High-Modulus Geocells for Sustainable Highway Infrastructure

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ABSTRACT

Technological innovation in geosynthetics such as high modulus (stiff) geocells (cellular confinement systems) can help achieve a more sustainable highway infrastructure. Research, testing, field trails, and case studies demonstrate how geocells increase pavement performance on one hand, while achieving sustainable goals on the other. Recent published research and testing of high-modulus Novel Polymeric Alloy (NPA) geocell-reinforced bases are briefly reviewed in this paper. NPA geocells improved strength and rigidity of flexible pavements as indicated by: increased modulus of structural layers, reduced stresses to the lower layers and decreased surface degradation. Field trials validate that NPA geocells improve the modulus of road base layers, even while reducing the structural thickness and utilizing on-site or recycled materials for structural infill. Sustainable roads can be built with less virgin resources and a smaller environmental footprint, while extending the pavement service life and decreasing maintenance.

INTRODUCTION

While huge investments are underway in India to build and upgrade its transportation infrastructure, the challenges are more than budgetary. Many roads traverse problematic soils that require stabilization, virgin aggregate resources are limited, and the quality/service life of pavements needs to be addressed. Sustainable pavements can help meet these challenges by improving the long-term road strength and rigidity [1].

Cellular confinement systems (geocells) – 3D honeycombed polymer matrices formed by interconnected strips and infilled with compacted granular infill – have been used for to confine unbound aggregates in the base reinforcement of roads since the 1970's. Early geocells were made from paper, cardboard, bodkin bars, aluminum and High Density Polyethylene (HDPE), which quickly became the most commonly used material. Novel Polymeric Alloy (NPA) geocells are the latest development in the industry and the subject of this paper. A literature review validates the geocell contribution to pavement performance.

The key mechanisms in geocell reinforcement that improve pavement strength are summarized by Han et al. [2] and Pokharel et al. [3,4]: lateral and vertical confinement, beam (tension membrane) effect and load distribution at a wider angle. Lateral confinement of infill materials prevents movement and shearing under loading. Infill stiffness is increased by the transfer of vertical forces to hoop stresses on the geocell walls and by passive resistance from surrounding cells. Frictional resistance between the infill and cell walls – and the geocell-reinforced layer acting as a mattress – restrain soil from moving upward outside the loading area to provide vertical confinement. Aggregate lateral movement and attrition are minimized, while the distribution of lateral and vertical stresses is maximized.

LITERATURE REVIEW

Early studies on the utility of geocells in reinforced road bases and the geocell reinforcement mechanisms was carried out in the late 70's at the US Army Engineer Waterways Research Station by Webster & Watkins [5], Webster [6] and Mitchell at al. [7]. These demonstrated that reinforcement with geocells can improve bearing capacity significantly compared with unreinforced soil.

Kazerani and Jamnejad [8] were among the first to conduct studies with dynamic loading of large models and in geocell-reinforced paved roads. In the 1990's studies of the confinement effect using large triaxial compression test and laboratory model test were conducted by Bathurst & Karpurapu [9] and Rajagopal et al. [10]. Additional studies investigating geocell loading, infills, and materials were published by Mhaiskar & Mandal [11,12] and Mandal & Gupta [13]. Later work included investigation of the bearing capacity of footings/foundations on geocell-reinforced sand by Dash et al. [14,15]. Mahavi et al. [16] studied geocell reinforcement on earth embankments over weak foundation soil through laboratory model tests and proposed a simple method for the design of geocell-supported embankments.

A comprehensive overview of 26 technical papers on geocell-reinforced base course by Yuu [17] in 2008 aimed to identify key influencing factors in cellular confinement. Most of those studies demonstrated significant enhanced performance of base layer using geocells by increasing bearing capacity and reducing deformation. The most influential factors on the performance of geocell-reinforced base courses were: geometric variables of geocells, quality of infill soil, subgrade strength, loading type, and location. The author concluded that the use of geocells for base reinforcement of roads was limited due to a lack of research on dynamic loading conditions and flexible pavements and the lack of design methods.

Hedge & Sitharam [18] points out that many of these studies were carried out on geocell structures made of paper, aluminum, geogrids, PVC (Polyvinyl Chloride), geotextiles, as well as HDPE, and that few researchers used commercially available geocells. Bull [19] notes that experimental field trials are more realistic to evaluate geocell performance, as geocells are complex composites with a wide number of interdependent variables that influence performance.

Research that utilized field installations of commercial HDPE geocells to reinforce the base of asphalt pavements was conducted by Emersleben & Meyer [20,21]. Field studies of a section of a reconstructed highway pavement validated the results achieved with large scale test boxes in the laboratory. Geocell reinforced bases in these studies increased the load bearing capacity by a factor of 5, reduced differential settlement by up to 80% and decreased vertical stresses in the subgrade by more than 40% as compared to unreinforced bases.

An analysis and design methodology for the use of geocells in flexible pavements was recently proposed by Babu and Kumar [22]. The analysis using the Indian Roads Congress (IRC) design code verified that the use of geocells enables a reduction in the pavement thickness.

LITERATURE REVIEW OF NPA GEOCELLS

The Novel Polymeric Alloy (NPA) for geocells from PRS-Mediterranean is a composite alloy of polyamide nano-fibers dispersed in a polyethylene matrix. It provides ductility similar to HDPE with elastic behavior similar to engineering thermoplastics [23]. The NPA geocell is embossed, perforated and characterized by long-term plastic deformation measured by accelerated SIM test as: ≤0.5% at 44°C; ≤0.6% at 51°, ≤0.7% at 58°C (at 6.6 kN/m, ASTM D-6992 modified, according to the manufacturer's specifications). In addition to the development of the NPA material, new comprehensive research programs with geocells made from NPA have furthered our understanding of the mechanism and influencing factors in geocell reinforced road bases.

A comprehensive research program at the University of Kansas [24] has conducted studies on NPA geocell-reinforced base courses since 2006, including box tests, 3D modeling and field trials. Laboratory plate loading tests on geocells showed that the performance of geocell-reinforced bases depends on the elastic modulus of the geocell [25]. The geocell with a higher elastic modulus had a higher bearing capacity and stiffness of the reinforced base. Geocells made from NPA were found significantly better in ultimate bearing capacity, stiffness, and reinforcement relative to geocells made from HDPE [2,4]. NPA geocells showed better creep resistance and better retention of stiffness and creep resistance [26] particularly at elevated temperatures, verified by plate load testing, numerical modeling [27, 28] and full scale trafficking tests [25](see figure 1). Stiffness of the geocell has been identified as a key influencing factor for geocell reinforcement [29]. Increased geocell stiffness increases the stiffness of the soil and pavement layers, and therefore increases the rigidity of the entire pavement structure [1]. Additional research in this program studied the on-site reuse of Recycled Asphalt Pavement (RAP) materials as NPA geocell-reinforced base courses with a thin new overlay, as the cellular confinement could minimize creep deformation of RAP materials [30].

Figure 1. NPA Geocell test sections being installed (Kansas University facility, University of Kansas study)

Comparative field tests with geogrid-reinforced bases were also conducted by Van Gurp & Westera [31]. Test results showed that the NPA geocell had the highest average Road Base Thickness Reduction Factor (0.72) of any tested product; none of the geogrids exceeded a reduction factor of 0.5.

Research involving loading tests of model NPA geocell reinforced rail embankments was carried out by B. Leshchinsky [31]. The results showed that NPA geocells greatly restricted vertical deformation (by 40-72%) and lateral displacement (by 50-67%) under controlled cyclic loading, well within the stress amplitude of many transportation applications (railways, highways, etc.).

A field demonstration project by White et al.[33] under the auspices of the US Strategic Highway Research Program (SHRP2) compared geosynthetic reinforced road base sections using multiple QC/QA testing methods (within the framework of advanced roller compaction technology evaluation). NPA geocells showed the lowest permanent deformation and high modulus of all the geosynthetics.

Rajagopal et al. [1] investigated the improvement in the strength and stiffness (modulus) of the subbase layer in an NPA reinforced reconstructed pavement by field and laboratory plate load testing. The resulting Modulus Improvement Factor (MIF) of 2.84 the authors conclude, enables a 50% reduction in pavement thickness, is economically competitive and contributes to sustainable objectives in road design.

Research by Sitharam and Hedge [18,34] describes a case history of the construction of a 3m embankment of a NPA geocell-reinforced foundation over soft clay mud in Orissa, India, and model plate load tests and numerical simulations of the NPA geocell reinforced soft clay beds. These results showed an increase in load carrying capacity by 5 fold.

An additional case study by Pokharel et al. [35] discusses the design, construction and performance of an NPA geocell reinforced causeway for oversized load carrying trucks over very weak (muskeg) subgrade.

These studies lead to the following conclusions about the contribution of NPA geocells to the goal of sustainable pavements:

- The modulus improvement factor strengthens locally available 'marginal' granular soils and recycled materials.
- High-quality imported base layer aggregate can be replaced in most cases with locally available subbase quality infill.
- The required thickness of structural layers with geocell reinforcement can be reduced by as much as 50% while achieving the same performance as an unreinforced road.
- Reliable roadways, highways and embankments can be built over weak subgrade and expansive clays
- Total cost of the pavement system per unit area is competitive with unreinforced sections due to reduced aggregate processing, hauling and earthworks and lower long-term maintenance costs. Increased stiffness improves the pavement performance enabling higher traffic, heavier loading and an extended service life.

The lower environmental footprint of road construction reinforced with NPA geocells reduces virgin aggregate use, hauling, and earthworks. Societal benefits of the enhanced performance of the geocell road surface include more reliable and safer transportation, as well as all-weather access to markets for the rural populations. Economic benefits include lower capital costs of construction, and lower life-cycle maintenance with fewer traffic disruptions [36].

This article highlights case studies of some of the research on NPA based 3D cellular confinement systems conducted by leading geotechnical researchers and institutes including lab tests, field tests and demonstration projects in the US (case studies 1,2,3), India (case study 4), Israel (case study 5) and Holland (cases study 6). The studies demonstrate the efficacy of NPA geocells to meet the sustainable construction goals in India and other rapidly developing economies.

SELECTED CASE STUDIES, RESEARCH REPORTS & FIELD TESTS

1. PERFORMANCE, EVALUATION AND DESIGN OF GEOCELL REINFORCED BASES AT UNIVERSITY OF KANSAS

1.1 Comprehensive Research Program

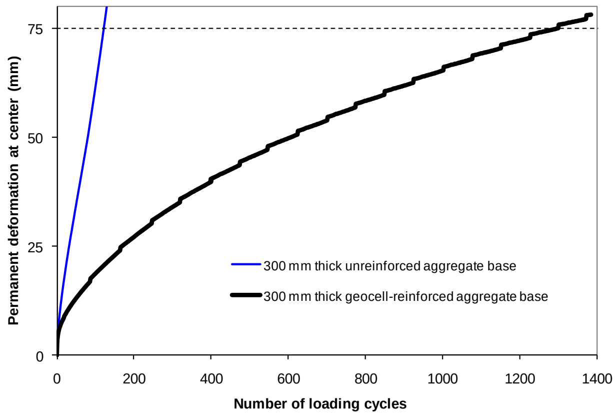
Research under Han et al. [2,24] at the University of Kansas was conducted studies on NPA geocell-reinforced base courses since 2006 in cooperation with the Kansas Department of Transportation (KDOT), with the following goals (Figure 2):

Figure 2. Installation of NPA geocell and instrumentation in Accelerated Pavement Testing (APT) facility, Kansas State University

- Obtain performance data and verify theoretical solutions and results obtained from the geotechnical box testing study.
- Evaluate the benefits of different types of NPA geocells as base reinforcement with different quality of infill materials in full-scale trafficking tests.
- Develop a design method for geocell-reinforced roads using the mechanical properties of NPA geocells.

1.2 Laboratory Box Studies

Research by Pokharel [25] subjected unreinforced and NPA geocell-reinforced bases courses of different infill materials and geocell arrangements to a series of static and repeated plate loading tests in medium size boxes (60x60 cm / 80x80 cm). The tests examined the effect of infill types (Kansas River sand, quarry waste, and well-graded aggregate) on the performance of geocell-reinforced bases. Figure 3 shows a typical result from the box test. The key findings are summarized below [2]:



- Circular shaped geocell had higher stiffness and bearing capacity than elliptical shaped geocell.
- NPA geocell reinforcement increased the granular base course stiffness by up to 2 times and bearing capacity by up to 2.5 times as compared to the unreinforced base course. The geocell with a higher elastic modulus material produced greater improvement.
- Under repeated loading, NPA geocell reinforcement significantly reduced the permanent deformation of the granular base. The percentage of elastic deformation was higher for stronger infill material as compared to weaker fill material.
- NPA geocell reinforcement significantly reduced creep deformation of recycled asphalt pavement (RAP). It recommended that non-creep cover material be used above the geocell.

Cyclic plate loading tests were performed in a large-scale testing box (2.2 mx 2m x 2 m high) with a load actuator of 245 kN capacity [25,30]. A cyclic load at the maximum magnitude of 40 kN (loading pressure of 550 kPa) was applied at a frequency of 0.77 Hz on geocell-reinforced bases over weak subgrade. In general, the degree of improvement depended on the geocell height and the infill material and density. The key findings are summarized below [2]:

- NPA geocell reinforcement improved unpaved road sections lifespan by increasing the number of loading cycles.
- NPA geocell reinforcement increased the stress distribution angle and reduced stresses to the subgrade.
- Strain measurements on the NPA geocell confirmed a beam effect on the reinforced base.
- Calculated resilient moduli showed NPA geocell reinforcement significantly reduced the rate of base course deterioration under cyclic loading.
- Infill density is important for the performance of geocell-reinforced bases.

1.3 Full-scale Moving Wheel Tests

Full-scale moving wheel tests (Figure 4) were conducted on NPA-geocell reinforced unpaved road sections over weak or intermediate subgrade using the Accelerated Pavement Testing (APT) facility at Kansas State University [3,28,37]. 16 sections were evaluated utilizing: RAP, well graded AB-3 limestone, Kansas River sand and quarry waste as well as an unreinforced control section. Each of the 4 test sections underwent wheel loading of 100,000 passes of 80-kN (18-kip) single axle load repetitions or 7.5 cm rut depth whichever came first. The testing included multiple instrumentation and performance monitoring. The key findings are summarized below [2]:

Figure 3. APT facility and unpaved test sections

- NPA geocells could reduce the required base thickness to achieve the same performance of the unpaved roads over weak subgrade. The geocell reinforced sand exhibited the largest improvement over the unreinforced section.
- NPA geocell reinforcement improved the life of the unpaved road sections, increased the stress distribution angle, and reduced the vertical stress transferred to the subgrade as compared with the unreinforced control section.

1.4 Conclusions

The laboratory experimental studies, full-scale moving wheel tests, and field demonstration in this comprehensive research have demonstrated clear benefits of NPA geocell reinforcement in terms of increased stiffness and bearing capacity, wider stress distribution, reduced permanent deformation, and prolonged roadway life. A basic conclusion of each type of study was that the benefit of geocell reinforcement increased with an increase of the modulus (tensile stiffness) of the geocell. The study concluded with modeling and calibrating of design methodologies for roads with NPA geocell reinforced bases [2,24].

2. NPA GEOCELL REINFORCED RAP ROAD BASE RESEARCH PROJECT

2.1 Investigation of RAP in Base Layer

RAP (Reclaimed Asphalt Pavement) is an economically and environmentally sustainable practice, but it is not widely utilized in the base layer of pavements because it is a time, temperature and stress-dependent material, and creeps under sustained loading. Han et al. [38] investigated the contribution of NPA geocell confinement and reinforcement to reduce creep and to attain sufficient strength and stiffness in RAP base layers in a study for the Mid-American Transportation Center (MATC) and the US DOT.

Figure 4. Cyclical loading in geotechnical test box, University of Kansas

Han et al. [39] and Thakur et al. [2626] developed the concept of using 100% RAP for base material – reinforced by NPA geocells – without additional processing. The tested pavement structure was reinforced RAP base over laid by a thin asphalt surface.

Cyclical plate loading tests were performed in a large geotechnical box (2.2x2x2m) with full instrumentation (e.g., pressure cells and strain gauges) to evaluate the RAP influencing properties with NPA geocell reinforcement: asphalt binder content and viscosity, aggregate properties, compaction curve, and CBR (Figure 5). A subgrade of sand and Kaolin with CBR= 5% was used. Thickness of the base courses were 15 cm, 23 cm and 30 cm, including unreinforced control sections. Double layers of NPA geocells were used in the 30 cm base. All geocells were 10 cm height (depth). The surface layer was 5 cm compacted HMA (Hot Mix Asphalt). Pavement sections were tested under cyclic loading up to 25-mm rut depth.

2.2 Results

Test results showed that NPA reinforced RAP bases compared to unreinforced bases:

- Showed 50% higher stress distribution angle (Figure 5)
- Ratio of loading cycles for the NPA geocell reinforcement was 10x unreinforced section (increase the pavement life – by a factor of 10)
- Had lower compression of subgrade, base and HMA layers
- Equivalent performance to 50% thicker layer

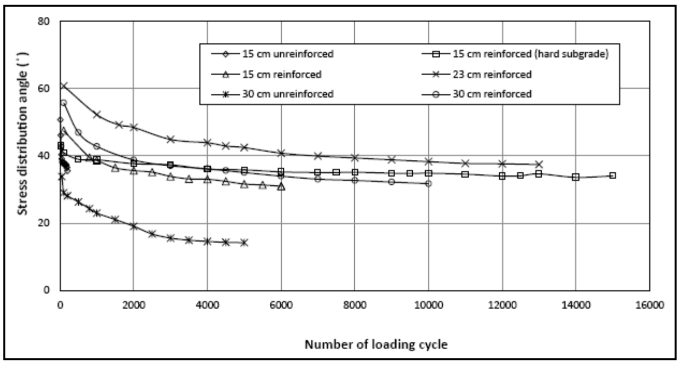


Figure 5. Stress distribution angle versus the number of loading cycles

The study concluded that RAP base reinforcement with NPA geocells can: prevent lateral creep inherent in RAP; strengthen the base layer modulus to a level similar to asphalt; reduce total pavement thickness of base and asphalt layers; enable onsite use of RAP without processing. The data in this research will be used to develop new design methodologies for RAP with NPA geocells. The goals are to reconstruct damaged pavements by heavy trucks, further the use of un-recycled asphalt materials and improve the sustainability of road networks.

3. COMPARATIVE TEST IN US STRATEGIC HIGHWAY RESEARCH PROGRAM

3.1 SHRP2 Roadeo

The Roadeo was a comparative field test in State Road 9B in Jacksonville, Florida, 2012, showcasing geosynthetic products with new "intelligent" compaction technology, part of the SHRP 2 (US Strategic Highway Research Program) (Figure 7). Four geosynthetics were installed in poorly-graded sand embankments and evaluated by 8 conventional QC and QA methods: NPA geocells (Figure 8), biaxial geogrids, geogrid/geotextile geocomposites and polypropylene woven fabrics [33].

Figure 6. SHRP2 compaction Roadeo report

3.2 Testing

Six different in situ testing methods were used in this study to evaluate the in situ soil engineering properties: a) light weight deflectometer (LWD) with 300 mm diameter plate to determine elastic modulus (E); b) cyclic plate load test (PLT) to determine elastic initial/reload modulus and permanent deformation characteristics; c) dynamic cone penetrometer (DCP) to determine California bearing ratio (CBR); d) static cone penetrometer test (CPT) to measure cone tip resistance (q LWD t) and skin friction (f); e) Troxler nuclear gauge (NG) to measure moisture (w) and dry unit weight (γ); f) sand cone density testing to measure w and γ; g) vibration monitoring testing to monitor peak particle velocities (vibrations) during vibratory compaction of fill material, and; (h) realtime kinematic (RTK) global positioning system (GPS). Total earth pressure cells (EPCs) were installed in soil layers to monitor total horizontal and vertical stresses before, during, and after vibratory compaction.

3.3 Results

According to White et al. [33], "Sand and gravel are improved more with NPA geocells than any other geosynthetic." Cyclical plate loading tests showed that the NPA geocells had the lowest permanent deformation (4.1 mm vs. 5.6 mm for geogrid) and the highest modulus of all the geosynthetics (E = 161 MPa). The modulus improvement factor (MIF) of the sand as a result of NPA geocells confinement was consistent with the results of other field tests, which produced a MIF of 2.5-4.0.

Figure 7. Layout and infill in installation of NPA Geocells in SHRP2 Roadeo

The benefits of NPA geocells were noted by the authors – lateral confinement increases stiffness and shear strength of the soils, which distributes wheel loads more widely and reduces rutting. They concluded that NPA geocell confinement technology is applicable to a wide variety of highway construction: a) New embankment and roadway construction over unstable soils; b) Roadway and embankment widening; and c) stabilization of pavement working platforms.

The demo project underscores the efficacy of NPA geocells to increase the stiffness and lifespan of pavement structures in order to achieve more sustainable road infrastructure.

4. VALIDATION OF MODULUS IMPROVEMENT FACTOR, INDIA

4.1 Phaltan Project

Rajagopal et al. [1,23] conducted cyclical plate load tests on NPA geocell reinforced and unreinforced pavement sections on a new constructed access road at the Govind Dairy Factory, Phaltan, India (Figures 9, 10) and then investigated the influencing factors to validate the results with laboratory testing in a geotechnical test box. Pressure-settlement data were used to estimate the Modulus Improvement Factor (MIF) for NPA geocell reinforcement.

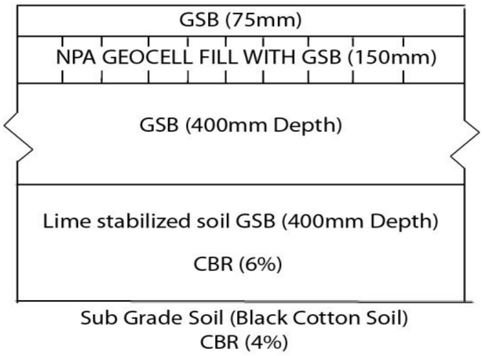


Figure 8. Section of Access Road Layers

4.2 Modulus Improvement Factor (MIF)

According to the Indian Road Congress (IRC) formulas for moduli of soil layers in CBR values:

Subgrade[8]

$$E(\text{MPa}) = 10{*}\text{CBR} \quad \text{for CBR} \le 5 \text{ and}$$
$$= 176{*}(\text{CBR})^{0.64} \quad \text{for CBR} > 5$$

Granular Sub-base and Base[7]

$$E_2 = E_3{*}0.2 * h^{0.45}$$

Where:

- **E2** = composite elastic modulus of granular sub-base and base (MPa).
- **E3** = elastic modulus of subgrade (MPa).
- **H** = thickness of granular layers (mm).

* Poisson's ratio for layer was taken as 0.4.

The MIF is determined by = E-Value (reinforced layer) / E-Value (unreinforced layer).

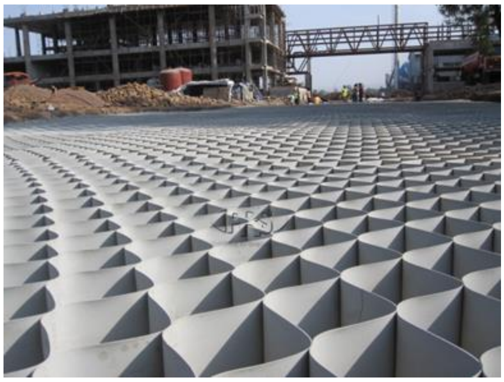


Figure 9. Access Road with NPA Geocell

4.3 Field Test

The investigators used the average settlements from the plate load test (3.35 mm) in the field under 10T of load on the reinforced section and tested for the corresponding modulus that would yield the above settlement using the Kenpave pavement analysis program. The analysis used a load of 100 kN and plate contact radius of 150 mm (contact pressure = load/area =100/area of plate = 1414 kPa). The modulus of the NPA geocell layer was selected by trial and error process to match the measured settlement at a load of 100 kN (see Table 1 below).

4.4 Results

The MIF value of 2.75 calculated by finite element software analysis from the NPA geocell field test was validated by values obtained from laboratory testing: 2.92 for 150 mm NPA geocell height, 2.84 for 50 mm and 100 mm NPA geocell height. These are supported by MIF reported by Kief and Rajagopal [36]. These tests substantiate the validity and accuracy of the MIF as a tool for pavement design with NPA geocells.

Table 1 – Phalton Field Test MIF from E-Value / avg. settlement

Improvement Factor	E-Value	Average Settlement
1	105628.43 kPa	4.32
2	211256.86 kPa	3.57
2.5	264071.08 kPa	3.41
2.75	290478.18 kPa	3.35
3	316885.29 kPa	3.29
4	422513.72 kPa	3.14
5	528142.15 kPa	3.03

5. DESIGN IN CROSS-ISRAEL HIGHWAY 6 DEMONSTRATION PROJECT

5.1 Highway Research

The Cross-Israel National Highway 6 (Class I grade highway) concessionaire investigated the impact of structural reinforcement in the pavement base layer with NPA geocells [23](Figure 11).

Figure 10. Cross Israel Highway 6

5.2 Design Method

Design of the solutions was based on mechanistic-empirical method for flexible pavements using the layered elastic model, based on the following parameters (Figure 12):

- CBR according to seasonal damage.
- Evaluation of Equivalent Single Axle Loads (ESAL's) based on 18-kip single axle (W18).
- Definition of the NPA geocell reinforcement properties, including the Modulus Improvement Factor (MIF) for fully and partially confined zones.
- Examination of fatigue and rutting failure criteria.

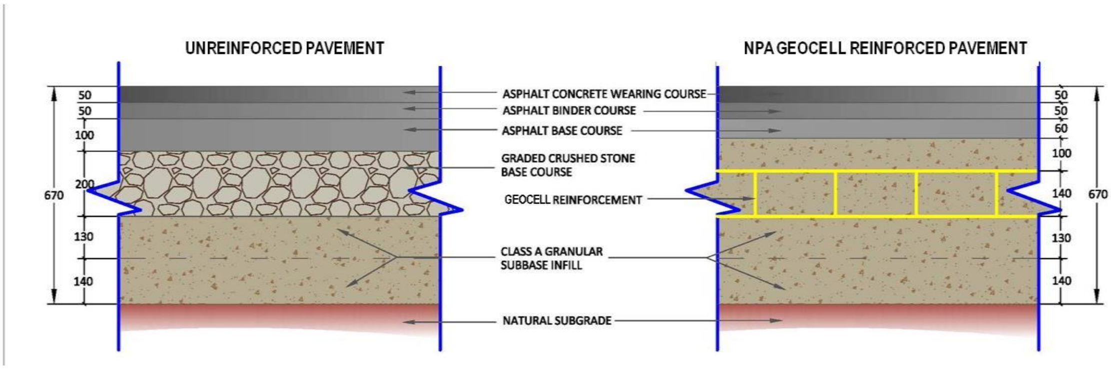


Figure 11 Conventional vs. NPA geocell -reinforced pavement

5.3 Results and Conclusions

The contribution of the NPA geocell reinforcement to the base layer was calculated from the elastic modulus of the infill material (E-128 MPa) x MIF of 2.92 = modulus of 374 MPa. This enables replacement of the base layer with less expensive subbase quality infill, as well as a reduction in the asphalt base course. The following were achieved with NPA geocells:

- *Asphalt* – reduced by 22.5% (45 mm) due to improved aggregate base modulus.
- *Base* – replaced crushed stone base with lower cost granular subbase infill (-38% /m^3).
- *Subbase layer* – reduced thickness by 7.4% (20mm).
- *Improved modulus* – enables increased traffic (ESAL) loadings.
- *Pavement maintenance* – eliminate 1 complete deep scraping & overlaying of asphalt over 20 year design life.

The economic benefits achieved by utilizing NPA geocells include:

- Saving of 5.8% of direct construction costs vs. the conventional design.
- Saving of 50% of the conventional 20-year expected pavement maintenance costs.
- Total savings of 21.5% of the conventional life cycle cost anticipated.

Additional indirect savings due to lower equipment requirements include logistics, hauling, compaction, manpower and less traffic restrictions.

6. NPA GEOCELL VS. GEOGRID REINFORCEMENT OF ROAD BASE FIELD TRIAL

6.1 General

The KOAC institute in the Netherlands conducted controlled field trials for geosynthetics reinforcement of road bases, under Van Gurp & Westera [**Error! Reference source not found.**] (Figure 13). The test beds were comprised of 30 cm of recycled aggregate base layer from concrete/masonry rubble (0/31.5 mm size) and the geosynthetic under test over 55 cm clay subgrade (CBR=1.4%). Parallel control sections were also used. The full-scale structures were installed in controlled conditions (large enclosed hangars). NPA geocells were the only geocell in the test of seven brands of geogrids, and the only product tested with inferior aggregate.

Figure 12. KOAC-NPC Enclosed Hangar Test Facility and Road Base Test Sections

6.2 Testing and Results

Falling Weight Deflectometer (FWD) as well as Light Weight Falling Deflectometer (LWD) loading plate (300 mm) were used to assess the stiffness modulus. The results are based on the stiffness modulus of the combination of subbase and subgrade and the geosynthetic reinforcement in order to derive at the Road Base Thickness Reduction Factor used in the CROW design chart. The design chart/method was developed by KOAC-NPC for the CROW Transport Research Knowledge Centre, Netherlands.

The calculated mean road-base thickness (RF) Reduction Factor (unlimited) for NPA geocells with a subgrade CBR of 1.5 was 0.73. This value was off the chart (Figures 14, 15), as the highest published RF for geogrid reinforcement was 0.5. Whereas geogrid RF values do not normally exceed 0.5, KOAC set this value as the maximum limit for the test. Even within these limitations, the mean 0.43 RF for NPA geocells is higher than all other tested products.*

(***NOTE**: Maximum RF values are truncated to 0.50 according to CROW test standards)

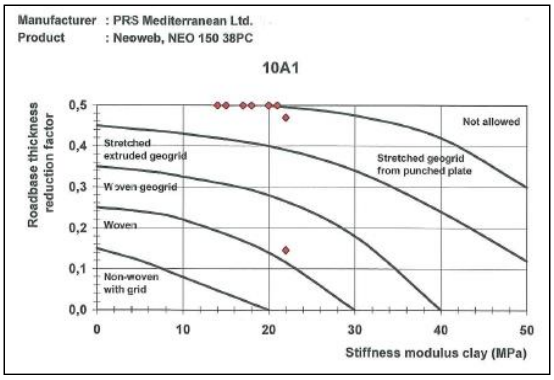


Figure 13. Roadbase reduction factor for NPA geocells (limited)

Roadbase thickness reduction factor station 10A1

Control section	Station	Roadbase thickness reduction factor	Roadbase thickness reduction factor (NO LIMIT)	Stiffness clay control
(-)	(-)	(-)	(-)	(MPa)
Section 1B	1B2	0,50	0,77	15
Section 1B	1B4	0,50	0,88	15
Section 3B	3B1	0,50	0,87	14
Section 3B	3B2	0,50	0,76	14
Section 4C	4C2	0,50	0,63	18
Section 4C	4C3	0,50	0,76	18
Section 5A	5A1	0,50	0,72	17
Section 5A	5A2	0,50	0,74	17
Section 5B	5B2	0,50	0,81	20
Section 5B	5C3	0,50	0,83	20
Section 6B	6B1	0,50	0,95	21
Section 6B	6B2	0,50	0,83	21
Section 8C	8C1	0,15	0,15	22
Section 8C	8C2	0,47	0,47	22
	Minimum	0,15	0,15	
	Maximum	0,50	0,95	
	Mean	0,47	0,73	

Figure 14. Actual roadbase thickness reduction factors (limited vs. unlimited)*

6.3 Conclusions

NPA geocells exhibited the highest road base thickness RF of seven leading geogrid products tested (both limited / unlimited values). NPA geocells were the only reinforcement product that could be tested with inferior infill, as the 3D vertical zone of influence is based on confinement and interlock (of specific sized aggregate). These factors have important ramifications for the sustainability of road construction projects.

DESIGN METHODOLOGY FOR NPA GEOCELL-REINFORCED PAVEMENTS

Introduction

Theoretical research into NPA geocell reinforcement mechanisms, influencing factors of loading in plate tests and accelerated wheel load tests at the University of Kansas, led to the development of a design method for NPA geocells [2,232425,27]. A simplified design method was developed for NPA geocell-reinforced bases for unstable subgrades/unpaved roads utilizing bearing capacity,is based on a modification of the Giroud and Han (2004) method. A design method for incorporating NPA geocells into roads with stable base and subgrade is based on the resilient behavior of pavement structures and follows the Mechanistic-Empirical design procedure.

Modulus Improvement Factor (MIF)

It was well accepted that confinement increases the resilient modulus values of granular materials used in pavement structures; and especially of inferior fill, such as fine granular soils and recycled materials. The increase in modulus or stiffness of NPA geocell reinforced base layers has been verified by field tests, modeling and numerical analysis by Rajagopal, et al. [1], Kief et al. [23], Yang and Han [27] and Pokharel [25]. The increased modulus of the base course is defined as a Modulus Improvement Factor (MIF). The MIF of the base layer relates to the improvement of the base modulus by the NPA geocells, as shown by the following formula:

$$MIF = \left(\frac{E_{\text{bc (reinforced)}}}{E_{\text{bc (unreinforced)}}} \right)$$

Generally, the MIF applied in NPA geocell-based projects ranges between 1.5 to 5.0 dependent on material of infill, subgrade and relative location and depth of the reinforced layer [23].

Unpaved Road Design

Pokharel [25] developed a design formula for the design the unpaved roads with NPA geocells. The well-known design equation developed by Giroud and Han for planar geosynthetic reinforcement was modified for 3-dimensional geosynthetic reinforcement.

$$\text{Required thickness, } h = \frac{\left\{ 0.868 + k \left[\frac{r}{h} \right]^{1.5} \log N \right\}}{\{1 + 0.204(R_E - 1)\}} \times \left\{ \sqrt{\frac{P}{\pi r^2 \, m \, 5.14 c_u}} - 1 \right\} r$$

$$m = \left(\frac{s}{f_s} \right) \left\{ 1 - 0.9 e^{\left[-\left(\frac{r}{h} \right)^2 \right]} \right\} \qquad c_u = f_c \, CBR_{sg}$$

$$R_E = I_f \frac{E_{bc}}{E_{sg}} = Max \left\{ 7.6, \; I_f \left(\frac{3.48 CBR_{bc}^{0.3}}{CBR_{sg}} \right) \right\}$$

$$I_f = \left(\frac{E_{bc(\text{reinforced})}}{E_{bc(\text{unreinforced})}} \right)$$

Where,

r = radius of tire contact area (m);
N = number passes;
P = wheel load (kN);
cu = undrained cohesion of the subgrade soil (kPa);
s = allowable rut depth (mm);
fs = factor equal to 75 mm; and bearing capacity factor = 5.14;
fc = factor equal to 20.5 kPa;
RE = modulus ratio;
Ebc = resilient modulus of base course (MPa);
Esg = resilient modulus of subgrade soil (MPa);
CBRbc = California Bearing Ratio (CBR) of base course; and
CBRsg = CBR of subgrade;
Factor k - varies with type of infill material: 0.52 for gravel; 0.54 for sand and RAP.

This formula was incorporated in the design of the causeway at Algar Lake Oil Sand road and the access road for MEG Energy Christina Lake facility [35](Figure 15). The performance evaluation of the latter is ongoing. Preliminary results have shown that this design method is suitable for high ESAL heavy haul roads as well.

Figure 15. Installation of NPA geocell at MEG Energy Christina Lake facility

Layered Elastic Model

The layered elastic model is one of the mechanistic models that are used to mathematically model pavement physics. A layered elastic model can compute stresses, strains and deflections at any point in a pavement structure resulting from the application of a surface load.

A pavement design is evaluated by first modeling the multi-layered pavement configuration - each layer is defined by thickness, elastic modulus and Poisson's ratio. Then the typical load configuration is applied, using one of the commercially available layered-elastic analysis programs for pavements.

The design theory is based on replacing an unreinforced pavement design with a reinforced design. The NPA geocell improved performance of the structure is expressed by improving the modulus of (usually) the base layer utilizing the MIF.

Implementation of the elastic response in transfer functions provides the ESAL's performance for reinforced pavement structure. This is then validated for the critical failure modes: fatigue – failure of the asphalt layer; and rutting – failure of subgrade bearing capacity. An iterative process is used to optimize the cost savings in terms of the layer thickness and infill type with an equal or greater performance compared to the unreinforced design.

These design methods enable road engineers and road planners to be able to compare the sustainability of an NPA geocell reinforced road with an unreinforced road [23].

SUMMARY & CONCLUSION

Research has broadened our understanding of 3D geocell reinforcement mechanisms and the influencing factors, demonstrating that not all geocells are equal. Geocells made of stiffer material with a higher elastic modulus produced greater improvement of pavement stiffness, bearing capacity, stress distribution and reduced deformation. These factors directly influence the pavement layer thickness, infill materials and lifespan. The investigations, field tests and case studies cited in this paper demonstrate the efficacy of Novel Polymeric Alloy (NPA) geocell solutions for sustainable for roads and highways.

The High Modulus Improvement Factor (MIF) of NPA geocells improves the modulus of locally-won, marginal quality or recycled infill materials by an average factor of 2.75 or more. This enables a reduction in the thickness of structural layers by as much as 50% compared to an unreinforced road. The results on sustainability are manifold. Virgin aggregate resource use is reduced, as is aggregate screening, crushing, processing and hauling. Less in-site placement (and less subgrade replacement) means less earthworks / equipment operations. This in turn reduces fuel use, vehicle pollution, airborne dust, sediment runoff and the project carbon footprint.

In addition to reducing the construction environmental footprint, the capital costs of construction can be reduced as well. NPA geocells are not limited to solutions for weak subgrade and expansive clays. NPA geocells also enable the replacement of high-quality base-layer aggregate with lower cost, granular subbase material. This extends the envelope for potential geocell solutions making them more economical and applicable to a wider range of infrastructure projects.

The increased stiffness of the NPA geocell reinforcement also improves the pavement performance enabling higher traffic, heavier loading and/or extended service life. This means fewer repairs, longer life-cycle maintenance and more reliable and safer roads.

The research, validation and design methodologies reviewed in the paper demonstrate the multiple engineering, environmental and economic benefits of NPA geocell technology and the role it can play in the development of sustainable roads, highways and infrastructure.

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