Geocell-Reinforced Pavement Structure State of Practice in Canada

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ABSTRACT

Geocell reinforcement at the base and subbase courses of pavement structures is one of the recent developments in the field of geosynthetics soil reinforcement. Geocells are honeycomb-shaped three-dimensional materials usually made from polymeric alloys and High-Density Polyethylene. Geocells improve the modulus and strength of the reinforced soil composite and durability of the road structure by providing lateral confinement, wider load distribution and also through a semi-rigid slab or beam effect. Novel Polymeric Alloy (NPA) is the latest technology used as geocell material which provide increase tensile strength, higher modulus and creep resistance compared to the geocells made from other types of material. Geocells can be used in both paved and unpaved roads contributing to the sustainability of the project by reducing the overall thickness of the pavement structure and decreasing the amount of virgin aggregate required. This in turn decreases the environmental footprint of the project and reduces the overall construction cost. Over the past decade a number of roads (paved and unpaved) have been constructed in Canada using the NPA geocell reinforcement. This paper discusses the current state of the practice in designing pavement structure with geocells. Few projects designed with geocell reinforcement are also discussed in detail to provide insight into the challenges faced during construction, long-term performance of the geocell-reinforced pavement structure and contribution of the geocell in each project to reduce environmental footprint and construction cost of the projects. In summary geocells have enabled the owners to save on the construction cost and lower the CO_2 emission associated with the construction while improving the pavement performance and reducing pavement distresses.

INTRODUCTION

The history of road construction dates back to ancient days as roads are the foundations of any human settlements and subsequent development. Road and transportation networks also take up major share of the investments made by any modern society. Although it is always attempted to construct a perpetual road structure it has been a challenge even to construct a road to last for the intended design period. The pavement structure needs to be strong enough to withstand the ever-growing traffic demand while optimizing the construction costs and utilized resources. As such, extensive efforts have been made to create an approach that balances the pavement structure and cost of construction to ensure the justified use of the available resources. These methods aim to determine pavement structure in order to provide adequate support for a certain amount of traffic loading in a certain period of time. There are generally two different approaches to pavement design, namely empirical design methods and mechanistic-empirical design methods. Empirical design methods are developed by predicting the behaviour of the pavement structure by comparing them to the previously observed pavement behaviors. The most widely-used empirical pavement design method used by pavement engineers is the method developed by American Association of State Highways and Transportation Officials (AASHTO) commonly known as AASHTO 1993 design method. Accelerated traffic loading was applied to a wide range of pavement structures to evaluate the effect of different variables on the pavement performance and develop a relationship between the traffic loading and pavement layer thicknesses. The empirical methods have their limitations with regards to performance prediction as there are multiple other factors such as different climate conditions in different regions that are not taken into account in empirical design approaches (Pavement Interactive, 2019). As such a new approach was required; mechanistic-empirical (M-E) methods were the next generation of pavement design methods that relate the pavement performance to its mechanistic responses. Their main objective is to predict pavement performance over time more accurately in order to optimize the pavement design and use of resources. The most important factors in M-E pavement design methods are known to be pavement layer thicknesses, traffic loading, the climatic conditions the pavement will be exposed to and the material properties of different pavement layers (Erlingsson, 2017).

Regardless of the pavement design method used it is known that if the pavements are under-designed or poorly constructed, they will start to show signs of structural distress prematurely. As such, pavement engineers have started thinking about means of designing pavements that have more resistance to structural cracking and rutting. However, this might be challenging since for a given material quality the only way to prevent such failures is to increase the thickness of pavement layers (Newcomb, 2010) which could also be challenging due to material availability and cost. The challenges of the ever-growing traffic loading and the need for more robust pavement structures pose additional burden on the supply of depleting virgin high quality granular material at an affordable price. New methods of pavement design and construction are required as the current practice needs innovative approach to respond to the needs of the transportation industry. Pavement researchers have tried many different methods to overcome this challenge over the years including the use of geosynthetic materials in the pavement structure to improve its structural strength. performance of a given pavement structure can be characterized by service life and load support capacity (Giroud and Han, 2016); geosynthetics will contribute to the pavement performance through a longer service life or a reduced pavement structure. There are a variety of geosynthetic products available in the market, however the most commonly used geosynthetics in the pavement construction are known to be geotextiles, geogrids and geocells (Han *et* al., 2013). Geotextiles and geogrids can be placed either above the subgrade to improve its bearing capacity or within the base course to improve the modulus of the base course. Geocells are usually used to reinforce the base or sub-base course and improve the modulus of the reinforced layer (Pokharel et al., 2016). Since this paper focuses mostly on the application of the geocells in pavement structures it is of value to discuss the concept of geocells and its reinforcement mechanisms through which the geocells contribute to the pavement structure. Han et al. (2010) concluded that geocells contribute to the pavements by the means of lateral and vertical confinement, by distributing the applied load at a wider angle to a larger area and by beam or slab effect. Lateral and vertical confinement of the reinforced soil prevents shear failure and movement of the reinforced soil and also increases the stiffness of the soil by transferring the vertical stresses to hoop stress of the geocells. Also, friction between the soil and the geocell walls provides additional resistance to movement of the aggregate which in turn results in a higher degree of load distribution over the underlying layers. (Pokharel et al., 2009).

One of the biggest contributions of the geocell to the pavement industry is through enabling the designers to use inferior quality and locally available granular material on the pavement structure while still improving the modulus of the layer by up to 7.5 times (Pokharel, 2010) which eliminates the need for hauling quality material that maybe located far from the construction sites. This in turn will result in reducing the required trucking of the aggregates which ultimately will minimize the CO_2 emission associated with the construction activities (Pokharel et al., 2016). These cost saving and environmental benefits of geocell reinforcement make them an attractive option from a sustainable development perspective.

This paper will discuss the current state of pavement design and construction using geocell reinforcement including the advantages and disadvantages of including them in the pavement structures. Towards the end of the paper some projects designed and constructed in Canada will be discussed. The performance, benefits and other contributions of the geocell reinforcement to these projects will be illustrated in detail.

A discussion on the methods used to evaluate the performance of the pavement structures and their suitability to evaluate pavement structures that include geosynthetics will be provided.

STATE OF DESIGN PRACTICE IN CANADA

The most commonly used materials to manufacture geocells were High-Density Polyethylene (HDPE) until a few years ago. In the recent years high strength geocells made from Novel Polymeric Alloy (NPA) have been introduced to the market that resulted in manufacturing stiffer geocells (Kief, 2015). The projects and design methods described hereinafter have been calibrated for the characteristics of the NPA geocell material.

Kief et al. (2011) describe a pavement design method using the NPA geocells utilizing concepts of modulus improvement factor and layered elastic theory. He accepted that the geocell reinforcements will improve the modulus of the reinforced soil by a factor ranging from 1.5 to 5 time the modulus of unreinforced soil depending on different factors such as quality of reinforced soil, level of subgrade support and also the relative location of geocell reinforcement in the pavement structure. Using layered elastic theory, the improved performance of the reinforced pavement was evaluated by replacing the unreinforced layer's modulus by the improved modulus of the reinforced layer. The pavement responses found using the improved modulus was used to validate the pavement structure for the intended traffic loading (Kief et al., 2011).

The state of practice discussed in this paper for the paved road structure is modified AASHTO 1993 design method that the authors used to design pavement structures that are reinforced with geocells. The AASHTO 1993 design method defines a layer coefficient for different layers used in a pavement structure which then determines the Structural Number (SN) of the pavement. SN is used to determine the life of the pavement in respect to how many repetitions of Equivalent Single Axle Load (ESAL) can be applied before it reaches its terminal serviceability. The coefficient for base and sub-base layers are a function of that layer's elastic modulus as defined in Equation 1 and Equation 2.

$$\boldsymbol{a_{base} = 0.249 * (log\, E_{base}) - 0.977} \qquad \text{Equation 1}$$

$$\boldsymbol{a_{subbase} = 0.227 * (\log E_{subbase}) - 0.839} \qquad \text{Equation 2}$$

The values of the layer coefficients recommended by Alberta Transportation (AT) with some local calibration to be used in AASHTO 1993 are shown in Table 1 (AT, 1997).

Geocells reinforce the road structure through different mechanisms. Base layer is reinforced through improvement of wheel load distribution to wider area and lateral restraint of base course material (Giroud and Han, 2016). Pokharel (2010) showed that depending on the quality of the base material the layer's resilient modulus can be increased as much as 7.5 times. The same study indicates that the improvement factor is between 3.4 to 7.5 times. While designing paved road using NPA Geocells the lower range of the spectrum, an improvement factor of 3.5 to 4.5, is usually used. Using Equation 1 and Equation 2 the modified layers' coefficient for the reinforced zone of base and subbase layer would be 0.27 and 0.22, respectively. These values will be used to estimate the SN for a given structure and to determine the number of ESALs a pavement structure can endure before reaching the threshold of failure. To utilize M-E methods in design of the pavement structure, a more straight-forward process is possible as M-E methods already use the layers' moduli as an input. Therefore, to design the pavement using geocells would be as easy as easy using the improved layer's modulus as the input. However, there is not a comprehensive industry-accepted M-E model that the authors could rely on to design pavement structures in the harsh climatic conditions of western Canada. Most predictive models have been calibrated for climate conditions that are wildly different than the conditions pavement designers have to deal with in Canada and as a result those models cannot be used to design pavement structures in Canada. It would be a fantastic topic for future pavement researchers to establish a model that predicts pavement failures in the specific Canadian climate condition.

To design the gravel surfaced roads Pokharel (2010) modified the Giroud and Han (2004) design methodology for planar geosynthetic reinforcement to 3-D NPA geocell reinforcement based on static, cyclic plate loading tests and several accelerated moving wheel tests. The modification included changing the planar geosynthetic dependent parameters (such as aperture modulus) to geocell dependent parameters. These parameters were calibrated by the laboratory cyclic plate loading tests and full-scale accelerated moving wheel tests on NPA Geocell-reinforced granular bases over weak subgrade. In the design methodology a maximum allowable rut depth is set (together with all other parameters), and the pavement thickness is determined by the formula shown in Equation 3.

$$h = \frac{\left(0.868 + 0.52\left[\frac{r}{h}\right]^{1.5}\log N\right)}{\left\{1 + 0.204\left(R_E - 1\right)\right\}} \times \left(\sqrt{\frac{P}{\pi r^2 m 5.14 c_u}} - 1\right) r \qquad \text{Equation 3}$$

Where, h = required base course thickness (m)

r= effective radius of tire contact area (m)

N= number of wheel passes or equivalent single axle load (ESAL)

P = wheel load (kN)

c_u = undrained cohesion of the subgrade soil (kPa)

R_E = modulus ratio of base course to subgrade soil

m = bearing capacity mobilization factor

In this design formula, known as Han and Pokharel (2015) design method, the thickness of the base course is calculated based on the subgrade and base course California Bearing Ratio (CBR), the traffic ESAL, equivalent radius, the loading traffic and improvement factor provided by the NPA Geocells.

APPLICATION OF GEOCELLS IN PAVEMENT PROJECTS IN CANADA

The authors have been involved in design of numerous pavement projects and constructed them in Canada using the design methods described earlier. The projects discussed in this paper are 7th street in Nisku (Pokharel et al., 2017), Alberta, Village of Ryley main street in Alberta (Norouzi et al., 2017), MEG Energy Access road in Alberta, Long Run Exploration Access road in Alberta and access road to Canadian Forest Service (CANFOR) logging yard in British Columbia (Pokharel et al., 2015).

MAIN STREET OF THE VILLAGE OF RYLEY, ALBERTA

The Village of Ryley located in Beaver County in central Alberta needed to re-construct the village's main street which is approximately 1.8km long. The street was in very poor condition and had not gone through any rehabilitation in years, it had only received minimal maintenance and some patch repairs. The village was looking for reliable alternatives to minimize the construction cost of the pavement re-construction so NPA Geocells as base course reinforcement was proposed as an innovative solution to help the Village save some capital investment and minimize the recurring maintenance cost.

Table 2 summarizes the design inputs used in developing different alternatives for the pavement structure of this project. Estimated traffic for the design life of this street was 500,000 ESALs. The subgrade resilient modulus was determined to be 40MPa through in-situ Dynamic Cone Penetration (DCP) tests. Serviceability and reliability inputs were chosen according to AT's pavement design manual. Figure 1 shows the design alternatives that were being considered for this project. The conventional option would have been to construct 100mm Asphalt Concrete Pavement (ACP) over 300mm GBC. With the use of NPA Geocells the layers' thickness were reduced by 25% down to 75mm of ACP and 225mm of GBC reinforced with NPA Geocell. Table 3 **Error! Reference source not found.** summarizes the quantities required for each item for the respective alternatives.

Reduced quantity of material does not necessarily translate to a lower construction cost of the project as the cost of the reinforcement material (geocell in this case) has to be accounted for in any decision-making process. A detailed Cost Benefit Analysis was prepared for this project and demonstrated that using high strength geocell reinforcement in the pavement structure saved the road owner CAD 135,000 which was approximately 10% of the capital construction cost. It is to be noted that this amount accounted only for the savings as part of the initial construction cost and did not include other savings as a result of reduced maintenance of the pavement structure. The benefits of geocell reinforcement in reducing the required maintenance has been discussed in more detail in the next section for another project. The other contribution of employing geocell reinforcement in the pavement structure and resulting reduction of the pavement thickness means the construction is more environmentally-friendly. Through using a reduced pavement thickness, designers were able to help reduce the CO_2 emission due to the construction activities by as much as 25% (Norouzi et al, 2017).

This section of the road has not been evaluated using normally conducted pavement performance evaluation tests such as Falling Weight Deflectometer (FWD); however, it has been closely monitored for visual pavement distresses such as rutting and cracking. Figure 2 shows the state of pavement three years after the construction. This pavement structure was constructed in summer of 2016 and has experienced three spring-thaw seasons to date. It would require a few more years to conclude on the long-term performance of the pavement structure, however it is encouraging to note that as per the latest observation on April 9, 2019 after the 2019 spring thaw season there are no visual signs of pavement distresses along the length of the road. This gives an added impetus to the current practice of geocell reinforced pavement designs especially, compared to the similar pavement structures that are built in the similar climatic condition without the benefit of the geocell reinforcements. The pavement will be continuously monitored in the future to provide a better understanding of the long-term performance of the geocell-reinforced pavement structures in Canadian climatic condition and also to validate the design methods used.

7TH STREET IN NISKU INDUSTRIAL AREA, ALBERTA

The industrial area of Nisku located in Leduc County, Alberta experiences some of the heaviest industrial traffic in the region. This requires a pavement structure that is stronger and lasts longer than the typical sections. Conventionally, Cement Treated Base (CTB) has been a standard practice within the County of Leduc to overcome this challenge. However, for the construction of the 7th street the County decided to explore an innovative alternative and compare the performance of the CTB against it. An alternative pavement structure consisting of high strength NPA geocells as base reinforcement was put forward and accepted by the County. The 1km stretch of the 7th street was divided into two 500m stretches that were physically divided by a railway track cutting through the 7th street. The northern section which experiences heavier and more frequent traffic was constructed using the Geocell reinforcement while the southern half of the roadway was constructed using conventional CTB method. According to Pokharel et al. (2017) the geocell used in this project had tensile strength of 21.5kN/m and the elastic modulus at 2% strain was 620MPa. The geocell was non-perforated and had the height and thickness of 150mm and 1.1mm, respectively. The pavement cross section in the CTB side consisted of 200mm thick CTB while the geocell section consisted of 200mm GBC reinforced with 150mm high geocell; both sections were surfaced with 65mm of ACP.

Using the values provided in Table 1 and Table 2 for reinforced GBC and CSBC layer coefficient reveals that the structural number for geocell-reinforced section was 73.5mm while the CSBC section had a SN of 72mm, respectively. However, following the conclusion of construction a series of FWD tests were conducted on both sections to evaluate the structural capacity of each section and the results showed that the CTB section had higher structural capacity. This confirms the findings of previous researches that indicated that FWD tests are not the most appropriate method to test the pavement sections constructed with geosynthetic reinforcements (Pokharel et al., 2017 and Giroud and Han, 2016). They identified that the deformations induced by the deflectometer are too small to mobilize the contribution of geosynthetics however, under real life traffic loading geosynthetics can minimize the deterioration of granular bases so that the modulus of the base is retained for a longer performance period. Therefore, in order to accurately evaluate the performance of these two pavement sections another approach was taken to investigate the differences in their performance in terms of pavement distresses. The pavement sections therefore were closely monitored following the construction for visual pavement distresses and signs of structural failure. Figure 3 shows the condition of each section one year after construction. As observed, the CTB section started showing pavement distresses and cracks one years after construction while the sections built using high strength geocell reinforcement did not show any visual distresses. FWD tests that were done three years after the original construction indicated that both sections needed an asphalt overlay however, the visual inspection of the pavement did not reveal any signs of failure in the NPA geocell section. This confirmed the opinion of Giroud and Han (2016) that FWD testing is not the best option to evaluate the pavement sections constructed with geosynthetics and pavement performance measures such as International Roughness Index (IRI) pavement crack measurements should be used to decide whether or not pavement rehabilitation is warranted.

Both the CTB and geocell-reinforced sections were overlaid in three seasons. Figure 4 and Figure 5 show the state of the pavement three and six years after the construction respectively (right before the overlay construction and 3 years after the overlay) and exhibit pavement distresses including reflective cracks in CTB section while the geocell-reinforced section does not show any visible surface distresses.

GRAVEL-SURFACED ACCESS ROADS (GSAR), ALBERTA AND BRITISH COLUMBIA

GSAR projects have been designed using the Han and Pokharel (2015) method that was modified from planar reinforcement design method and calibrated earlier by Pokharel (2010). Several projects designed with this method have been constructed in the western Canadian provinces of Alberta, British Columbia and Saskatchewan over the last 10 years. This formula was also validated by Pokharel et al. (2015) using the real-life projects that were constructed in western Canada. MEG Energy P-3 connector, Long Run Exploration Access Road, Meg Energy C-Road, CANFOR Access road and Grizzly Oil Causeway are a few example projects that were monitored post-construction to provide a better understanding of the validity of the design method used. Figure 6 shows two GSAR projects at different stages of construction. The nature of the GSAR necessitates on-going maintenance work on them which makes it challenging to perform any type of investigative analysis on the validity of the design method in real life projects; these representative projects were chosen because the maintenance work, if any, performed on them after construction were on record which made the investigation more realistic.

MEG Energy P-3 connector road was constructed in the summer of 2012 in Conklin, Alberta. This access crossed stretches of deep muskeg and was designed for 250,000 ESALs. The primary mode of traffic on this road was 777 rock trucks. This road has been in service for more than 7 years now. Following the construction of the P-3 connector another connecting road was also designed using the Han-Pokharel (2015) design method; this project which is known as the C-Road was upgraded to an all weather gravel surfaced road and widened to 10m from the existing 8m.

CANFOR needed to improve their access road leading to their logging yard in Ft. St. John, BC, Canada. This road serves as the primary access to a logging facility and faces tremendous amount of heavy traffic on a daily basis therefore the structure was designed for 500,000 ESALs. There was also minimum maintenance and added gravel after the construction which made the inspection and investigation of the road possible.

The last GSAR mentioned here as an example is a causeway designed for Grizzly Oil Sands near Fort McMurray for 100,000 ESALs, it had the road surface 4m below the standing water table (Pokharel, 2013).

The major mode of failure in the gravel surfaced roads is known to be rutting. Table 4 compares the design traffic and critical rutting criteria for these roads against the actual measure values.

DISCUSSION

Investigating the effectiveness of the geocell reinforcement within the pavement structure in the projects completed in western Canada indicates that geocells contribute to the pavement structure either through reducing the layer thicknesses or increasing the service life. The design methods used in the Canadian practice to design the pavement structure with geocells modify the existing design methods. The use of the AASHTO 1993 design with modified layer coefficients based on the modulus improvement factors has proven to be successful in design of flexible pavement structures that provide a balance between construction cost, service life and maintenance cost of the pavement structure. Long term performance monitoring of the structure will be required before further conclusions can be drawn. The use of Han-Pokharel (2015) method to design GSARs has also been proven to be an effective way of designing. This design method at some instances seems to be underestimating pavement performance that provides additional factor of safety.

High strength geocells improve the modulus of the reinforced layer by a factor of up to 7.5 times depending on many variables; the inferior infill material tends to show higher improvement. Through improving the modulus, they increase the reinforced layer coefficients used in AASHTO 1993 pavement design method. Based on the improved modulus of the structural pavement layers for a typical GBC layer used in Canadian pavement practices the layer coefficients could be as high as 0.30 for the highest grade Geocell, however the authors use a factor of 0.27 for design purposes at the current stage. This improvement will in turn result is a thinner GBC requirement for a comparable design which could result in cost savings in the projects. Also, thinner GBC or GSBC layers translate into more environment-friendly projects; this was the case in Village of Ryley main street pavement project where the inclusion of geocell reinforcement enabled the pavement designer to save 25% on GBC and ACP thickness which resulted in reduced the Carbon footprint associated with the construction activities by 25%. Through the reduction in pavement layers thicknesses overall construction cost was reduced by as much as 10%.

A test section constructed using CTB and geocell reinforcement in the pavement structure led showed that the geocell reinforcement provides a long-lasting reinforcement compared to CTB and ensure the pavement integrity over a longer period of time. Three years after the original construction the section constructed with CTB showed numerous signs of failure supported by the FWD test results that the road owner decided to overlay the entire section. Although the test section that was constructed using high strength geocell reinforcement did not show any signs of failure the entire length of the road test section was overlaid which provided another opportunity to study the effectiveness of geocell reinforcement in eliminating reflective cracks afterward. Figure 5 shows the condition of the two pavement sections six years after the original construction and three years after the overlay. As seen, the cracks have found their way up to the newly constructed overlay in the CTB section while the geocell-reinforced section still does not show any noticeable pavement distresses which suggests that the high strength NPA geocell reinforcement initially prevent the pavement distresses from happening and also will minimize the reflective cracks that propagate to the pavement overlay following the overlay construction. This finding also confirmed the suggestions put forward by other researchers that the FWD tests are not the right tests to evaluate the structural capacity of the pavement structures reinforced with geosynthetics and that pavement performance measures such as IRI, crack measurement, rideability and other measures should be used to evaluate these structures instead.

In regards to GSARs, a comparison between estimated and measured rut depth as shown in Table 4 reveals that the roads hold good for the rut design criteria for given number of ESAL. Therefore, the design method has worked well for unpaved road however the design formula seems to be over predicting the rutting in some cases which results in designing the structure with a higher safety factor. In summary, the design formula used for the first time almost 10 years ago in real life projects in Canada proved to be reliable.

CONCLUSION

With saving in construction time and reduction in the amount of virgin aggregate material through the use of high strength NPA geocell reinforcement resulted in cost savings in the order of 25% and more than 25% in overall CO_2 emission compared to the conventional designs. Comparing the pavement structures constructed using CSBC and geocell reinforced GBC showed that use of geocells in the pavement structure decreases the pavement distresses observed in the pavement over the years. Geocell reinforcements also contributed to minimizing the reflective cracks observed after asphalt overlay is constructed on top of the original structure. Comparing the pavement distresses to the FWD results performed on the structure at different stages over the life of the road also seem to suggest and agree with Giroud and Han (2016) that

FWD is not the most appropriate test method to evaluate the structures constructed using geosynthetic reinforcements. The methods used to design the pavement using geocell reinforcement have proven to be efficient while more research and long-term monitoring of the pavement structures are recommended to evaluate the ability of the design methods in predicting long-term performance of the pavement structures. Geocells have also been used widely in many different projects to construct access roads in the western Canada using the design method known as Han-Pokharel (2015) design method. An evaluation of the structures designed using this method on unpaved gravel surfaced road revealed that the structures met their intended goal however the design formula in some cases might be predicting conservative values of ruts compared to the actual ruts measured at the site.

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Table 1 Layers' Coefficient by AT and AASHTO 1993 Guide

Layer	Alberta Transportation Layer Coefficient	AASHTO 1993 Layer Coefficient
Asphalt Concrete	0.40	0.44
Granular Base Course (GBC)	0.14	0.14
Granular Sub-Base Course (GSBC)	0.1	0.11
Cement Stabilized Base Course (CSBC)	0.23	varies

Table 2 Design Inputs used in the Village of Ryley Project

Design Parameter	Value
Design Life	20 years
Total ESALs	500,000
Reliability (R)	85%
Overall Standard Error (S_0)	0.45
Initial Serviceability Index	4.2
Terminal Serviceability Index	2.7
Asphalt Concrete Layer Coefficient	0.40
Unreinforced GBC Layer Coefficient	0.14
Reinforced GBC Layer Coefficient	0.27
Unreinforced GSBC Layer Coefficient	0.10
Reinforced GSBC Layer Coefficient	0.22
Design Subgrade Resilient Modulus	40 MPa

Table 3 Material Quantities for the Two Alternatives

Item	NPA Geocell Alternative	Conventional Alternative
Excavation	2380 m^3	3173 m^3
Granular Base Course	8675 MT	11566 MT
Asphalt Concrete	3016 MT	4022 MT
NPA Geocell	17506 m^2	-

* MT = Metric Tonne

Table 4 Design Vs Actual measurements (reproduced from Pokharel et al., 2015)

Project	Design tire pressure (kPa)	Design ESAL (no.)	Design Rut (mm)	Estimated ESAL (no.)	Measured Rut (average) (mm)	Remarks
MEG P-3 connector	832	250000	62	150000	20	After 3 months
MEG C-Road	832	500000	62	100000	30	After 6 months
CANFOR access road to yard	760	500000	62	400000	25	After 18 months
Grizzly Oil Cause way	862	100000	75	23400	10	After 3 months

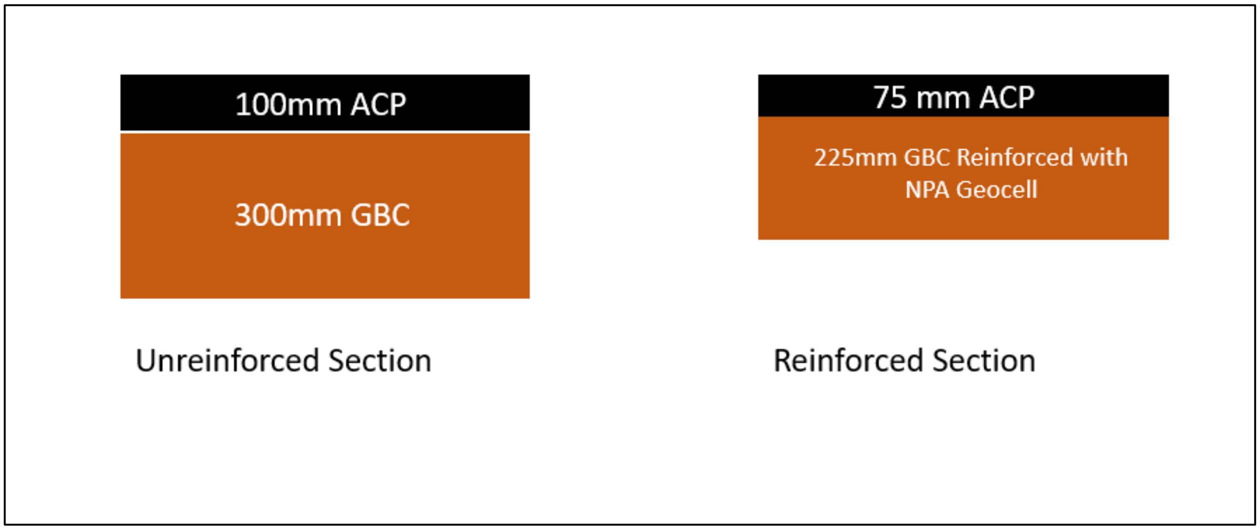
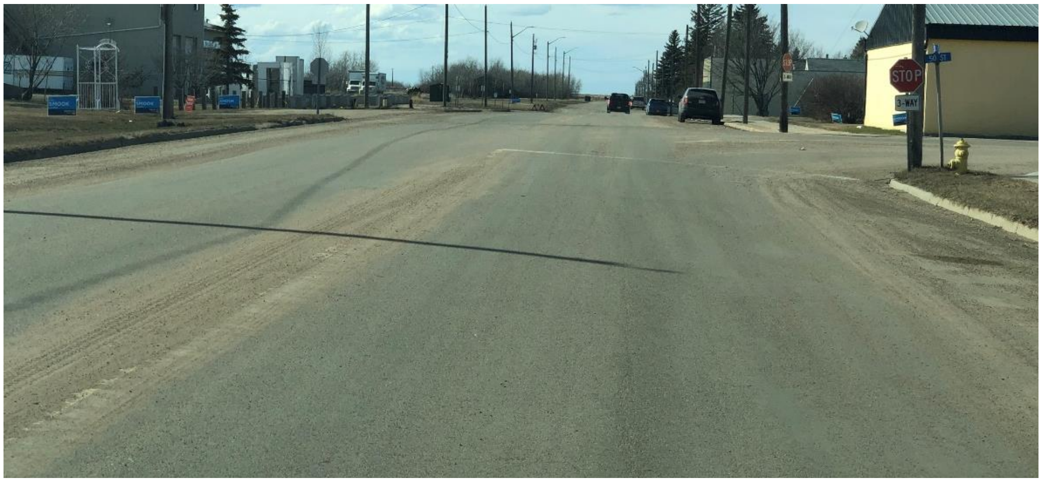


Figure 1 Cross section of the two alternatives considered for Village of Ryley's Main Street



b) At 50 St. Intersection

a) At the west end of the road

Figure 2 General pavement condition three years after the original construction- Village of Ryley’s main street

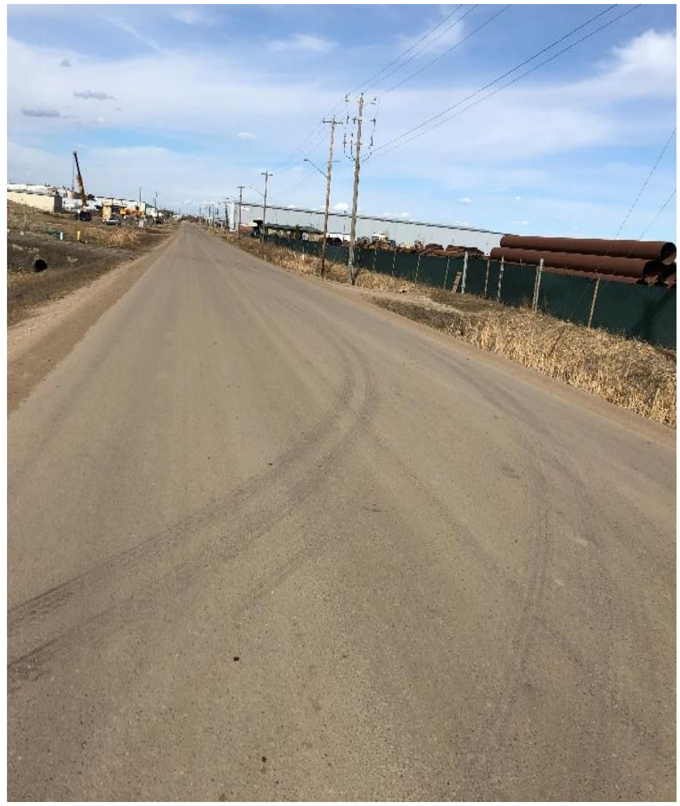
Figure 3 CTB section on left and NPA Geocell-reinforced on right side of rail track one year after construction, summer of 2013. (reproduced from Pokharel et al. 2017)

a) CTB Section

b) NPA Geocell Reinforced Section

Figure 4 state of the pavement three years after original construction

a) CTB Section



b) NPA Geocell Reinforced Section

Figure 5 State of pavement 6 years after original construction and three years after the overlay at Nisku's 7th Street.

a) Long Run Exploration Access Road

b) Grizzly Oil Causeway

Figure 6 GSAR reinforced with geocells (reproduced from Pokharel et al. 2015)