stiffness	m-N/deg	ASTM D7864 [16]

3.0 Experimental studies

3.1 Laboratory Model Test

Most of the prior researchers have used the laboratory model tests set up to check the effectiveness of geogrid in the flexible pavement. The typical test setup contained a tank with varying size ranging from the smallest dimension 0.3×0.3×0.2 (L×B×H) to the largest dimension 2.4×2.35×2.20 is used in previous studies. Static cyclic type of loading is employed to simulate actual traffic on the laboratory test section by Elleboudy et al. [17], Suku et al. [18], Sun et al. [19], Góngora & Palmeira [20] and Tavakoli M. & Khazaei [21]. Monotonic loading is employed by Biswas et al. [22]. Wu et al. [23] used loaded wheel tester (LWT) & Cyclic plate loading. Correia & Zornberg, [24] used repeated cyclic load by wheel tracking facility. Ling Hoe I. & Liu Z. H. [25] used monotonic, cyclic and dynamic loading on pavement test section and it is observed that the improvement due to the incorporation of geogrid was more significant in case of dynamic loading compared to monotonic loading.

Majority of the researcher used square-shaped aperture geogrid in their study. Almost in all the above study deformation at top of the asphalt layer, tensile strain at the bottom of asphalt concrete layer and compressive strain at top of subgrade are the governing factor for improvement due to geogrid reinforcement.

3.2 Laboratory Testing

Kuity & Roy, [26] observed that the unsoaked and soaked CBR value of mix Soil: Pond ash (2:3) is increased by 1.44 and 1.08 times than parent soil for the inserted geogrid at the half-height of the mould.

Singh M. et al. [27] using a single layer and double layer of glasgrid, geogrid and geomat as reinforcement at a different height in CBR mould and work out that single layer reinforcement the geogrid performs well than other geosynthetics used in this study while the geomat performs best for double layers.

Chen X. et al. [28] investigated the shear behavior of geogrid reinforced weathered mudstone (coarse-grained soil) through large-scale triaxial tests. With increasing confining pressure and number of the geogrid layer the shear deformation resulting in to strain hardening behavior. Apparent cohesion of granular soil is enhanced due to the insertion of the geogrid layer.

To evaluate resilient and permanent deformation of geogrid reinforced specimen repeated load triaxial test was performed by Abu-farsakh M. et al. [29] and worked out that inclusion of geogrid layer resulting in less permanent deformations under cyclic loading compared to unreinforced specimens. The geogrid geometry and tensile strength had perceptible effects on the samples' performance. It is noticed that due to the inclusion of geogrid, resilient modulus of reinforced sample is significantly improved.

3.3 Interaction of Geogrid with Pavement Material

Interlocking effect (passive resistance) associated with the functions of geogrid. Interlocking effect of geogrid is described by interaction parameters such as interface friction angle (ϕ_r), coefficient interaction (C_i) and efficiency factor (E_ϕ). A large direct shear test and pull-out test are used to find out the interaction parameter followed by ASTM D3080 [30] and ASTM D6706 [31] respectively.

The pullout test was performed on geogrid, woven and non-woven geotextile embedded in granular soil by Choudhary & Krishna, [32] and worked out the influence of D_{50} size of soil on the interface coefficient. The soil with larger average particle sizes (D_{50}) show an increase in the soil-geosynthetic interface resistance. The friction efficiency factors (E_ϕ) were evaluated from the calculated values of 'ϕ' and 'δ_{GT}' using equation 3.

$$E_\phi = \frac{\tan \delta GT}{\tan \phi} \quad (3)$$

Where ϕ = Angle of internal friction, δ_{GT} = interfacial friction angle. The coefficient interaction factors (Ci) were evaluated from the calculated 'T' pull-out resistance per unit width using equation 4.

$$Ci = \frac{T}{2 \times Le \times \sigma' n \times \tan \phi} \quad (4)$$

Where T = pullout resistance per unit width (kN/m), ϕ = internal friction angle of soil, L_e = L-peak pullout deformation (m) and σ'_n = effective normal stress on geosynthetic (kN/m^2). The pullout interaction coefficient is found in the range of 0.67- 1.72 for different geosynthetics and test condition, the highest value 1.72 observed for geogrid.

The large direct shear test is employed by Liu et al. [33] to encounter the influence of transverse ribs in the soil-geogrid interaction. The result large direct shear test shows that interfaces of sand-geogrid are expressively greater than that of the interface of sand-geotextile. A higher value of interface mainly due to friction between sand & rib, sand-sand shear at aperture openings and the transverse ribs gives an additional input to the total interface value of sand-geogrid. Approximately 10% of interface shear resistance is only due to transverse ribs.

Goud & Umashankar, [34] determine interface shear parameters for various pavement materials with geogrid and wire mesh reinforcement by using large size direct shear test apparatus. Interaction coefficients range from 0.73 to 1.16 for geogrid reinforced interfaces, whereas it varies from 0.95 to 1.45 for wire mesh reinforced interface under normal stress ranging from 30 to 90 kPa.

Interface shear modulus of different interfaces obtained in this study ranges from about 12,165–37,433, 15,018–54,440, and 19,773–57,337 kPa/m corresponding to the normal stress equal to 30, 60, and 90 kPa respectively.

4.0 Field Studies

Sixteen sections of stabilized pavement foundations were studied by White J. D. et al. [35] with ground conditions ranging from soft to very stiff. Different geosynthetic material such as geocell, woven and nonwoven geotextile, biaxial and triaxial geogrid is used at the interface of subbase and subgrade. Estimation of modulus of pavement layer is done by using FWD, LWD, and RICM (roller integrated compaction monitoring) technology. Benefits of geosynthetic stabilization are not discussed throughout the study as the focus of study mainly on developing correlations between RICM and FWD.

Tang X. et al [36] constructed six test sections at Pavement Research Facility of the Louisiana Department of Transportation and Development in Port Allen. Section no. 1 and 4 are control section. Section no. 2 consist dual layer of triaxial geogrid first at $1/3^{rd}$ from the top surface of the aggregate layer and second at the interface of aggregate and subgrade. Section 3 consists of a single layer of triaxial geogrid at the interface of aggregate and subgrade. Section 5 and 6 consists of a single layer of high strength geotextile with an aggregate layer of varying thickness. Repeated moving loading was applied to the test section by using accelerated load facility (ALF). Section 1 and 4 exhibit higher rutting than the geosynthetic reinforced section it shows benefit of geosynthetic.

Zornberg J. G. et al. [37] evaluate the performance of geosynthetic-reinforced and lime-treated low volume roads under both traffic loads and environmental conditions. The overall performance of the road sections under traffic loads and environmental conditions were carried out by using the Index of Pavement Performance (IPP). An IPP was used to compare and rank the overall performance of the road sections. This index of pavement performance is defined as the summation of all weighted distress percentage and given by,

$$IPP = \sum_{i=1}^{n} Wi \times Di \quad (5)$$

Where D_i = percentage of each distress, W_i = corresponding weighing factor.

On the basis of IPP value, it is confirmed that the geogrid reinforcement improved the performance of the road.

Eight-year field performance of secondary road consisting geosynthetic at the interface of subgrade and base was carried out by Al-Qadi I. L. and Alexander A. K. [38]. The road section was constructed at Bedford County, Virginia. Total 9 sections were constructed with each 15 m length and forming group of three sections having 100, 150, and 200 mm base layer thicknesses. In every group one section is geotextile reinforced, one is geogrid reinforced and one is control section. Structural analysis of all sections is carried out by using the base damage index and surface curvature index with the help of deflection data obtained from falling weight deflectometer (FWD) test. Rutting measurements were also carried out on all the sections. Results show that the geosynthetic notably improved the performance unpaved road in terms of rutting and deflection data.

Fannin & Sigurdsson, [39] constructed unpaved five test sections in Vancouver, British Columbia each 16 m long and 4.5 m wide. Three sections with different geotextiles, one section with geogrid and one section are unreinforced. Loading was done by vehicular trafficking of standard axle load passes. Rutting was the performance criteria for all the section. Significant improvement was observed in terms of trafficability for the inclusion of geosynthetic at base and subgrade interface.

Holder H. W. & Andreae J. [40] constructed geogrid reinforced pavement section in the city of Twin Falls, Idaho at the intersection of Washington Street and Filer Avenue in 2001. The FWD data were used to investigate the benefits of geogrid reinforcement. Analysis of FWD data with AASHTO (1993) [41] method shows no benefit, while second analysis by Modulus 5.1 software (developed by the Texas Transportation Institute 1997) show that base course thickness can be reduced by 20% with geogrid reinforcement. As there was no control section the evaluation of benefits of geogrid reinforcement becomes absolutely critical.

To identify the effectiveness of geogrid in the low volume road, nine test sections were constructed at the University of Illinois Advanced Transportation Research and Engineering and Laboratory (ATREL) by Al-Qadi I. L. et al. [42]. A total of 173 instruments were used to capture the performance of test sections subjected to accelerated loading system. Test sections were divided into three groups on the basis of the thickness of the base thin base pavement, intermediate base pavement, and thick base pavement, each group consisted of one control section for comparison. Effectiveness of geogrid was given in terms of 'Reinforcement Index' (RI),

$$RI = \frac{Pavement\ Response}{Pavement\ Depth} \times 100\% \quad (5)$$

Different pavement responses considered in this study to show the effectiveness of geogrid such as base (transverse strain), base (longitudinal strain), the subgrade (vertical deflection), the subgrade (vertical pressure) and HMA (transverse strain). Results show that the efficiency of geogrid is more notable when used with the thick base pavement.

Cowell T. et al. [43] constructed four instrumented roadway section on poor subgrade soil and stabilized with select fill material, geosynthetics, and cement. Loading was applied by using 1000 passes of consecutive truck and profile survey was done to measure rutting data. Results show that geosyntheticaly stabilized sections with thin aggregate base course (ABC) layer performing better than the section stabilized with cement and select fill material. In geosyntheticaly stabilized sections both geogrid and geotextile shows equal performance in terms of reduced rate of rutting.

Imjaia T. et al. [44] constructed 4 full-scale trial sections in Thailand in order to examine the performance of geosynthetics (geotextile and geogrids) in flexible pavement. Structural response of all sections was monitored by strain gauges on geosynthetics, pressure sensor, settlement point (SPO) and settlement plate (SPL). Rutting was captured by using SPO and SPL. A series of wheel load test was performed on each section at a specific interval by using a pre-specified test truck.

Effectiveness of geosynthetics was quantified by 1) Traffic benefit ratio (TBR), 2) Rutting reduction ratio (RRR) and 3) Effectiveness ratio (EF).

$$EF = \frac{TBRr - TBRu}{TBRu} \quad (6)$$

Where TBR_r = Traffic benefit ratio for reinforced section and TBR_u = Traffic benefit ratio for unreinforced section. A two-dimensional Finite element model was developed in ABAQUS to cross-check the benefit of geosynthetic observed in a field study. The obtained field results show a good agreement with the numerical prediction (less than 12%). Table 2 shows the results of rut measurement, TBR, RRR and EF for all four sections.

Madhavi L. et al. [45] built seven unpaved low volume road section over weak subgrade with geosynthetic in IISc Bangalore campus. Geosynthetic material such as geotextile, geogrid (biaxial and uniaxial) and geocell was using at the interface of base and subgrade.

Table 2. Rut depths, RRR, TBR and EF Results [44]

Values	Unreinforced Section	Geotextile in Asphalt concrete layer	Geotextile at bottom of Asphalt concrete layer	Geotextile at bottom of Asphalt concrete layer and Geogrid at top of the subgrade
SPO (mm)	23	19	20	17
SPL (mm)	10	8.0	11	7.0
RRR	1.0	0.8	0.9	0.7
TBR	1.0	10	9.0	14
EF	-	9.0	8.0	13

The rut was measured at three different locations for each section. Loading was applied by using a moving vehicle load of 250 passes of the scooter. Comparing to unreinforced section geosynthetic reinforced section sustain number of passes of vehicle.

CONCLUSIONS

[1] Classification of geogrid on the basis of the manufacturing process and function is discussed in this study. Characterization of geogrid on the basis of physical, mechanical and chemical properties along with test methods is well defined in this study.

[2] This study focuses on the available methods for designing geogrid reinforced unpaved road. Giroud and Han and Leng and Gabr method are the two methods are discussed in this study with their advantages and limitations.

[3] 'Interface value' is one of the important parameters for soil-structure modeling. In view of this, the current study helps to understand the interface behavior between the geogrid and different type of soil. The 'D_{50}' size of

soil, aperture size and apertures shape of geogrid affects the interface value of the geogrid-soil interaction.

[4] The effective location of geogrid in base and subbase layer is thoroughly discussed in this study. Generally, geogrid placed at 33-50% from the bottom of the base gives the best result for a single layer of geogrid. In case of multiple layers of the geogrid first geogrid layer at 33-50% from the bottom of the base and second geogrid layer at the interface between base and subbase layer gives the best result.

[5] Laboratory tests such as triaxial testing; repeated load triaxial, CBR is supportive to understand the effect of geogrid reinforcement on shear strength, permanent deformation and bearing ratio, etc. on reinforced soil sample up to some extent. Laboratory results show that improvement in the shear strength of the sample, reduction in permanent deformation and improvement in bearing ratio in geogrid reinforced soil sample compared to unreinforced soil sample.

[6] Field studies include the use of old and modern equipment such as field plate load test, field CBR, scale accelerated load facility (ALF), Lightweight deflectometer (LWD), falling weight deflectometer (FWD) to access the effect of geogrid reinforcement in trial pavement test sections. Field studies prove that geogrid reinforcement can be effectively used in the pavement with several benefits.

References

1. Das A.: Analysis of Pavement Structure, CRC Press, Taylor and Francis Group, ISBN: 13: 978-1-4665-5856-4 (2015).
2. Koerner R.M.: Designing with geosynthetics 5th Edi. Pearson, ISBN 0-13-145415-3 (2005).
3. Shukla S.K. and Yin J.H.: Fundamentals of Geosynthetic Engineering, Taylor & Francis Group, London, UK, ISBN13 978–0–415–39444–4 (2006).
4. Giroud J. P. and Han J.: Design method for Geogrid-reinforced unpaved roads. I.Development of Design method, J. Geotech. Geoenviron. Eng. 130(8) 775-786 (2004).
5. Giroud J. P. and Han J.: Design method for Geogrid-reinforced unpaved roads. II. Calibration and Applications, J. Geotech. Geoenviron. Eng. 130(8) 787-97 (2004).
6. Leng J., Gabr M. A.: Deformation-resistance model for geogrid reinforced unpaved road, Transportation Research Record Journal of the Transportation Research Board 1975 (1) 146-154 (2006).
7. ASTM D5199: Standard Test Method for Measuring the Nominal Thickness of Geosynthetics (2012).
8. ASTM D4595: Standard Test Method for Tensile Properties of Geotextiles by the Wide-Width Strip Method (2017).
9. ASTM D6637: Standard Test Method for Determining Tensile Properties of Geogrids by the Single or Multi-Rib Tensile Method (2015).
10. ASTM D7864: Standard Test Method for Determining the Aperture Stability Modulus of Geogrids (2015).

11. ASTM D4218: Standard Test Method for Determination of Carbon Black Content in Polyethylene Compounds By the Muffle-Furnace Technique (2015).
12. ASTM D4355: Standard Test Method for Deterioration of Geotextiles by Exposure to Light, Moisture and Heat in a Xenon Arc Type Apparatus (2005).
13. EPA 9090: Compatibility Test for Wastes and Membrane Liners, (1992).
14. ASTM 5732: Standard Test Method for Stiffness of Nonwoven Fabrics Using the Cantilever Test (1995).
15. ASTM D1388: Standard Test Method for Stiffness of Fabrics (2018).
16. ASTM D7864: Standard Test Method for Determining the Aperture Stability Modulus of Geogrids (2015).
17. Elleboudy, A. M., Saleh, N. M., & Salama, A. G.: Assessment of geogrids in gravel roads under cyclic loading. Alexandria Engineering Journal, 56(3), 319–326 (2017).
18. Suku, L., Prabhu, S. S., & Sivakumar Babu, G. L.: Effect of geogrid-reinforcement in granular bases under repeated loading. Geotextiles and Geomembranes, 45(4), 377–389 (2017).
19. Sun, X., Han, J., Kwon, J., Parsons, R. L., & Wayne, M. H.: Radial stresses and resilient deformations of geogrid-stabilized unpaved roads under cyclic plate loading tests. Geotextiles and Geomembranes, 43(5), 440–449 (2015).
20. Góngora, I. A. G., & Palmeira, E. M.: Influence of fill and geogrid characteristics on the performance of unpaved roads on weak subgrades. Geosynthetics International, 19(2), 191–199 (2012).
21. Tavakoli Mehrjardi, G., & Khazaei, M.: Scale effect on the behavior of geogrid-reinforced soil under repeated loads. Geotextiles and Geomembranes, 45(6), 603–615 (2017).
22. Biswas, A., Asfaque Ansari, M., Dash, S. K., & Murali Krishna, A.: Behavior of Geogrid-Reinforced Foundation Systems Supported on Clay Subgrades of Different Strengths. International Journal of Geosynthetics and Ground Engineering, 1(3), 20 (2015).
23. Wu, H., Huang, B., Shu, X., & Zhao, S.: Evaluation of geogrid reinforcement effects on unbound granular pavement base courses using loaded wheel tester. Geotextiles and Geomembranes, 43(5), 462–469 (2015).
24. Correia, N. S., & Zornberg, J. G.: Strain distribution along geogrid-reinforced asphalt overlays under traffic loading. Geotextiles and Geomembranes, 46(1), 111–120 (2018).
25. Ling, H., & Liu, H.: Finite element studies of asphalt concrete pavement reinforced with geogrid. Journal of Engineering Mechanics, 129(July), 801–811 (2003).
26. Kuity, A., & Roy, T. K.: Utilization of Geogrid Mesh for Improving the Soft Subgrade Layer with Waste Material Mix Compositions. Procedia - Social and Behavioral Sciences, 104, 255–263(2013).
27. Singh M., Trivedi A. and Shukla S. K.: Strength Enhancement of the Subgrade Soil of Unpaved Road with Geosynthetic Reinforcement Layers, Transportation Geotechnics 19 54-60 (2019).
28. Chen, X., Zhang, J., & Li, Z.: Shear behavior of a geogrid-reinforced coarse-grained soil based on large-scale triaxial tests. Geotextiles and Geomembranes, 42(4), 312–328 (2014).
29. Abu-farsakh, M., M., Souci, G., Voyiadjis, G. Z., F., & Chen, Q.: Evaluation of Factors Affecting the Performance of Geogrid-Reinforced Granular Base Material Using Repeated Load Triaxial Tests, 24(January), 72–83 (2012).
30. ASTM D3080: Standard test method for a direct shear test of soils under consolidated drained conditions. ASTM International, West Conshohocken, PA (2011).
31. ASTM D6706: Standard test method for measuring geosynthetic pullout resistance in soil (2001).

32. Choudhary, A. K., & Krishna, A. M.: Experimental Investigation of Interface Behaviour of Different Types of Granular Soil/Geosynthetics. International Journal of Geosynthetics and Ground Engineering, 2(1), 4 (2016).
33. Liu, C., Zornberg, J. G., Chen, T., Ho, Y., & Lin, B.: Behavior of Geogrid-Sand Interface in Direct Shear Mode. Journal of Geotechnical and Geoenvironmental Engineering, 135(12), 1863–1871 (2009).
34. Goud, G. N., & Umashankar, B.: Interface Shear Strength Properties of Gravel Bases and Subgrades with Various Reinforcements. International Journal of Geosynthetics and Ground Engineering, 4(7), 14 (2018).
35. White, J. D., Becker, P., Pavana K. R. Vennapusa, Dunn, J. M. & White, I. C.: Assessing Soil Stiffness of Stabilized Pavement Foundations. Transportation Research Record: Journal of the Transportation Research Board, No. 2335, 99-109 (2013).
36. Tang, X., Abu-Farsakh, M., Hanandeh, S. and Chen, Q. Performance of Reinforced–Stabilized Unpaved Test Sections Built over Native Soft Soil Under Full-Scale Moving Wheel Loads. Transportation Research Record: Journal of the Transportation Research Board, No. 2511, 81-89 (2015).
37. Zornberg, J. G., Roodie H.G., & Gupta, R.: Monitoring Performance of Geosynthetic-Reinforced and Lime-Treated Low-Volume Roads under Traffic Loading and Environmental Conditions. GeoCongress 2012, ASCE, 1310-1319 (2012).
38. Al-qadi, I. L., & Appea, A. K.: Eight-Year Field Performance of Secondary Road Incorporating Geosynthetics at Subgrade – Base Interface, (03), 4–10 (2001).
39. Fannin, R. J., & Sigurdsson, O.: Field Observations on Stabilization of Unpaved Roads with Geosynthetics. Journal of Geotechnical Engineering, 122(7), 544–553 (1996).
40. Holder, H. W. & Andreae, J.: Geogrid Reinforcement to Reduce Pavement Section Thickness: A Case Study. GeoTrans 2004, ASCE, 1006-1013 (2004).
41. AASHTO: Guide for the design of pavement structures, American Association of State Highway and Transport Officials (1993).
42. Al-Qadi, I. L., Dessouky, S. H., Kwon, J., & Tutumluer, E.: Geogrid-Reinforced Low-Volume Flexible Pavements: Pavement Response and Geogrid Optimal Location. Journal of Transportation Engineering, 138(9), 1083–1090 (2012).
43. Cowell, T., Pyo, S., Gabr, M. A., Borden, R. H., & Kim, K. J.: Performance Assessment of Geosynthetics and Cement as Subgrade Stabilization Measures. Geotechnical Testing Journal (ASTM), 37(3) (2018).
44. Imjai, T., Pilakoutas, K., & Guadagnini, M.: Performance of geosynthetic-reinforced flexible pavements in full-scale field trials. Geotextiles and Geomembranes, 47(2), 217–229 (2019).
45. Madhavi Latha, G., Nair, A. M., & Hemalatha, M. S.: Performance of geosynthetics in unpaved roads. International Journal of Geotechnical Engineering, 6362(April 2010), 337–349 (2010).