MODULUS IMPROVEMENT FACTOR FOR GEOCELL-REINFORCED BASES

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Synopsis: *New developments in polymer materials for geosynthetics, as well as recent research and testing of cellular confinement have led to new understandings in geocellular reinforcement and new road design methodologies. Novel polymeric alloys make geocells very stiff, strong and durable. These "tough cells" improve the layer modulus for all types of roads and rails, even those without soft soils. Higher layer modulus enables the replacement of the base layer with lower quality infill (locally available or recycled materials), and/or a reduction of the layer thickness. The improved performance of reinforced road sections has been analyzed in laboratory box tests and field data to interpret and calibrate the modulus improvement factor (MIF) for this new type of geocell. The MIF can be used in the design of new roads to quantify the reinforcement contribution of novel polymeric alloy geocells. An example of a pavement design for a major motorway utilizing the MIF is provided. Novel polymer alloy geocells can revolutionize road reinforcement by reducing the quality and quantity of infill material, saving construction and maintenance costs. The end result is a more economic and environmental solution for creating a sustainable transportation infrastructure.*

1. INTRODUCTION

Although the original concept for geocell cellular confinement systems was for the reinforcement of the base layer of roads over soft soils, they are most frequently used at the subbase level to strengthen weak subgrades or in low volume roads. The use of conventional geocells in the upper layers of heavy duty pavements, particularly highways and railways, was limited, in part due to concerns about the stiffness and durability of geocells, typically made from HDPE.

PRS, an established player in the field of geocells, developed a novel polymeric alloy (NPA) for its Neoweb® geocells. The NPA, called Neoloy®, is a unique polymeric nano-composite alloy based on polyester/polyamide nanofibers in a polyethylene matrix. Geocells from this material have the flexibility for handling similar to HDPE with elastic behavior similar to engineering thermoplastics. In comprehensive research and testing

Han (2011) and Pokharel (2010) show that NPA geocells have significant higher performance compared to unreinforced bases, as well as to bases reinforced with HDPE geocells: increased stiffness of granular base course, reduced permanent deformation, lower creep deformation, and reduced vertical stress to the subgrade. The NPA geocell with the higher elastic modulus materials produced the greatest improvements. Laboratory plate load tests and back calculation analysis by Unni, et al (2010) clearly demonstrated lower pressure transmitted through the NPA reinforced pavement layers and a very high elastic modulus of the NPA reinforced layer than the unreinforced layer that can reduce rutting and extend the longevity of a pavement structure.

2. DESIGN THEORY

Studies of cellular confinement reinforcement mechanisms, numerical modeling and field trials by Han (2011), Pokharel (2010) and Wang (2010), included the development and calibration of design methods that could incorporate 3D NPA geocells. For unstable subgrades, the Giroud and Han (2004) method for design with geosynthetics was modified for Neoweb-reinforced bases (Han, 2011). For roads with stable base and subgrade, the design method for incorporating Neoweb uses the elastic behavior of pavement structures and follows the Mechanistic-Empirical design procedure.

2.1 Modulus Improvement Factor (MIF)

It was well established that geocells systems increase the resilient modulus of confined granular materials (Yuu et al 2008); the increased stiffness is more pronounced in low quality infill such as fine granular soils and recycled materials. The increase in the modulus (stiffness) of Neoweb reinforced base layers have been verified by modeling and numerical analysis by Han et al 2010, Yang, 2010, Pokharel 2010, Meyer (2007) and Kief and Rajagopal (2008). 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 modulus of the base by Neoweb, as shown in the following formula:

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

Where E_{bc} *(reinforced)* = the modulus of the reinforced base and E_{bc} *(unreinforced)* = the modulus of the unreinforced base. Quantifiable metrics and calibration of the MIF (Modulus Improvement Factor) derived from testing enable integration of the MIF into the mechanistic-empirical design method. MIF values for NPA geocells ranges from 1.5 to 5.0 dependent on material of infill, subgrade and relative position of confined layer.

2.2 Modification of the Design Methodology for Unpaved Roads

The Giroud and Han (2004) design methodology for geosynthetic (geotextile and geogrid) reinforcement of unpaved roads was modified for reinforcement with Neoweb (high-strength) geocells. The modifications include changing geogrid dependent parameters (such as aperture modulus) to geocell dependent parameters. These were, calibrated by the laboratory cyclic plate loading tests and full-scale moving wheel tests on Neoweb geocell-reinforced granular bases over weak subgrade. The second modification is the inclusion of the modulus improvement factor (MIF) in the calculations to define the increased modulus of the base course. The design formula was verified by the test data (Pokharel, 2010, Wang 2010).

2.3 Layered Elastic Model for Paved Roads

The layered elastic model allows for the evaluation of strains, stresses and deflections. It is based on an evaluation of the elastic multi-layer response to specific loading configurations. A mechanistic model of each pavement layer is created including its 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 methodology is based on replacing an unreinforced pavement design with one based on reinforcement. The improved performance of the structure due to the NPA reinforcement is expressed by improving the modulus of (typically) 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 (asphalt layer) and rutting (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.

3. PLATE LOAD TESTS TO DETERMINE MODULUS IMPROVEMENT FACTOR, INDIA

The expansion of the Govind dairy farm facilities in Phaltan included the reconstruction of an access road for its fleet of vehicles. The road is over non-homogenous soils, with black cotton clays of medium-high compressibility. These soils are characterized by high shrinkage and swelling properties, which lead to heaving and undulations in the surface and pavement failure. The client reinforced the weak subgrade and strengthened the pavement of one section of road with the Neoweb® cellular confinement system, manufactured by PRS, while other sections were constructed in a conventional manner without reinforcement. Installation took place during March-April 2010. The total pavement structure was 1m deep, as shown in Figure 1. A study was undertaken to evaluate the performance of the NPA (Neoloy® novel polymeric alloy) Neoweb reinforced and unreinforced pavements at the factory utilizing plate load tests to interpret the modulus of the different layers. The pressure-settlement data from these plate load tests was used to estimate the Modulus Improvement Factor (MIF) for the Neoweb reinforced section.

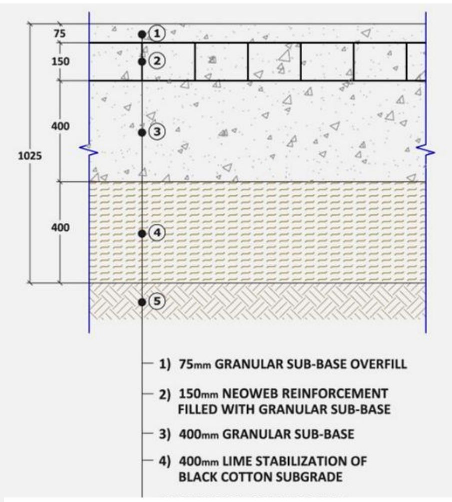

Figure 1. Pavement Structure with Neoweb NPA geocell Reinforcement

3.1 Visual Observations

The road sections have been in service for nearly 8 to 9 months and have undergone one severe monsoon season. The general observation was that the unreinforced road sections showed extensive undulations in the road sections while the NPA Neoweb geocell treated road sections had maintained a perfect level surface (see Figure 3 and Figure 4).

Figure 2.Unreinforced Section at Dairy Factory – Rutting Indicated by Arrows

Figure 3. Reinforced Section at Dairy Factory – Level Surface Shown by White Line

It is clear from the site observations and the feedback given by the owners of the site that the Neoweb reinforced pavement section showed good riding quality for the milk tankers while the unreinforced sections posed difficulties due to severe rutting. The unreinforced sections required frequent maintenance to make a level surface.

3.2 Technical Investigation

The following steps were used for conducting the test in field as per the relevant Indian Standards. All the field plate load tests were performed at 300 mm below the road surface during December 25-30, 2010. The loading increment was 12.5 kN as per code ISI888:1982. Some of the initial load tests did not result in meaningful data due to problems with the loading trucks used for reaction and the malfunctioning of loading jack. In addition boulder-size stones present at the subgrade of the unreinforced section produced skewered results; sampling on these sections could not be repeated.

Settlements observed for each increment of load after an interval of 1,2.25,4,6.25,9,16 and 25 minutes and thereafter at hourly intervals to the nearest 0.02 mm during testing on subgrade, each load increment done for not less than one hour and sometimes done when the rate of settlement gets appreciably reduced to a value of 0.02 mm/min. The plate loading tests generated the average settlement in mm per load.

3.3 Analysing the Data

The data from the plate load tests was back-analysed to estimate the modulus improvement factor of the geocell reinforced road base. The moduli of the GSB and other unreinforced layers were obtained using the empirical relations proposed in IRC-37 according to the Indian Road Congress (IRC) formulas for moduli of soil layers in CBR values.

Subgrade[8]

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

Granular Sub-base and Base[7]

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

Where:

E2 = 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 granular and subgrade layer may be taken as 0.4.

3.4 E-Values per Structural Layer

The modulus values of different layers in the pavement sections are estimated as illustrated in Table 1.

Table 1. Modulus Values of Different Layers

Layer	Detailed calculation	E Value (kPa)
GSB (75 mm thick) =	$55400*0.2*75^{0.45}$	=77324.53 kPa
GSB Neoweb (150 mm thick) =	$55400*0.2*150^{0.45}$	=105628.43 kPa
GSB (225 mm thick) =	$55400*0.2*225^{0.45}$	=126771.577 kPa
GSB (400 mm thick) =	$55400*0.2*400^{0.45}$	= 164235.39 kPa
Stabilized subgrade(CBR 6%)	$17.6*6^{0.64}$ = 55.40 Mpa	= 55400 kPa
Subgrade (CBR 4%)	10*4 =40 MPa	= 40000 kPa

3.5. Modulus Improvement Factor

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 Neoweb layer was selected by trial and error process to match the measured settlement at a load of 100 kN.

Table 2. Improvement Factor from E-Value/ Average Settlement

Improvement Factor	E-Value	Average Settlement
1	105628.43 kPa	4.32
2	211256.86 kPa	3.57
2.5	264071.075 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

The observed performance of the geocell reinforced pavement at the dairy factory was excellent. The section of the road reinforced with geocell layer did not exhibit any surface rutting or uneven settlements. The lorry drivers complimented that they could drive faster in the section with reinforcement while the driving over the unreinforced was quite tedious due to the several surface depressions. The difference in the performance was reported to be more evident during monsoon season. The unreinforced section had to be reconstructed soon after the initial construction due to the damage caused by the stagnant water. On the other hand, the section with geocell reinforcement did not show any distress even during the rains.

The back analysis of the plate load test data using Kenpave program has shown that the geocell reinforced soil layer has modulus improvement factor of 2.75. This result has significant influence on the economic design of highway sections.

4. CROSS-ISRAEL HIGHWAY 6 DEMONSTRATION PROJECT

4.1 Highway 6

Figure 4. Installation of Neoweb on Highway 6

The Cross Israel Highway 6 is a 140 km electronic toll road traversing the country's North-South corridor. The class I highway is a DBOT (Design, Built, Operate, Transfer) project funded by $1.4 billion in private investment and built in accordance with to the highest international road standards. (Figure 4) The Highway 6 concessionaire, Derech Eretz, decided to test the Neoloy-based Neoweb cellular confinement system and its ability to reduce construction costs – specifically the cost of infill and asphalt. As part of a road-widening project, a 0.5 km demo section was defined along with an unreinforced profile.

4.2 Structural Design

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

- CBR according to relative seasonal damage – 5.0%
- Equivalent Single Axle Loads (ESAL's) = 34.1×10^6 based on 18-kip single axle (W_{18}) (AASHTO 1993) and required design life of 20 years
- Modulus Improvement Factor (MIF) for fully and partially confined zones
- Examination of fatigue and rutting failure criteria

4.2.1 Calculating MIF

The elastic modulus of the native infill, granular subbase material, was calculated as E=128 MPa. The calculated MIF is determined from this value in addition to the support layer modulus (the subbase layer underneath the Neoweb) and the Neoloy reinforcement properties of the Neoweb. In this case, the specific MIF was calculated as 2.92, and therefore the modulus for the Neoweb reinforcement is = 374 MPa.

This improved modulus is valid for the depth of the Neoweb (140 mm cell height) in addition to 20 mm above and below the Neoweb (according to Han, 2010). This is defined as the fully confined zone. The design process then calculates the equivalent modulus by adding the partially confined zone to the fully confined zone. The partially confined zone is the additional 40 mm of base granular overfill, directly under the asphalt. The result is an equivalent MIF for the entire base = 2.54; therefore the equivalent modulus of the reinforced zone = 326 MPa.

4.2.2 Elastic Layer Modeling

This method models standard axle configuration and pavement structure properties, including layer thickness, Poisson's Ratio and elastic modulus to generate the pavement elastic response. The core of the pavement modeling is setting the improved value for the Neoweb reinforced modulus. The analysis was performed by Everstress® layer elastic analysis software to calculate the strains of the elastic response is the horizontal tensile strain for fatigue and rutting analysis.

4.2.3 Calculating Failure Criteria

The elastic response is the horizontal tensile strain at the bottom of the asphalt layer (used in fatigue analysis) and the vertical compressive strain at the top of the subgrade (used in rutting analysis for bearing capacity failure). These values were implemented by transfer functions to calculate the ESAL's performance in the pavement structure. The Neoweb design was verified by checking that the ESAL performance, as defined by the number of cycles to first failure for fatigue or rutting, exceeds the original design requirements of the road, ESAL=$34.1x10^6$. The ESAL's of the Neoweb based design exceeded the asphalt fatigue failure by 30% and the subgrade rutting failure by 60%.

4.2.4 Pavement Design

The alternative design to the conventional pavement structure is shown in Figure 5 below. Neoweb serves as a reinforcing interlayer in the upper pavement, directly under the asphalt, contrary to conventional practice, which puts geocells at the subgrade. This maximizes the 3D reinforcement mechanism on the pavement structure by better load distribution for higher stresses in the base and by increasing its bearing capacity. The stiffer support from the improved modulus enabled a reduction of asphalt thickness, and the use of lower quality (cost) infill for base layer.

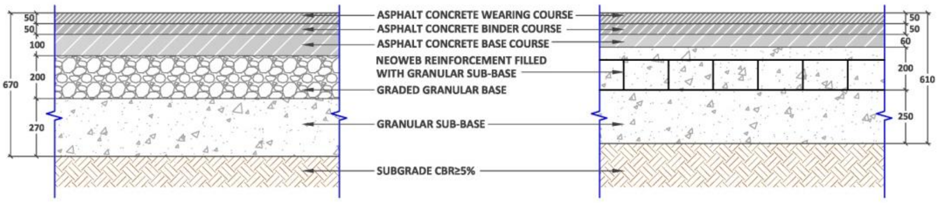

Figure 5. Unreinforced vs. Reinforced Pavement Sections

The use of the Neoweb reinforced structure achieved the following:

- *Asphalt concrete thickness reduction* – reduced asphalt base thickness from 200 mm to 160 mm due to improved modulus of reinforced aggregate base.
- *Base layer replaced* – replaced high cost crushed stone base infill with lower quality subbase material due to an improved modulus (-38% lower cost/m^3).
- *Subbase layer reduction* – reduced total subbase layer thickness by 20 mm (7.4%).
- *Estimated pavement maintenance* – save one complete deep scraping & overlaying of asphaltic layers for design life of 20 years.

4.2.5 Test Results

Monitoring was based on pressure cells inserted in specially excavated trenches during construction of the layer. The sections were tested by static load plate loading on compacted base layer surface; the vertical stresses were recorded by the pressure cells. The results shown in Figure 6 verify that the vertical stress of the two Neoweb reinforced

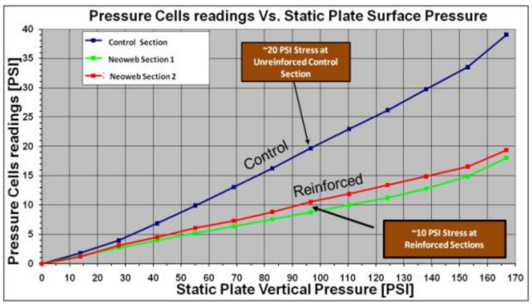

Figure 6. Pressure Cell Readings for Neoweb – 50% less Vertical Pressure

sections (green and red) are about 10 psi, which is 50% less than the unreinforced control section (blue line). These results can be used to verify the MIF by back-calculation of higher moduli for the reinforced layer.

4.2.6 Beam Effect

In effect, vertical loading on Neoweb infilled with compacted granular material creates a semi-rigid slab or "beam effect" over soft soils, as shown in Figure 7. Also known as the tensioned membrane effect, this refers to the tension developed in the curved geocell-reinforced mattress to resist the vertical load (Rajagopal, et al 1999). However, this effect is dependent upon significant deformation of the pavement structure (Han 2004). As the geocell-reinforced section is stiffer than the surrounding soil, the curved surface exerts upward reaction and reduces the net stress to the subgrade (Pokharel 2010). The beam effect distributes the load evenly and effectively over a wider area, thereby increasing bearing capacity and decreasing differential settlement. The zone of influence created by the geocell is slightly higher than the cell wall height – and applicable to any structural layer. The beam effect on the reinforced base was verified by strain measurements on the Neoweb geocell by Han (et al, 2011) and in other geocell research by Madhavi Latha et al (2008).

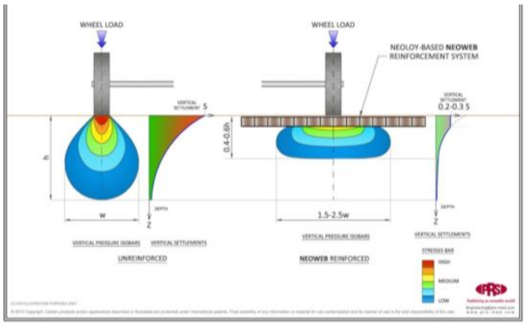

Figure 7. Beam Effect of Neoweb Reinforcement

4.3 Conclusions from the Cross-Israel Highway 6

The reduction of vertical stress and the beam effect have ramifications on long-term road performance, by enabling higher volume and heavier traffic. In addition, the stiff Neoweb confinement prevents movement and shearing of infill; this prevents permanent degradation and increases the higher loading cycles, thereby increasing the pavement life. It will also lower the IRI (International Roughness Index), as the pavement surface and structure will last longer than the original design; in addition to reducing maintenance and rehabilitation cycles. The important economic benefits achieved by utilizing Neoweb include:

- Save \$3.29/m^2 (5.8%) of direct construction costs vs. the conventional design.
- Save \$15.58/m^2 (50%) of conventional 20-year expected maintenance costs.
- Total savings of 21.5% of the conventional anticipated life cycle cost.
- Additional in-direct savings due to lower equipment requirements – logistics, hauling, compaction, manpower and traffic restrictions.

5. SUMMARY AND CONCLUSION

Although geocells were originally designed for the support of base layers in flexible pavements, their use was limited to unpaved low volume roads, due to concerns about stiffness, durability and a lack of design methodologies. Recent research and development by industry in collaboration with academia has changed that by creating a novel polymeric alloy (NPA) for geocells (Neoloy-based Neoweb). Not only do these

NPA geocells exhibit high tensile strength, resistance to creep and dimensional stability greater than conventional geocells. They significantly increase the strength of confined infill as well as the pavement layer elastic modulus.

Since NPA Neoweb geocells improve the moduli of pavement layers, it can now be deployed in the upper base layers of heavy-duty paved roads, as was shown in the demonstration project. High-quality aggregate base can be replaced with less expensive locally-available and recycled granular subbase material. The increased strength and bearing capacity provided by NPA geocells also enable a reduction in the layer thickness of the asphalt, base and subbase layers. This is an important example of a sustainable construction method with clear environmental and economic benefits suitable for all types of transportation infrastructure. Reinforcement with Neoweb also increases the service life of pavement structures, thereby reducing their operational and maintenance costs. This enables transportation management professionals to allocate limited budgets from maintenance and repair to the construction of new roads and infrastructure.

In addition to defining the reinforcement mechanisms and influencing factors, recent research has also calibrated and integrated the use of NPA geocells in road design methodologies. In particular, the modulus improvement factor (MIF), verified in multiple research projects and field demos provides a reliable method for quantifying the NPA geocell contribution to the pavement structure for use in the design of unpaved and paved roads and railways. The MIF value obtained from the field test, laboratory test and finite element studies is 2.75. This confirms similar results in other research, dependent upon the material of infill, subgrade and location of reinforced layer. It is hoped that this research will form a solid foundation for sustainable roads of all types in all localities.

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