COMPARATIVE STUDY ON BEHAVIOUR OF GEOCELL REINFORCED PAVEMENT

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Abstract. Infrastructure has become a major force for national development. Therefore, the development of ground improvement technology for weak subgrade composition has become an important goal in geotechnical engineering applications. Geosynthetics is one of the ground improvement techniques to improve bearing capacity of problematic subgrade soil. Geocell, the cell matrix expands to create radial stress and provide stability to the subgrade composition soil. In the past few years, the use of geocells and other methods to improve the properties of problematic soil, especially in pavement and foundation engineering, has been investigated. This paper focuses on presenting parameters such as increased bearing capacity, decreased settlement and increased stiffness when reinforcing various types of collapsible soils by addressing laboratory tests and field investigations for geocell configuration and highlights their advantages in various applications and future research. Research shows that geocells can improve the properties of problematic subgrade soil, making it suitable for many engineering applications.

Keywords: *geocell, dune sand, pavement bearing capacity, placement of geocell*

Introduction

The increasing demand for urbanization has led to a need for transforming weak soils into stable ground. Various ground improvement techniques such as mechanical stabilization like hydraulic stabilization, physical and chemical stabilization, and Geosynthetics have been developed to address issues like bearing capacity and settlement. Among these, soil reinforcement by geosynthetics, has gained popularity due to its versatility, feasibility, and simplicity. Results of this, in the last few decades, research on geosynthetics applications has increased at a rapid rate and also become the popular choice for geotechnical applications. Types of geosynthetics as per method of manufacturing are geotextiles, geogrids, geomembranes, geonets, geocomposites, geocells, geofoams, geopipes, geotubes, geobar, geomat, geomesh, geofabric, geonatural, geostrip, geomatress, electrokinetic geosynthetic, and geosynthetic clay liner. In 1960s, Vidal (1969) introduced the Principle of Reinforced Earth, Which help in rapid development of construction activities using reinforced earth technology in France, United Kingdon, Japan, USA, etc. Giroud (1986) proposed following reasons for wide acceptance of geosynthetics: (1) enhancing behaviour of soil: Geosynthetic exhibits unique membrane-like properties which will provide apparent cohesion property to granular cohesionless soil. Soils susceptible to erosion or settlement can greatly benefit from geosynthetics. Also, geosynthetic behaves as effective separators to separate different soil layers; (2) Layered construction: For geotechnical structures like pavement, foundation, retaining walls, geosynthetic materials used to enhance performance of soil; (3) Flexibility: The inherent flexibility of geosynthetics makes them an excellent match for structures that undergo differential settlement or deformation, ensuring a stable and long-lasting performance.

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Surface properties, dimensions, strength, stiffness of reinforcement, type of soil, state of soil under construction affects behaviour and performance of reinforced soil (Jones, 2005). Surface properties plays crucial role in mobilization of friction and tensile forces in reinforcement. Greater the frictional force between soil and reinforcement, more will be the tensile force and effectiveness of reinforcement reinforced soil structure. So, reinforcement having rough surface leads to better performance. Past studies consisting of laboratory tests, numerical simulation techniques were carried out to study efficiency of geocell in enhancing performance of problematic soils. Latest research done on actual field applications of geocell has been studied by few researchers. In present, research focus shifted to study response of geocell reinforced soil to repetitive or cyclic loading as application of geocell for railways, recycled asphalt pavements and protection of buried pipelines etc. Due to having fill having stable, free draining and relatively non-corrosive to reinforcing elements, cohesionless material is more preferable than cohesive fill.

Materials and Methods

Geocell

The concept of geocells originated in the early 1970s, developed by the US Army Corps of Engineers Waterways Experiment Station (WES) in collaboration with Presto to create stabilized, temporary sand roads for military vehicles. Researchers initially investigated grid confinement systems using a range of creative and experimental materials including coated craft paper; a plastic drainage pipe matrix fastened with staples; paper-thin, hexagonal glued aluminum; low and medium-density recycled materials; pure polyethylene without UV stabilization; and square cells similar to old fashioned egg carton separator. Since then, numerous researchers have built upon this foundation, advancing geocell technology through their contributions. Geocell, three-dimensional honeycombed cellular arrangement that provides confinement to infill material which generate frictional interaction which provide interlocking. Reinforcement will absorb shear stresses between subgrade and fill, so it improves pressure distribution on subgrade and reduces settlement (Hegde, 2017; Pokharel et al., 2015; Hufenus et al., 2006; Madhavi Latha et al., 2006). Vertical deformation develop due to pocket effect, which create concave shape in tensioned geosynthetic material. Curved reinforced material generates an upward force that counteracts the applied pressure, thereby enhancing the bearing capacity of the foundation (Dash et al., 2001; Perkins, 1999; Rajagopal et al., 1999). So, geocell reinforced soil considered as flexible raft foundation. It increases rigidity and bearing capacity as composite intercepts potential failure planes (Bathurst and Knight, 1998; Cowland and Wong, 1993) (F*igure 1*).

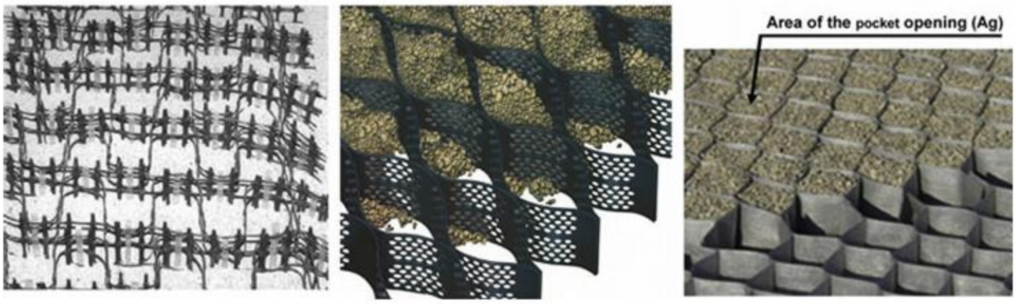


Figure 1. *(a) Handmade geocells with perforations; (b) perforated geocell and (c) non-perforated flexible geocell.*
Source: Tafreshi and Dawson (2012); Dash et al. (2003); Bathurst and Knight (1998)

Mechanism of geocell as reinforcement

In 1990’s geocells have added advantage than planar reinforcement due to its three-dimensional nature. Geocell layer enhance ensile strength, bending resistance, and shear strength, while also intercepting potential failure planes from the subgrade (Zhou and Wen, 2008). Researchers (Hegde and Sitharam, 2015a; 2015b; 2015c; 2015d) observed reinforcement mechanisms generated due to geocell reinforcement as Confinement effect, Stress distribution.

Confinement effect

Geocell have three-dimensional structure, which generate lateral confinement to the soil particles within the cells. Confinement in geocell will be provided in two ways. Friction between the infill material and the geocell wall. Also geocell-reinforced base resembling a mattress, which constrains soil movement upward and outward beyond the loading area. The studies (Han et al., 2008; Gourc et al., 2001) shows that due to confinement and load transfer mechanism between infill and geocell, geocells can significantly increase the elastic modulus and bearing capacity of the reinforced sand (*Figure 2*).

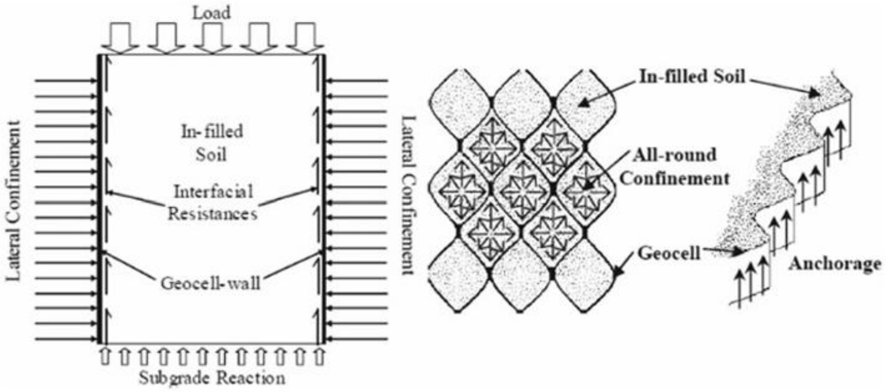


Figure 2. *Confinement effect of geocell.*
Source: Biswas and Krishna (2017)

Stress distribution

Denser the fill, higher the load-carrying capacity and geocell reinforcement distributes the load over wider area (Mhaiskar and Mandal, 1992). The wider stress distribution provided by geocell reinforcement decreases the stress concentration at the interface between the base and the subgrade, thereby increasing the bearing capacity and stiffness of the reinforced base (*Figure 3*).

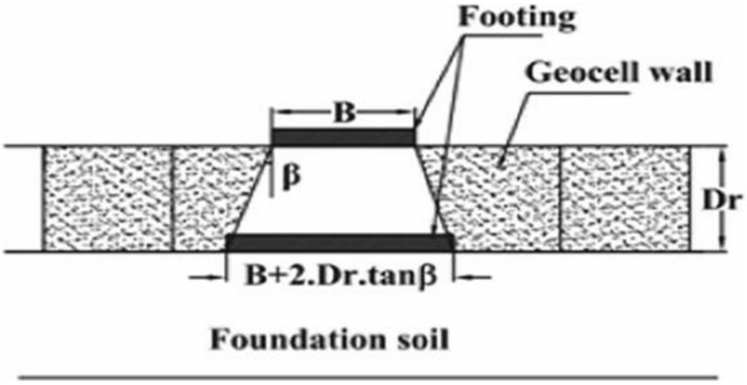


Figure 3. *Vertical stress distribution.*
Source: Sitharam and Hegde (2013).

Geocell reinforced subgrade

Improvement of bearing capacity of foundation soil is studied by several investigators (Mhaiskar and Mandal, 1992; Guido et al., 1986; Binquet and Lee, 1975). Research has clearly demonstrated the benefits of reinforcing foundation soils, particularly sand, to enhance bearing capacity and stiffness in terms of load-settlement behavior. Reinforcement leading to increased stability and reduced settlement. Bearing capacity ratio (BCR) is defined as the ratio of improved (or required) bearing capacity to the bearing capacity of foundation soil without reinforcement. Investigators (Kumar and Saran, 2001; Murthy et al., 1993; Shivashankar et al., 1993; Mhaiskar and Mandal, 1992; Guido et al., 1986; Binquet and Lee, 1975) developed design methods using different forms of reinforcement, types of footing and soil conditions. Zhou and Wen (2008) stated that the settlement can be reduced by 44% by geocell reinforcement. Pokharel et al. (2015) stated that adding a planar geogrid to the base of the geocell can increase the bearing capacity of the foundation by 30% more than what is achieved with geocell reinforcement alone (*Figure 4*).

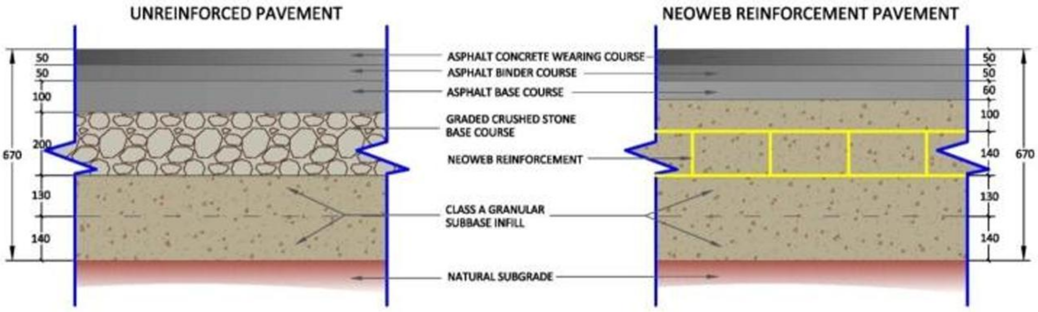


Figure 4. *Conventional vs. neoweb-reinforced pavement.*
Source: Kief and Toan (2011)

Influencing factors of geocell

Previous studies have primarily focused on investigating geocell behavior in pavement applications, examining the influencing factors that contribute to the significant performance enhancements achieved through geocell reinforcement. Some of the studies focused on shape, aspect ratio, pocket size of geocell, type of geocell, texture of geocell, properties of infill, placement depth.

Shape of geocell

The chevron-shaped geocell has been found to be more effective due to having higher joint density per area, which enhances both bending and shearing stiffness (Sitharam and Sireesh, 2005; Dash et al., 2001; Krishnaswamy et al., 2000; Webster, 1981). As per research on single geocell conducted by Pokharel et al. (2009) circular shape of geocell gives greater rigidity and load-carrying capacity than elliptical-shaped geocell. Higher stiffness of geocell provides uniform distribution of loads on soil beneath geocell layer. Also previous research pocket shape was assumed as chevron or diamond, whereas actual shape was honeycomb. Few numerical analyses (Gedela et al., 2021) on geocell pocket shape has been conducted, with all studies on geocell shape being experimental, providing valuable insights into the impact of shape on geocell performance.

Aspect ratio of geocell

Aspect ratio is defined as height to width of geocell. As aspect ratio increases number of pockets per unit area increase and provide large confining area from geocell so, interfacial shear strength increases (Kabiri Kouchaksaraei and Bagherzadeh Khalkhali, 2020). Sufficient height of geocell wall stops infill material against punching (Sireesh et al., 2009; Sitharam and Sireesh, 2005). As height of geocell layer increases, bending and stiffness of geocell mattress increase which improves performance of weak subgrade soil. *Figure 4* shows impact of aspect ratio of geocell on increment of shear strength. Expanding the width of the geocell layer effectively suppresses the formation of rupture planes within the soil bed. This, in turn, enhances the composite behavior of the geocell-soil system and mitigates surface heaving (Kabiri Kouchaksaraei and Bagherzadeh Khalkhali, 2020; Hegde, A., Sitharam; 2015c; Sireesh et al., 2009; Sitharam and Sireesh, 2005; Dash et al., 2001; Mhaiskar and Mandal, 1996; Murthyet al., 1993).

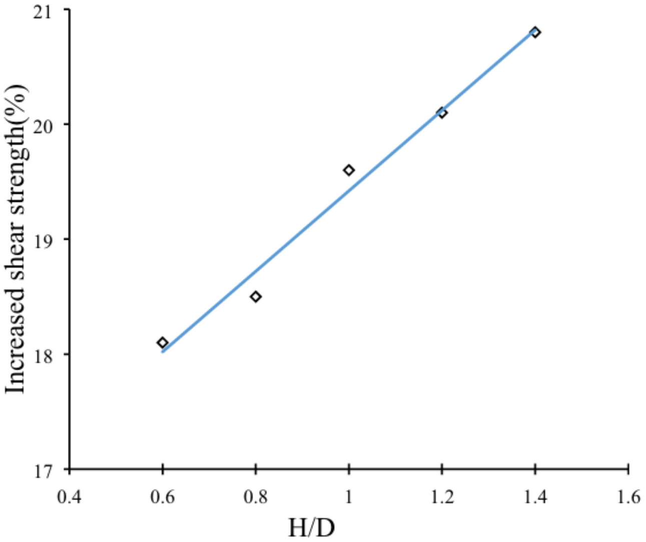


Figure 4. *Effect of aspect ratio (H/D) on increment of % shear strength.*
Source: Kabiri Kouchaksaraei and Bagherzadeh Khalkhali (2020).

Pocket size of geocell

The size of the pockets is defined using equivalent diameters. To calculate this, we convert the triangular shape of the pocket into a circle with the same cross-sectional area. This ensures that the pockets are symmetrical around their central axis. The size of the geocell pockets significantly influences the behavior of reinforced subgrade bed. Studies (Hegde and Sitharam, 2015d; Raj, 2010) concluded that the smaller pocket size of geocell greater confinement per unit volume, which result in increment of bearing capacity. The ideal pocket size by studies is 0.8B to 1B, where B is diameter of loading plate. Also, studies conducted to explore handmade geocells composed of geogrids, geotextiles, but commercially available, manufactured geocells are more commonly used in practical field applications.

Type of geocell

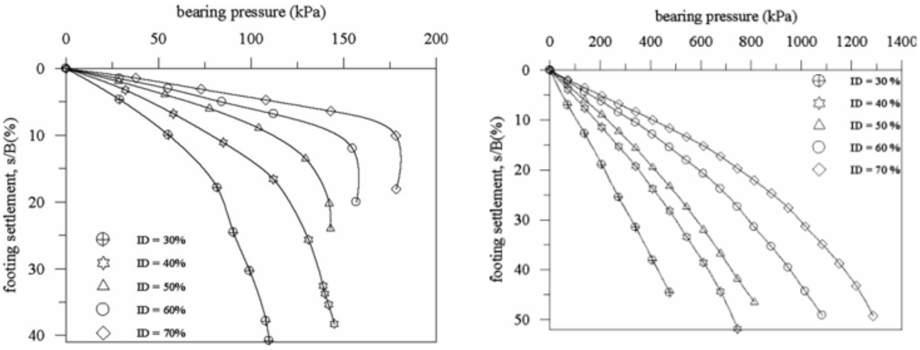
Two types of geocell implemented as reinforcement in subgrade are NPA (Novel Polymeric Alloy) and HDPE (High-Density Polyethylene). NPA geocells exhibit higher mechanical properties, including high tensile stiffness and strength, as well as low thermal expansion coefficient, compared to HDPE geocells.

Texture of geocell

Research has consistently shown that geocells with rough textures outperform their smooth-walled counterparts. The added surface roughness creates a stronger bond between the filler material and the cell walls, leading to improved overall performance. Notably, studies have also found that increasing the friction angle significantly increased the load-bearing capacity of reinforced foundation beds.

Properties of infill material

Relative density plays a vital role as it generates a beam or semi-rigid slab effect which is covered by vertical load. So, to get better efficacy of geocell-reinforced systems, relative density of filler material is maintained high as possible (Dash et al., 2010; 2001; Latha et al., 2009; Pokharel et al., 2009). The majority of studies used clay, sand, demolition waste, aggregate material, waste material as infill material, but limited studies have been used dune sand (fine sand) (*Figure 5*).



a

b

Figure 5. *Bearing pressure versus footing settlement: (a) unreinforced and (b) geocell reinforced foundation bed.*

Placement depth

Placement depth (u) is the distance from the surface to the top of the geocell mattress. This soil cushion distribute applied load to the geocell mattress evenly and avoid local buckling of wall of geocell as it is not directly in contact with loading plate. From studies, optimal value for depth of placement is between 0.1B to 0.33B, where B is width of loading plate (Tafreshi and Dawson, 2010; Yoon et al., 2008; Dash et al., 2001).

Laboratory test

In laboratory tests, the effectiveness of geocell-reinforced base or subbase layers is evaluated by simulating pavement sections in a tank. Various pavement layers are constructed and subjected to static or repetitive loading conditions to replicate real-world scenarios (*Figure 6*). Pavement composition is studied by simulating the pavement section in a tank with various infill material, subgrade material in various or same pavement layers placed, having different loading conditions like static or repetitive loading. Similarly, may studied carried out with respect to getting more suitable understanding of different materials, shape, aspect ratio, height of geocell (Cowland and Wong, 1993). In addition, different types of footing were also studied by researchers in the past. *Table 1* summarizes key findings from conducted research. Geocell reinforcement enhances the bearing capacity of the unpaved test section by a factor of 1.25 compared to the unreinforced base.

Table 1*. Overview of past studies based on laboratory tests.*

Sr. No.	Test	Subgrade	Infill	Conclusion
1	Plate load test, FE process(ANSYS)	Marine clay	Sand	b/B ratio of 0.625, H/B value of 2.8 improveemnt of 1.31 times compared to unreinforced case
2	Static and cyclic plate load tests	Poorly-graded Kansas River sand	Poorly-graded Kansas River sand	Stiffness of the reinforced sand improved by 1.5 compared to the unreinforced sand.
3	Static plate load test	Expanded polystyrene (EPS) geofoam blocks	Gravelly sand	54% reduction in surface settlements
4	Static plate load test	Dredged soil	Crushed quarry	50% increment in bearing capacity

			waste and Dolomite lime stone aggregates	
5	Static plate load test	Dredged soil	Reclaimed asphalt	Ultimate bearing capacity increased by 23 % and 58 % for base thickness of 120 mm and 150 mm respectively.
6	Static plate load test	Expanded polystyrene (EPS)	Poorly graded sand	Dispersion angle was influenced by height of the geocell and the roughness of the geocell surface.
7	Static plate load test	Clay	Reclaimed Asphalt	Resilient modulus increased by 2.5-3.3 time, permanent deformation reduced by 70-80%
8	Static plate load test, Field test	Dune sand	Dune sand	Improvement factor for stiffness and bearing capacity ranged from 1.35 to 2.0 and 1.4 to 2.6, respectively
9	Cyclic plate load test	25% Kaolin + 75% river sand mixture	Recycled asphalt material	Increment in percentage resilient modulus
10	Cyclic and mono tonic plate load test	Dry sand	Granular subbase material	More improvement in the geocell reinforced pavement than the planar type products like geotextiles and geogrids.
11	Cyclic plate load test	White Riverbed sand	Aggregate	As thickness of the reinforced section increased, the permanent deformation or the rut depth decreased.
12	Cyclic plate load test	-	Kansas River sand, quarry waste, and AB-3 aggregate	Modulus improvement factors ranged from 1.26 to 2.04, TBR value 8.0 for the single geocell reinforced bases and 12.0 for multiple geocell,
13	Cyclic plate load tests	Black cotton soil	Aggregate	Reducing rutting by 13-71% and increasing rut life by a factor of 1.6 to 3.5.
14	Cyclic plate load test	Texas soil	Aggregate	Geocell layer reduces vertical stress on subgrade by 30%
15	Cyclic plate load test	Poorly graded sand	Poorly graded sand	More than 70% reduction in rut depth
16	Cyclic plate load test	Expanded polystyrene (EPS) geofoam blocks	Well-graded sand	Settlement reduced by 41%, resilient modulus is increased by 25%, 34% and 53% for overlying soil thicknesses of 600, 500 and 400mm, respectively.

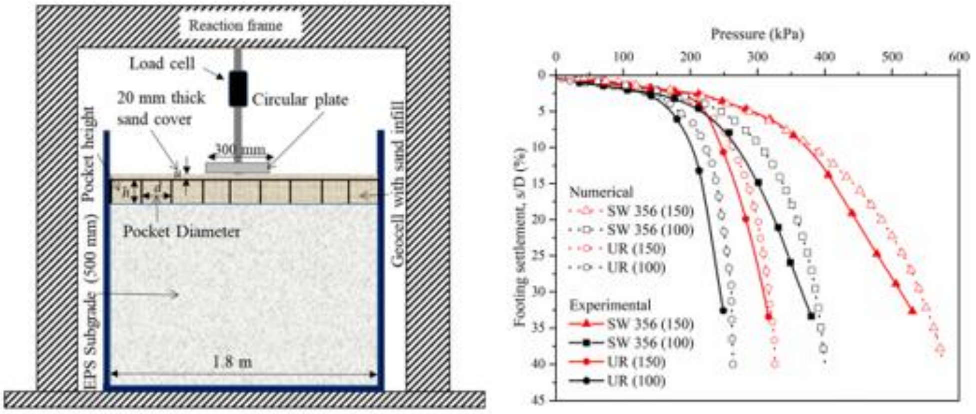


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Figure 6. (a) Schematic diagram of an eaaxperimental test setup, and (b) Pressure vs footing settlement s/D (%) response of reinforced sections.
Source: Gedela and Karpurapu (2021).

Results and Discussion

Laboratory experiments have consistently shown that geocell reinforcement is particularly beneficial when a soil-geocell composite layer is applied over poor subgrade layer. Extensive research has been conducted through numerical simulations, laboratory experiments, and field tests to evaluate the performance enhancements of geocell-reinforced pavements. Key parameters assessed include rut depth reduction, resilient modulus improvement, modulus improvement factor, and traffic benefit ratio.

Rut depth

Rut depth, also refers as depressions formation in roads by repeated wheel movement, is a critical factor affecting vehicle mobility on weak soil. IRC37, AASHTO guidelines specify critical rut depth range from 13 to 75 mm unpaved roads and 25 for paved roads (Congress, 2001; AASHTO, 1993). As pavement reached critical rut depth value, highway authority carried out pavement maintenance work. So, weak subgrade soil tends to generate rut depth quickly after construction. The Rut Depth Reduction (RDR) ratio is defined as the cumulative permanent deformation of the unreinforced layer divided by that of the geocell-reinforced layer, for a specified number of loading cycles. The Rut Depth Reduction (RDR) is widely used to quantify performance enhancements in geocell-reinforced layers. Recent studies have employed RDR to evaluate the improvement in geocell-reinforced layers over unreinforced layers under repetitive loading conditions (Saride et al., 2015). Rutting characteristics of pavement depends on traffic cycles, magnitude of loads, physical properties of pavement layers, thickness of layers. Inclusion of geocell layer to pavement effectively reduces rut depth by 13 to 71% (Hegde and Palsule, 2020; Siabil et al., 2020; Mamatha and Dinesh, 2019; Suku et al., 2016; Tanyu et al., 2013; Thallak et al., 2007).

Stiffness modulus

Stiffness modulus is representation of the relationship between applied force and resulting deformation. Stiffness modulus is the primary mechanical property to measure its elastic deformation behavior.

Modulus improvement factor

The Modulus Improvement Factor (MIF) is a measure of the enhancement in stiffness provided by geocell reinforcement under applied stress. MIF is calculated as the ratio of the modulus (stiffness) of the reinforced base or subbase layer (ER) to the modulus of the corresponding unreinforced layer (EUR), under identical test conditions of laboratory and field experiments. MIF is key indicator of effectiveness of geocell reinforcement in pavement. It is determined by both laboratory and field experiments. According to IRC:SP:59, when CBR value is less than 3, range of MIF will be 2 to 2.75. And if CBR value is greater than 3, range of MIF will be 1.4 to 2 (IRC, 2019). A higher MIF value indicates greater improvement in pavement layer stiffness due to geocell reinforcement. Researchers (Deshmukh et al., 2021; Chatterjee et al., 2020; Pokharel et al., 2018; Rajagopal et al., 2012; Kief et al., 2011) have conducted extensive laboratory and field experiments to determine the Modulus Improvement Factor (MIF) for various subgrade conditions, infill materials, and geocell properties. These factors significantly impact the MIF value.

$$MIF = \frac{Modulus\ (stiffness) of\ the\ reinforced\ based\ on\ subbase\ layer\ (E_R)}{Modulus\ of\ the\ corresponding\ unreinforced\ layer\ (E_{IJR})} \qquad \text{Eq. (1)}$$

Traffic benefit ratio

The Traffic Benefit Ratio (TBR) is a measure of the improvement in pavement durability due to geocell reinforcement. Increment in TBR values are due to confining mechanism within geocell, which lead to the lateral distribution of stresses due to loading. It is calculated as the ratio of the number of load cycles required to cause a specific permanent surface deformation in a reinforced pavement section to the number of cycles required to cause the same deformation in an unreinforced section with identical layer thicknesses (Perkins, 1999). As per AASHTO R50, TBR is used to design reinforced pavement. The Traffic Benefit Ratio (TBR) quantifies the enhancements in pavement performance achieved through geocell reinforcement, including reduced rutting, extended service life, and increased load-carrying capacity. Increment of TBR value indicates greater benefits from incorporating geocell reinforcement into pavement design, highlighting its potential for improved performance and durability. As per research (Gedela et al., 2021; Hegde and Palsule, 2020; Pokharel et al., 2018; Latha et al., 2010), TBR values varies between 1 to 32 depending on rigidity of geocell, number of geocell layers and pavement thickness.

Resilient modulus

The resilient modulus (M_r) is defined as the ratio of the cyclic deviator stress ($\sigma_{d(cyc)}$) to the elastic resilient strain (ε_1) that occurs during unloading.

$$M_r = \frac{\partial_{d(cyc)}}{1\varepsilon_1} \qquad \text{Eq. (2)}$$

The resilient modulus is crucial for evaluating pavement deformation and fatigue resistance under traffic loads. Geocell reinforcement significantly enhances this parameter, improving pavement performance and durability. Measured through laboratory cyclic triaxial testing or in-situ Falling Weight Deflectometer (FWD) testing, resilient modulus is a key input for determining pavement layer characteristics under repetitive loading. Due to challenges and costs associated with laboratory tests on geomaterials, in-situ tests like FWD or plate load tests are often used to estimate resilient modulus (Mr) through back analysis of deflection values (Christopher et al., 2006).

$$M_r = \frac{n(1-\mu^2)qa}{2\Delta} \qquad \text{Eq. (3)}$$

Where, q=applied pressure, μ=Poisson's ratio, a=loading plate radius, Δ=deflection value below the loading plate. The field technique has two key benefits: Direct interpretation of results and eliminating the need for subsurface sampling. However, its limitations include potential discrepancies between field-derived moduli values and those obtained through laboratory testing. Furthermore, existing mathematical models developed by researchers often have limited applicability, typically restricted to unreinforced cases, highlighting the need for more comprehensive models that account for reinforced scenarios.

Conclusion

Laboratory and field tests by numerous researchers have conducted to evaluate performance improvements in geocell-reinforced ground, focusing on rut depth, resilient modulus, modulus improvement factor, and traffic benefit ratio. Key factors influencing performance include geocell shape, aspect ratio, pocket size, type, texture, infill properties, and placement depth. These factors significantly enhance bearing capacity, stiffness, resilient modulus, and traffic benefit ratio while reducing rut depth. The inclusion of a geocell layer in pavements reduces rut depth by 13% to 71%. The Studies indicate that adding a geocell layer increased the Modulus Improvement Factor (MIF) from 1.26 to 2.04. According to IRC: SP:59, for subgrades with CBR values below 3, MIF ranges from 2 to 2.75, while for CBR values above 3, MIF ranges from 1.4 to 2. Furthermore, geocell reinforcement can increase modulus of the geocell-soil composite by 2.5 to 3.5 times compared to unreinforced sections, depending on geocell height. The Traffic Benefit Ratio (TBR) varies between 1 and 32, influenced by factors such as geocell rigidity, number of layers, and pavement thickness.

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Conflict of interest

The authors confirm that there is no conflict of interest involve with any parties in this research study.

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