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Sustainable pavement with geocell reinforced reclaimed-asphalt-pavement (RAP) base layer

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ABSTRACT

According to the Federal Highway Administration Policy, recycled material should be the highest priority in selecting pavement materials. However, the quality of the reclaimed/recycled material should meet the minimum standard to ensure long-term benefits. This study uses geocell to enhance the performance of reclaimed asphalt pavement (RAP) material. Three pavement test sections were constructed with 0.15, 0.20, and 0.30m thick geocell reinforced RAP bases (GRRBs) by replacing the existing base layer of a farm-to-market road located in the southern part of Fort Worth, Texas, USA. These test sections were monitored for a period of three years to evaluate the pavement performance in terms of rutting, cracking, and riding quality. In addition to the regular monitoring falling weight deflectometer (FWD) tests were also conducted to determine the base layer modulus. Results showed that the geocell layer reduced the permanent deformation by at least 36% compared to the unreinforced section. The application of geocell also helped control the test sections' bottom-up longitudinal cracking by providing uniform support. The FWD test revealed that the geocell enhanced the GRRB layer stiffness by 20%. The construction cost of the GRRB layer was 22.9% less than the traditional flex base layer. Replacement of flex base material with GRRB material could reduce the emission of CO_2 by 37 tons for each lane-km.

1. Introduction

Federal and state agencies spend billions of dollars annually to repair and maintain existing roads and highways (Das et al., 2019). Maximizing the utilization of recycled material is the prime concern for transportation agencies (Chen and Wang, 2018). However, the quality of the recycled material does not always meet the design requirements (Chesner et al., 1998), and modification/reinforcement is required to achieve the desired goal (Puppala et al., 2012).

According to National Asphalt Pavement Association (NAPA), the estimated amount of RAP stockpiled nationwide increased by 9.10%, from 93.59 million tons at the end of 2016 to 102.11 million tons at the end of 2017 (Williams et al., 2018). According to the reclaimed material policy of the Federal Highway Administration (FHWA), reclaimed materials should get first consideration in material selection. However, state transportation agencies are concerned about using a higher percentage of this material since there is a lack of guidance and a lack of data available on their performance (Ezzat et al., 2016). The maximum utilization of RAP is limited in many states across the United States; for example, its usage in the form of Texas is restricted to 15–19% (George, 2018).

In comparison with the virgin aggregate, the permanent deformation of RAP is 1.7–3.0 times (Kim and Labuz, 2007). This underlines the poor mechanical properties of the RAP materials, which limit the maximum amount of RAP to 30% of the composite aggregate mixtures for constructing the base layer (Ezzat et al., 2016). The construction and rehabilitation work still need a massive volume of virgin aggregates. Alternative solutions are always sought to maximize the utilization of the reclaimed aggregate material. Researchers are trying to adopt different stabilization techniques to optimize the utilization of reclaimed materials (Hoyos et al., 2011). Transportation agencies utilize reclaimed material, e.g., reclaimed asphalt pavement (RAP), by blending them with virgin aggregates to enhance the sustainability of the pavement structures (Bennert et al., 2000). Applying cement or kiln dust can increase the RAP material's dry density and compressive strength (Taha et al., 1999). The durability tests on cement/fly ash-treated RAP showed a low volumetric strain and good retaining strength (Puppala et al., 2017). One of the major concerns with the chemical stabilization method is environmental pollution, as the chemically treated bases can increase the pH of the surrounding area, which may affect the vegetation

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and water quality (Sambodh, 2017).

On the other hand, expansive soil is considered one of the most common causes of pavement distresses (Dessouky et al., 2012). During heavy rainfall events, the moisture content of the subgrade soil increases and leads to an increase in soil volume, also known as "volumetric swell strains". Conversely, the reduction of moisture content during the dry period is known as "volumetric shrinkage strains". The cycles of swell and shrink-related volume changes can result in significant deformation of upper layers, including pavements, which is considered the primary cause of pavement failures in the northern Texas region (Puppala et al., 2019).

The utilization of planar or two-dimensional (2D) geosynthetics can improve the performance of the reclaimed-base layer; however, cellular-type three-dimensional (3D) geosynthetics can increase the load-bearing capacity and restrict the permanent deformation of the reclaimed-base layer by providing the lateral confinement. The planar type geosynthetics, i.e., geotextile, geogrid, are widely used in pavement infrastructures to reduce the volume of virgin aggregate material and increase the pavement's service life (Li et al., 2011). The application of planar geosynthetic at the interface of the base and subgrade layers can reduce an unpaved road section's required base layer thickness (Giroud and Han, 2004). The confinement provided by planar reinforcement can improve the bearing capacity of the reinforced section. However, additional lateral confinement is required to restrain the excessive permanent deformation of the RAP material (Dash et al., 2001). The inclusion of a geocell can provide further confinement, which can eventually reduce the permanent deformation of the infill material. The effect of the geocell-reinforced RAP base (GRRB) layer has been studied in the laboratory by several researchers, focusing on permanent deformation (Pokharel et al., 2018) and vertical stress distribution criteria (Thakur, 2011). The reduction of vertical stress on top of the subgrade indicates a wider stress distribution angle, which enhanced the stiffness of the geocell-reinforced section by 2.5–3.3 times (George et al., 2019). The performance of the GRRB layer obtained from the laboratory must be verified in the field to check the constructability and monitor the long-term performance.

Only a few field studies are available on the geocell-reinforced unpaved roads, where the performance was monitored by observing the surface rutting after the end of short design periods (Pokharel et al., 2015). The average settlements observed from the static field load tests were used to back-calculate the elastic modulus of the unreinforced and geocell-reinforced sections (Kief et al., 2015). The elastic modulus ratio was used to calculate the improvement factor, which was further used for designing unpaved roads with geocell (Rajagopal et al., 2014). Pokharel et al. (2015) presented eight different case studies for unpaved geocell-reinforced roads, where the design rut depths were between 60 mm and 75 mm.

The allowable surface rutting for the flexible pavement is only 12.5 mm, and the expected design life is 20 years. Khan et al. (2020) present the performance of flexible pavement with the GRRB layer to control rainfall-induced subgrade layer movement. Norouzi et al. (2019) presented a few case studies where geocell was used in flexible pavement, and the performance of such sections was only monitored by visual inspection.

According to the Texas Department of Transportation design manual, the benefit of using geocell is widely accepted; however, the utilization is hindered due to the lack of information regarding the design and life cycle performance of the geocell-reinforced flexible pavement. There are no specific guidelines for the design and construction of geocell-reinforced flexible pavement as there is a lack of field data available to recognize the long-term performance of such pavement in field conditions. According to the authors, no study is available to address the environmental impacts of the geocell-reinforced flexible pavement structures constructed over expansive soil conditions.

The current study focuses on the mechanical performance and sustainability assessment of a geocell-reinforced recycled base layer constructed over an expansive subgrade. The objectives of the study are to determine the effectiveness of geocell reinforcement based on field performance and compare the life cycle cost and environmental impacts of the geocell-reinforced recycled base (GRRB) with the traditional flex base layer.

2. Research methodology

Several pavement sections were constructed with varying thicknesses of geocell to determine the best alternative, which can replace the flex base material with recycled/reclaimed material. These test sections were designed based on the stiffness of the unreinforced and geocell reinforced RAP layer obtained from the large scale repeated load testing (George et al., 2019). Multi-layered linear elastic theory was adopted for the design of the test sections to ensure a minimum design life of 20 years with regular maintenance work. The field performance of the pavement sections was evaluated based on permanent deformation and riding quality. The methodology adopted for this study is also shown in Fig. 1.

One of the primary performance criteria for flexible pavement is surface rutting, which indicates the remaining design life. The GRRB test sections with higher rutting values compared to the flex base section were not selected. The riding quality of the GRRB sections, equivalent to the flex base section, was considered for the life cycle cost analysis (LCCA) and life cycle sustainability analysis (LCSA).

3. Study area and construction of test sections

The study area was chosen after investigating several Farm to Market (FM) roads where pavement distresses were visible and regular maintenance works did not uphold the performance of the pavement. Most FM roads constructed over expansive subgrade suffered from rutting, cracking, shoulder dropping, and uneven support conditions. Longitudinal cracking, rutting, and shoulder depressions were the most common problems, and many of these are attributed to the underlying expansive soil. The study area selected for this study was FM 1807, a two-lane-two-way road. This road is in Venus, the southern part of the Dallas-Fort Worth (DFW) area.

3.1. Site investigation and selection of study area

Most of the road networks within this region are constructed over expansive soil formation. This farm to market road, FM 1807 site, was highly compromised due to expansive subsoil conditions. Transportation agencies had to spend a lot of money on the maintenance and rehabilitation of this road. Severe channelized rutting and cracking were observed during May 2015, as shown in Fig. 2a. The presence of expansive soil was identified as the primary reason for such distresses. This kind of soil changes its volume with the alternative wetting-drying cycles and leads to the differential movement of the subgrade and overlying layers. Most pavements with moderate thicknesses and flexible pavements will experience distress on these soils. Major rehabilitation work was necessitated in 2017 when a 0.050m thick asphalt overlay was placed on top of the existing road surface. However, the longitudinal crack reappeared in January 2018 along the longitudinal direction of the eastbound lane, as shown in Fig. 2b. These pavement sections' unremitting failures motivated the selection of this location as an ideal candidate for the construction of the test sections with the GRRB layer.

3.2. Test sections

The actual thickness of the constructed layers varied within the test section due to the adjustment of the road slope for drainage conditions. The cover thicknesses of the RAP layer varied from 0.025 m to 0.050 m to accommodate the difference in thickness, as shown in Fig. 3.

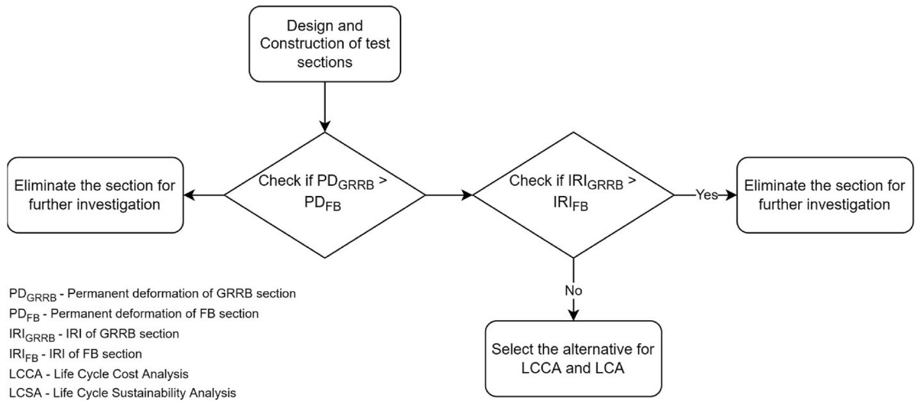

Fig. 1. Selection of alternative based on field performance.

Fig. 2. Pavement distresses on FM 1807: a) channelized rutting observed during May 2016, b) longitudinal cracks observed after six months of the major rehabilitation work during January 2018.

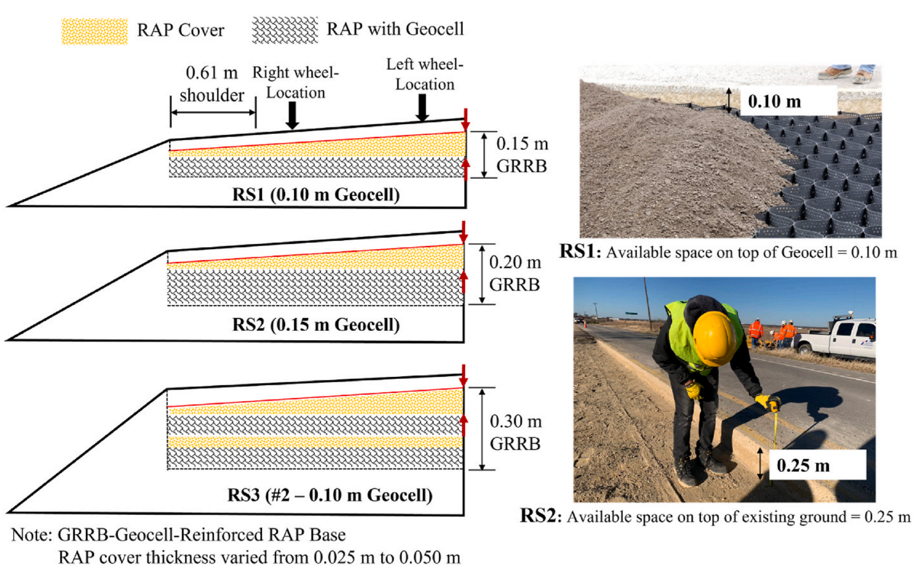

Fig. 3. Variability in Reclaimed Asphalt Pavement (RAP) cover thickness across the test sections.

Only a single lane (Eastbound) with a 4.6 m width was excavated for the construction of test sections, which did not allow the geocell panel's extension beyond the road's centerline. The locations of wheel paths are shown in Fig. 3, which indicates that the extended length of geocell beyond the right wheel-path is greater than the extended length available beyond the left wheel path. The longitudinal profile of the reinforced section, located within the eastbound lane is shown in Fig. 4. The length of each test sections was 39.6 m and all the reinforced sections had 0.05 m asphalt layer at the top followed by 0.05 m thick RAP cover layer.

Reinforced section 1 (RS1) consisted of 0.15 m Geocell reinforced RAP base (GRRB), which includes 0.10 m geocell filled with RAP and 0.05 m RAP cover. GRRB layer thicknesses for the RS2 and RS3 were 0.20 m and 0.30 m RS3 had intermediated RAP cover of 0.05 m, which was located between two geocell layers. The westbound lane of the road, including the unreinforced sections (UR1, UR2, and UR3), was defined as the control section (CS). The longitudinal profile of the control section is shown in Fig. 5.

The total length of the control section is 118.9 m; however, for comparison purposes, the 39.6 m segment parallel to the RS2 section was considered for monitoring and comparing roughness and rutting distress in the control section.

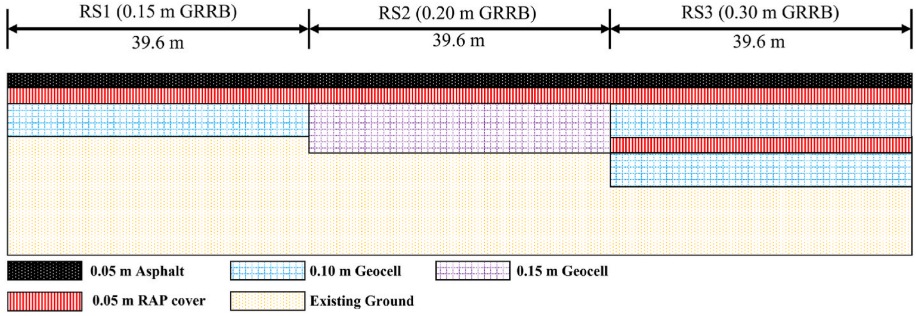

Fig. 4. Long section profile of different reinforced sections.

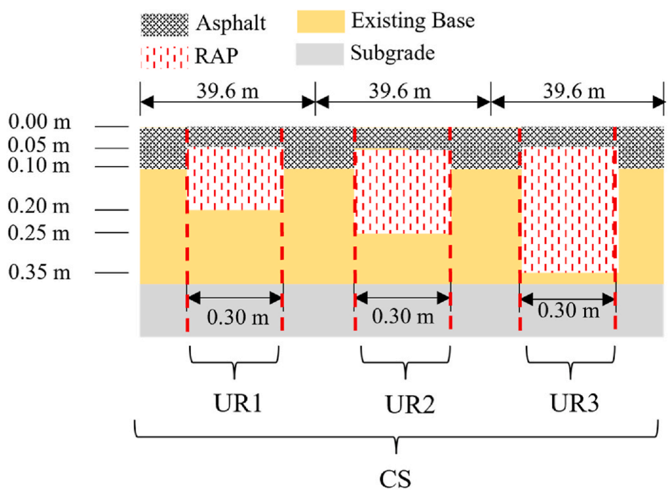

Fig. 5. Details of the control sections (CS) within the westbound lane.

3.3. Installation technique of geocell panels

The performance of the GRRB layers may vary depending on the geocell's aspect ratio (height-to-depth ratio). RS1 and RS2 sections were constructed with 0.10 m and 0.15 m geocells, having the same opening diameter of 0.25 m, to achieve two different geosynthetic layer aspect ratios of 0.40 and 0.60. The geocells used for RS3 sections had the same aspect ratio (0.40) as RS1; however, the total thickness of the GRRB layer was twice that of RS1. Regardless of the aspect ratios, the size of the panels was the same, and after full stretch, the geocell layer was 9.1 m long x 2.3 m wide. The plan area of each test section was 39.6 m × 4.6 m, which required at least eight panels of geocell to cover a single layer. Since RS1 and RS2 were constructed as a single-layer system, the total number of panels needed was 8. RS3 had two geocell layers, equaling to 16 panels. The construction sequence of GRRB layer is shown in Fig. 6.

The construction work required a milling machine, excavator, ship-footed motor grader, pneumatic roller, and vibratory compactor. No additional equipment was necessary for the construction of the geocell section. The extra time needed for the placement of the geocell in single layer test section was 2 h, which is about 1.51 m^2/min. Base stabilization with geocell is faster than the chemical stabilization methods. Chemically stabilized bases required at least 7 days of curing, whereas the geocell reinforced bases are ready to use.

4. Performance evaluation of the test sections

4.1. Rutting performance

One of the major criteria for the flexible pavement design is the measurement of permanent deformation along the wheel paths, which is also known as rutting. The rutting was measured along the right and left wheel paths for over three years. The rutting along the left wheel path was significantly higher than the right wheel path. This may happen due to the difference in the geocell panel's extended length (l_e) beyond the load application area. The availability of l_e near the right wheel path was more than 0.90 m, near the road's shoulder. The availability of l_e near the left wheel path was less than 0.60 m, as shown in Fig. 7. The surface rutting observed under the right wheel paths are presented in Fig. 7.

It was observed that the maximum rutting recorded under the

Fig. 6. Field installation sequence of geocell-reinforced reclaimed asphalt pavement base layer on FM 1807 road: a) excavation of existing road section with milling equipment; b) installation of geocell panels; c) use of excavator for dumping the RAP material into the geocells; d) use of motor grader for spreading the RAP material; e) use of pneumatic roller for the compaction of the reinforced base layer; f) use of vibratory drum roller for the temporary surface layer.

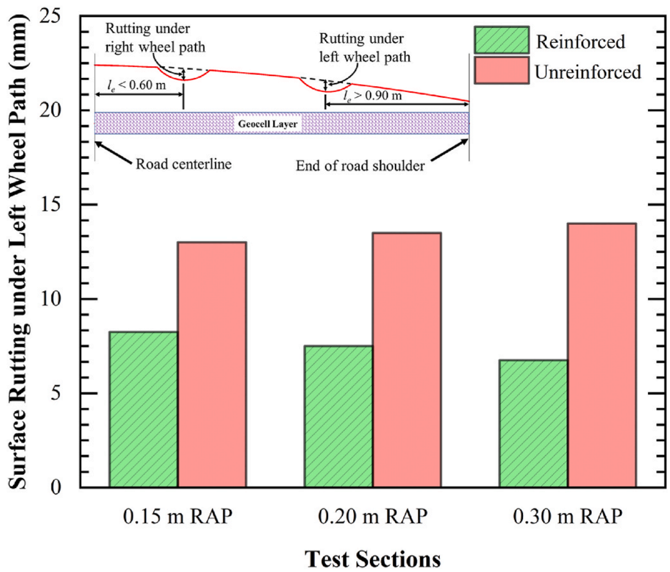

Fig. 7. Rutting performance of different test sections with 0.15 m (RS1), 020 m (RS2) and 0.30 m (RS3) reclaimed asphalt pavement (RAP) layer with and without geocell reinforcement.

reinforced sections was at least 36% lower than the corresponding unreinforced sections. The maximum allowable rutting for the flexible pavement is restricted to 12.5 mm (Yang, 2004). The minimum rutting observed under unreinforced sections was more than 13.0 mm, which indicates the inferior performance of the unreinforced RAP material under field conditions. The maximum rutting observed within the reinforced area was less than 8.5 mm, within the permissible limit. The presence of geocell helped to contain the RAP material in-place and restricted the horizontal movement while shearing. The restriction of horizontal movement also helped to decrease the overall volume-change behavior of material under vertical compression. The reduction of vertical deformation of the geocell-reinforced layer helped to reduce the overall permanent deformation of the pavement sections.

4.2. Longitudinal cracking control

Expansive soil undergoes seasonal volume changes due to the change in moisture level during the wetting and drying period. Differential movements occurred due to the difference in volume of the expansive soil foundation of flexible pavements, especially for the farm-to-market roads where the total thickness of the pavement section is less than 0.6 m. The eastbound lane of the FM 1807 suffered from longitudinal cracking near the shoulder as shown in Fig. 8. The edge drain location near the shoulder may serve as a potential source of water migrating inside the pavement during the wetting period. The intrusion of moisture near the edge of the pavement created different moisture zones within the pavement sections. The zone near the edge of the pavement had higher moisture whereas the zone near the pavement-lane center had lower moisture. Due to the difference in moisture level, the outer edge of the pavement moved upward, and shearing failure occurred. This failure transferred to the pavement's surface through the base layer, and the longitudinal crack near the edge showed up (Fig. 8 (left)). It is believed that the geocell layer acts as a rigid mattress and prevents the differential movements of the pavement foundation. Restriction of the upward movement of the expansive soil results in the elimination of surface cracking within the test sections, as shown in Fig. 8 (right).

The amount of rainfall recorded during the last three years was significantly higher than the average rainfall in the study area in the past ten years. It is expected that the increase in moisture during the wetting period would increase the swell pressure; however, the presence of geocell helped to distribute the upward swell pressure over a wider area, which restricted the differential movement. The restriction of differential movement with geocell helped to control the longitudinal cracks. An experimental study by Tamim (2017) also showed that the geocell layer could restrict the vertical movement of the expansive soil by 29%. The Geocell layers restricted the upward movement of the expansive soil due to shear resistance acting between the wall of geocell and infill RAP material.

4.3. Riding quality

Longitudinal profiles for RS1, RS2, RS3, and the control section (CS) were evaluated twice throughout the performance monitoring period of three years. The first profiler test was conducted after 21 months, and the second one was performed after 30 months from the date of construction. No significant changes in *IRI* values were observed between the two profiler tests. The *IRI* observed after 30 months were reported, as shown in Fig. 9.

The *IRI* value of the existing road (CS) was lower compared to the geocell-reinforced sections. The structural capacity of the CS was higher due to the presence of an additional 0.05 m of the asphalt layer. The geocell-reinforced section with similar riding quality was selected for further study. The recommended *IRI* values for good quality roads should be below 2.5, for a speed limit above 50 kph (Dela Cruz et al., 2021). Only the RS1 with 0.10 m thick geocell had an *IRI* value greater than the threshold limit. The *IRI* of RS2 with a single layer of 0.15 m geocell was lower than the RS1 and RS3, which had single and double layers of 0.10 m geocell. The ratio of RAP cover to geocell height for the RS1 and RS3 was 0.50, whereas the RAP cover to geocell height ratio for the RS2 was 0.33. The RS2 section exhibited better riding quality due to the lower ratio of RAP cover to geocell height. The *IRI* values were further used to determine the pavement serviceability rating (*PSR*), as shown in Fig. 9. The *PSR* of the RS1 section was less than 4, indicating good condition. The reinforced sections with thicker GRRB layers showed a *PSR* value greater than 4, representing a smoother road surface.

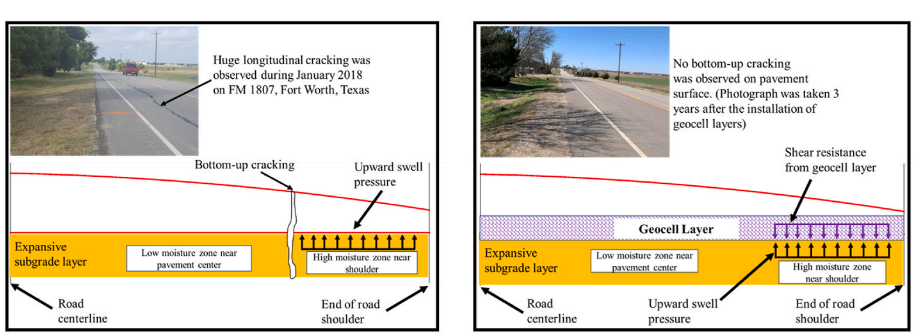

Fig. 8. Expansive soil-induced longitudinal crack resistance performance of traditional flexible pavement (left) and geocell-reinforced flexible pavement (right).

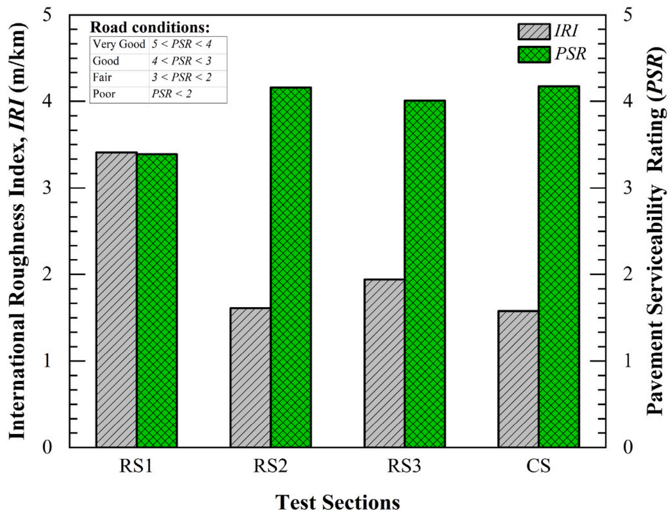

Fig. 9. Riding quality of different test sections in terms of international roughness index (*IRI*) and pavement serviceability rating (*PSR*).

4.4. In-situ layer modulus

Base layer modulus is one of the major design parameters for the design of flexible pavement, and the outcome of this non-destructive FWD results would be useful for the design and analysis of the pavement section with geocell reinforced base layer. In-situ base layer moduli for different pavement sections were determined from the falling weight deflectometer (FWD) testing conducted 21 months after the construction. Several tests were conducted within the same test section to check the consistency of the base layer performance and evaluate the stiffness based on back calculation procedures. The in-situ base layer modulus was determined based on ASTM D 5858, where the stiffness of the asphalt and subgrade layers were kept constant. The base layer varied until the deformation bowl obtained from the field matched with the predicted deflection bowl. Field test results indicated that the RS2 (0.20 m GRRB) with 0.15 m geocell had a higher in-situ modulus among all the reinforced test sections, as shown in Fig. 10. This field study also suggested that the geocell helped maintain uniform support, and the modulus variability within the test section was much lower for the reinforced section than the existing road section (CS). The in-situ base layer for the RS2 and CS were 430 and 433 MPa and it is expected that both test sections will provide an equivalent service life in terms of traffic loading. Application of geocell within the RS2 will have additional benefits as it can resist the bottom-up caracks due to the resistance of differential heaving. A three-year monitoring period with geocell suggested that the application of geocell helped to resist the longitudinal cracking, which was impossible with the traditional approach applied before the construction of the test sections.

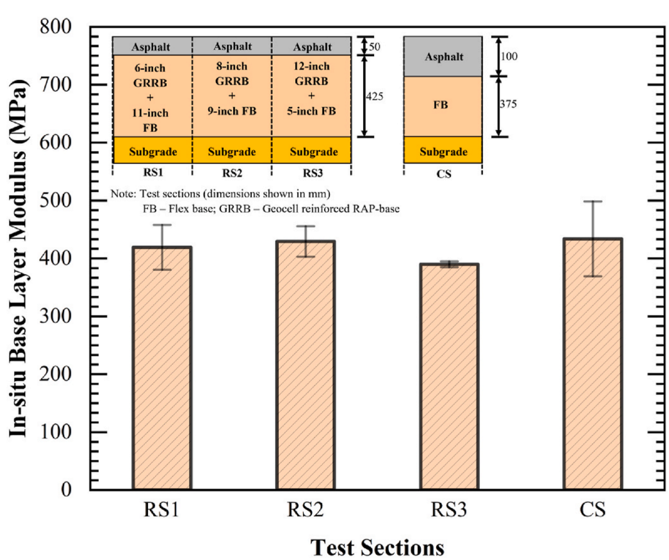

Fig. 10. In-situ base layer modulus for different test sections based on the Falling Weight Deflectometer test.

The FWD test results by Francois et al. (2019) showed that the average modulus of the unreinforced RAP base layer is 334 MPa. In this study, the average modulus of the GRRB layer was around 400 MPa, which demonstrated 20% enhancement in the RAP layer modulus with geocell reinforcement. The field performance results showed that the RS2 section with 0.15 m height geocell had an equivalent performance with the traditional flex base material. The pavement section with 0.15 m geocell was considered for life cycle cost analysis (LCCA) and life cycle sustainability analysis (LCSA).

5. Life cycle cost analysis (LCCA) geocell-reinforced pavement sections

Utilizing geocells can provide distress-free pavement performance with longer design life; however, a life cycle cost analysis (LCCA) is needed to help the designer select the alternative that will be the most economical and sustainable. This research focuses on reinforcing the pavement base layer with geocells, which allows 100% utilization of reclaimed materials, such as RAP material, as a base layer. The replacement of RAP with traditional flex base material has also proven to be cost-effective since this results in a 50% reduction of the base material, which can be realized as a 30% saving of total material cost; however, the cost of the geocell itself must be factored in. The LCCA analysis aims to help transportation agencies achieve maximum benefits without compromising performance.

5.1. Design alternatives

Pavement life cycle cost was comprised of raw material production, construction, utilization, maintenance/rehabilitation, and end of life. The agency and user costs were estimated separately for each phase. Two alternatives with the same thicknesses were considered, and this analysis is assumed to be performed for a service life of 30 years. According to the Texas Department of Transportation (TxDOT) strategic plan, LCCA is only required if the volume of the annual average daily traffic (AADT) is higher than 10,000, which is the volume that this LCCA study was designed for. The traffic consisted of 10.6% trucks and 89.4% passenger cars, and traffic growth was assumed to be 0.75% for the design life. The subgrade condition was considered similar for all the alternatives. All the pavement sections were expected to have at least two major rehabilitations during their design life of 30 years.

The required thicknesses of the asphalt and subgrade layers were determined from the pavement analysis based on linear elastic approach. The current field studies showed that the stiffness of the 0.20 m GRRB (0.15 m geocell) layer had an equivalent performance with a similar flex base layer, and the thickness of the base layer was kept constant for both alternatives. Since the stiffness of the base layer was the same, the overall thickness required for other layers was also the same. The materials considered for the base layers for alternative 1 (A1) was virgin aggregate, also known as flex base (FB), and the material considered for alternative 2 (A2) was the geocell-reinforced base (GRRB).

5.2. Pavement analysis and determination of maintenance activities

Pavement analyses were conducted to determine the number of rehabilitations required for each alternative for an assumed service life period of 30 years. All other options assumed the elastic and subgrade modulus as 3447 MPa and 83 MPa. The elastic moduli for the flex base and GRRB were considered 430 MPa. A 0.05 m thick overlay was considered the major rehabilitation work needed for all the alternatives at different times, as shown in the schematic diagram depicted in Fig. 11. Due to the budget constraint, TxDOT flexible pavement design manual (2021) allows two or three major rehabilitation activities within the total analysis period of the flexible pavement. The initial performance periods are estimated based on the subgrade rutting criteria and from the TxDOT recommended software tool (FPS 21).

Milling of the existing road section before placement of the overlay ($1.67/m^2) and the cost of a 0.05 m thick overlay ($8.25/m^2) were considered as the costs for the rehabilitation works during the first phase (R1). The maintenance works needed to service the pavements in the second phase (R2).

5.3. LCCA approach

An LCCA can be conducted using either a deterministic or probabilistic approach (Babashamsi et al., 2016; Inti, 2016). The deterministic approach applies all the techniques and procedures without considering the variability of the inputs. In this study, the deterministic and probabilistic approaches were used for determining the LCCA, based on RealCost 2.5 software, which FHWA recommends. The following sections describe both approaches used in this research.

5.3.1. Deterministic approach

The cost of the different alternatives was determined based on agency and user costs. Some of the cost elements were not considered in this LCCA, as they were either unavailable or may not have a significant impact on the analysis.

5.3.1.1. Determination of agency costs. The cost of construction, maintenance, and other costs associated with the demolition of pavement at the end of life is considered the agency's cost. This study evaluated salvage values as the pavements will not be destroyed at the end of the design life. The cost of construction was estimated for a one-mile-long section. The unit prices of individual items for alternative 1 (A1) and alternative 2 (A2) are shown in Table 1 and, Table 2, respectively.

The cost of the geocells was determined from the current field study. The unit cost of the elements was obtained from the average low bid prices of the Fort Worth District that TxDOT publishes. It is expected that the unit cost of geocells may decrease with the advancement of technology and increasing market demand.

5.3.1.2. Determination of costs of GRRB layers. The material cost of the GRRB layer was calculated based on RAP's fee and the geocell's cost per unit area. The cost of RAP material was 2.4 times lower than that of flex base material, and an additional saving was realized because the material didn't have to be hauled from a longer distance. It was expected that the existing roadway section could be milled and placed simultaneously, saving time and money; however, the cost of the geocell, which varies with the layer's height, would increase the cost of the GRRB layer. The unit cost for 0.15 m geocells was $6.40/m^2. The overall unit cost of RAP material was $10.04/m^2 for an 0.20 m thick section, resulting in a total cost of $16.44/m^2. The cost of traditional flex base material for an 0.20 m thick section was $20.21/m^2, which was 22.9% more than the material cost for an 0.20 m thick GRRB layer.

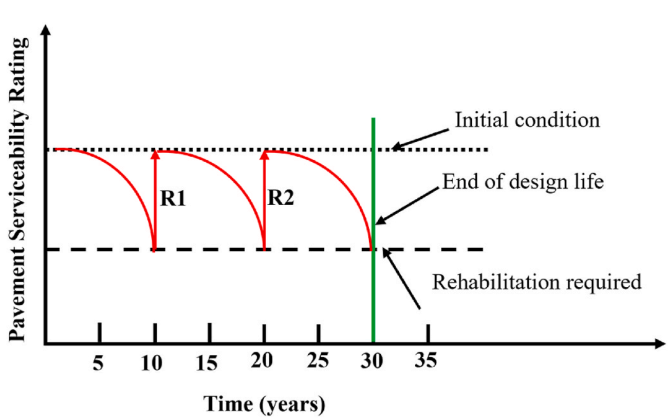

Fig. 11. Rehabilitation schedule based on pavement serviceability rating.

Table 1
Unit material costs for the flexible pavement with flex base layer (alternative 1).

S. N.	Item	L (m)	W (m)	A m^2	Unit cost (USD/m^2)	Amount (USD)
1	Asphalt concrete 0.10 m thick	1000	4.6	4600	18.4	84,640
2	Tack coat	1000	4.6	4600	1.9	8740
3	Prime coat	1000	4.6	4600	0.7	3220
4	Flexible base 0.20 m thick	1000	4.6	4600	20.2	92,920
5	Subgrade Preparation	1000	4.6	4600	3.8	17,480
Total unit cost per mile						207,000

Note: L = length; W = width; A = area.

Table 2
Unit material costs for the flexible pavement with geocell reinforced reclaimed asphalt pavement base layer (alternative 2).

S. N.	Item	L (m)	W (m)	A m^2	Unit cost (USD/m^2)	Amount (USD)
1	Asphalt concrete 0.10 m thick	1000	4.6	4600	18.4	84,640
2	Tack coat	1000	4.6	4600	1.9	8740
3	Prime coat	1000	4.6	4600	0.7	3220
4	0.20 m thick GRRB	1000	4.6	4600	16.4	75,440
5	Subgrade Preparation	1000	4.6	4600	3.8	17,480
Total unit cost per mile						189,520

Note: L = length; W = width; A = area.

5.3.1.3. Determination of user costs. The user costs include the cost of the roadway, which is comprised of vehicle operation costs (VOC), crash costs, and delay costs. The vehicle operating costs were not considered for the LCCA studies as it was expected that all the alternatives would provide a similar level of service throughout the design life. On the other hand, the user delay cost that will occur during construction, maintenance, and rehabilitation was high in terms of sustainability. The user delay cost may vary for different alternatives, as the time required to prepare the base layer will not be the same. The transportation agencies estimate the user delay costs each year, and it is significantly different for different types of vehicles. The user delay costs calculated by TxDOT for the last five years are summarized in Table 3.

The user costs were estimated based on the distribution of traffic, the number of lanes open to traffic, work zone capacity, work zone speed, queue dissipation capacity, working hours during maintenance, duration of maintenance work, and discount rate. The input required for the RealCost 2.5 software is listed in Table 4. A discount rate of 4% was taken based on the recommendation from Inti (2016), and other

Table 3
TxDOT user costs from 2017 to 2021.

Year	2017	2018	2019	2020	2021
Passenger car (USD/Vehicle hour)	22.4	28.7	29.4	30.1	30.5
Truck per hour (USD/Vehicle hour)	32.7	36.3	39.5	41.3	41.9

Table 4
Software inputs required for user cost analysis.

Parameters	Value	Parameters	Value
AADT	10,000	Maximum total AADT	12,000
Percentage of cars in AADT	89.4	Work hours	9AM-5PM
Truck percentage of the AADT	10.6	Speed limit (operational)	97
Annual traffic growth rate	0.75	Work zone speed limit (kph)	65
Discount rate	4	Work zone length (km)	3.2
Number of lanes in each direction	1	Maximum queue length (km)	8
Free-flow capacity (vphpl)	2000	Work zone capacity (vphpl)	1415
Traffic distribution type	Urban	Lanes open in each direction	2
Queue dissipation capacity (vphpl)	1818		

Note: vphpl-vehicle per hour per lane; AADT: Annual average daily traffic.

Table 6
Summary of life cycle cost analyses.

Approach	Costs		Cost per lane per km ($1000)	
			A1	A2
Deterministic Approach	Agency cost		207.00	189.50
	User cost		1.90	2.10
Probabilistic Approach	Agency cost	Min.	241.70	212.90
		Max.	253.40	222.90
		Mean	249.60	219.60
		S.D.	2.50	2.20
	User cost	Min.	1.60	1.80
		Max.	2.30	2.40
		Mean	2.10	2.20
		S.D.	0.12	0.12

Note: Min. - minimum; Max. – maximum; Avg. – Average; S.D. – standard deviation.

parameters were collected during the construction of the test section.

5.3.2. Probabilistic approach

Probabilistic analyses were conducted to account for the variability of the discount rates, queue dissipation capacity, value of time for different types of vehicles, work zone capacity, and agency construction costs, as listed in Table 5.

5.4. LCCA results summary

These analyses aimed to select the best alternative based on the overall life cycle cost. It was evident from the results that A1, utilizing traditional flex base material according to the AASHTO 1993 pavement design guideline, results in the highest rate of declination of natural resources. The other alternative contributes by replacing the natural resources with reclaimed material. The user delay costs for different sections vary due to the differences in the amount of time required to construct them. A1 is expected to be built in the least amount of time with fewer user delays, whereas a slightly longer time is needed to make a GRRB (A2). It takes approximately 20% extra time to install a geocell-reinforced base layer than it does to install a flex base layer without a geocell. This information was incorporated into the LCCA study, and the results obtained for both the deterministic and probabilistic approaches are shown in Table 6.

The deterministic approach showed that A2 had lower agency costs, whereas alternative A1 had lower user costs. The results obtained from the probabilistic analysis showed that the average agency cost of A1 was 13.7% higher than A1 due to the utilization of pricier virgin aggregate material. The average user cost for A2 was 4.5% higher than A1, as the additional time required to install the geocell panel will be responsible for traffic delay-induced cost. The standard deviations for agency and user costs were found to be the lowest for A2. The cumulative probability plot for the agency cost and user cost is shown in Fig. 12. Though A2 had a higher user cost, the agency cost was significantly higher for A1. These results will be helpful to designers and owners as they select the most effective alternative design option for pavement construction (see Fig. 13).

The overall cost for A2 was lower than A1, and it should provide economic benefits. However, evaluating the sustainable aspects of geocell-reinforced pavements is still necessary. The following section offers a comprehensive sustainability analysis of the GRRB section and a flex base aggregate layer section.

6. Life cycle sustainability analyses of geocell-reinforced pavement sections

Maximizing the utilization of RAP enhances the sustainability benefits, as it is predominantly reclaimed material, but the addition of an HDPE geocell layer, which is a polymeric-rich material, may have some adverse environmental impacts. The application of geocells is economically advantageous; however, the environmental aspects should be explored before installing GRRB layers of pavement on expansive soils. The overall performance and life cycle environment of the geocell-reinforced pavement should be assessed for the duration of the design period; otherwise, the only environmental issues that will be assessed may transpire from rehabilitation works that are needed due to the distress caused by expansive subsoils. The following section will discuss the methodology adopted for the environmental assessment.

6.1. Life cycle sustainability assessment approach

Environmental impacts considered for a life cycle sustainability analysis are generally related to the production of raw materials, transport, construction of pavement, and end-of-life use. In this study, the scope of the environmental analysis was limited to the impacts associated with the raw material production, transport, construction, and design of the base materials for the two alternatives discussed above. An excel-based software, PaLATE, was used to estimate the environmental impact of the flex base, cement-treated base, and RAP-based layers, but it did not have a database for the inclusion of the effects of geocells.

The environmental impacts associated with geocell production were

Table 5
Inputs considered for probabilistic approach.

Parameters	Probability distribution	Values					Remarks
		Min.	M.L.	Max.	Avg.	S.D.	
Discount rate (%)	Triangular	3	4	7	–	–	Inti (2016)
Queue dissipation capacity (vphpl)	Normal				1818	144	Greenroads Manual v1.5
Value of time for passenger cars ($)	Triangular	22.4	30.5	30.0			Table 5
Value of time for trucks ($)	Triangular	33.7	41.0	41.9			Table 5
Work zone capacity (vphpl)	Normal				1415	200	Inti (2016)
Agency Construction cost (%)	Normal				–	10	Assumed

Note: vphpl – vehicle per hour per lane; Min. - minimum; M.L. – most likely; Max. – maximum; Avg. – Average; S.D. – standard deviation.

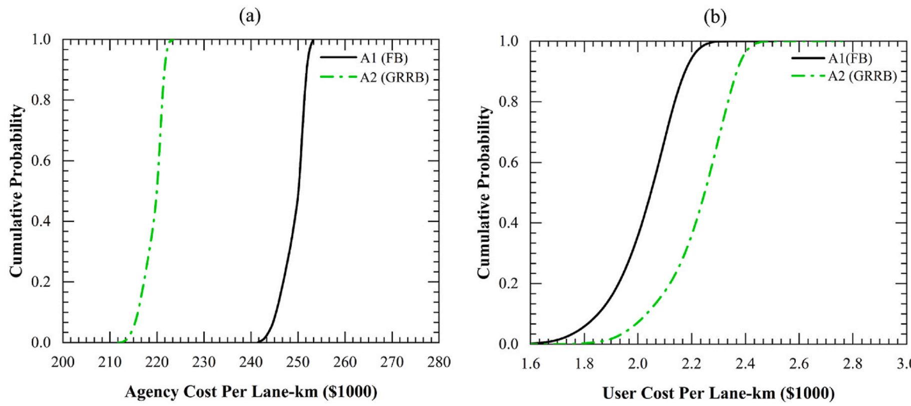

Fig. 12. Cumulative probability plots: a) agency cost, b) user cost.

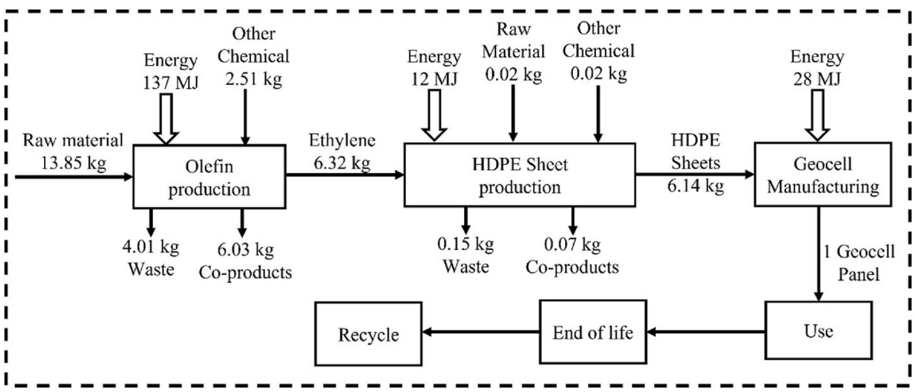

Fig. 13. System boundary for production of a geocell panel.

assessed separately and then combined with the data obtained for the RAP base layer to determine the environmental impacts of the GRRB layer. The process, material, and energy required to produce a single panel of geocells are shown in Fig. 9. One single geocell panel was produced from 6.14 kg (13.5 lbs.) of HDPE sheets. The process, energy, and materials required to make the geocells were collected from the manufacturer and HDPE production processes described by Treenate et al. (2017).

6.2. Life cycle sustainability assessment results

The traditional approach to constructing flexible pavement is utilizing the flex base material described for A1. As it will not be readily available at the site, transporting it, especially from a long distance, will have environmental impacts. Processing the raw material for the flex base will also have negative effects, as it uses natural resources.

Using RAP material alone is the most sustainable approach; however, it does not perform satisfactorily due to its excessive permanent deformation. Adding geocells to the RAP, as described in A2, enhances the capacity but negatively impacts the environment due to the emissions and energy costs associated with the polymeric manufacturing process. The HDPE used to produce geocells has a shallow carbon black content (<1.5%). The environmental assessment results for different alternatives are summarized in Table 7.

The total energy required for the generation of CO_2 and water is significantly lower for geocell-reinforced pavement than traditional pavement with flex base layer. The overall performance of the two alternatives is presented in a radar chart format, as shown in Fig. 14. Twelve categories are normalized with the values corresponding to A1. An impact factor of one was assigned to each category under A1, and relative impact factor for A2 were determined.

Table 7
Summary of environmental assessment results for one-lane mile.

Alternatives	A1	A2 (excluding geocell)	A2 (including geocell)
Base Type	FB	RAP	GRRB
Energy [GJ]	1712	579	899
Water Consumption [kg]	177	3	47
CO_2 [Mg] = GWP	89	11	30
NO_x [kg]	2468	503	1532
PM_{10} [kg]	1056	5	205
SO_2 [kg]	40,577	40,418	40,480
CO [kg]	227	14	100
Hg [g]	0.4	0.1	0
Pb [g]	30	1	10
RCRA HW [kg]	4344	240	2101
HTP (Cancer)	74,060	52,983	58,517
HTP (Non-cancer)	817,814,644	94,340,801	101,129,315

Note: FB- Flex base; CTB- Cement treated base; RAP- Reclaimed asphalt pavement; GRRB- Geocell Reinforced RAP Base; CO_2 – Carbon dioxide; NO_x – Nitric oxide; PM_{10} – Particulate matter; SO_2 – Sulphur dioxide.
CO – Carbon monoxide; Hg – Mercury; Pb – lead; RCRA HW - Resource Conservation and Recovery Act. Hazardous waste; HTP – Human Toxicity Potential.

The best design alternative with the most sustainable practice solution is the one with the lowest area under the polygon. The length of each side of the polygon was used to measure the area for A1 and A2, resulting in measurements under the polygon of 3.0 for A1 and 0.6 for A2. It can be concluded that A2 has the lowest environmental impact and is the most sustainable option. The difference in the generation of CO_2 may be used to quantify the benefits. The selection of A2 over A1 will reduce the generation of CO_2 by 37 t for each lane km. According to

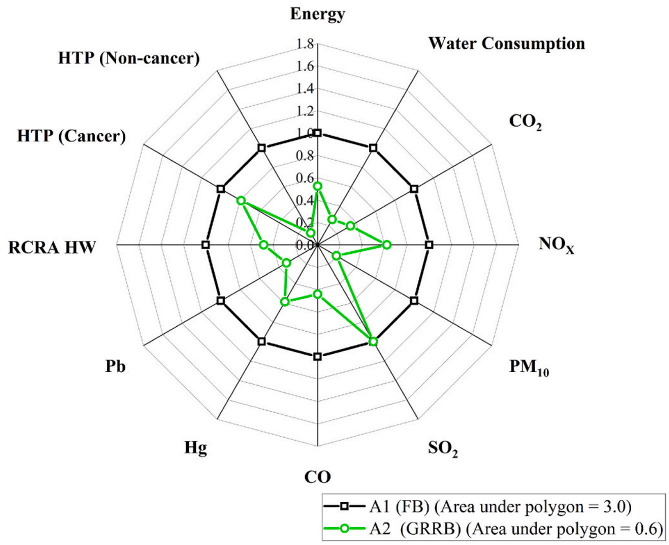

Fig. 14. Comparative performance of flexible pavement section with flex base (F.B.) and geocell reinforced reclaimed asphalt pavement base (GRRB) layer.

the EPA, reducing 37 t of CO_2 from the environment is equivalent to recycling 12.5 t of waste, recycling the waste in 1.8 garbage trucks, and recycling 1550 trash bags of waste rather than sending all of it to the landfill. The above analysis shows that a flexible pavement with a GRRB layer provides an excellent sustainable solution for building pavement sections with GRRB with RAP layers on expansive subgrade conditions. The pavements with GRRB layers provided the best performance in both LCCA and LCSA studies and are recommended for designing sustainable and resilient pavements in expansive subsoil conditions.

7. Summary

The results obtained from the field study provided significant insight regarding the use of geocell reinforcement to enhance pavement layer performance and the cost associated with constructing such reinforcement. The design of flexible pavement with geocell layers allows the pavement designer to choose the reclaimed material for the base layer application, which is essential to designing low-distress pavements on expansive soil. The confinement offered by the geocell enhances the performance of the geocell-reinforced base layer, which in turn provides stable and uniform support to pavements with less rutting and cracking. The feasibility of the current stabilization method with geocells was further assessed by comparing it with traditional alternatives based on the LCCA and LCSA study. The significant outcomes of the present study are summarized below.

- The time required for the installation of the geocell panel was 1.51 m^2/min, which was faster than other stabilization techniques. No additional equipment was needed for the construction of the geocell-reinforced layer.
- Geocell reduced the pavement rutting by 36% by controlling the lateral movement of the infill RAP material. The reinforcement length should be extended by more than 0.90 m from the wheel paths to ensure proper load distribution.
- The geocell layer restricted expansive soil-induced bottom-up cracks by providing a uniform support system and curtail the upward swell pressure. Regular field monitoring results indicated no significant cracking.
- The minimum thickness of 0.15 m geocell reinforced layer was required to restrict the *IRI* to the threshold of 2.5 m/km. Minimum *IRI* was observed when the RAP cover to geocell height ratio was 0.33.
- In-situ base layer modulus obtained from the FWD provided evidence of enhanced performance as the variability of the modulus was minimum within the geocell reinforced section, compared with the traditional flex base section of the existing roadway. The in-situ modulus of the 0.15 m geocell showed an in-situ modulus of 430 MPa, comparable to the flex base layer.
- The unit cost of the 0.20 m GRRB layer is $16.4/$m^2$, which is 22.9% cheaper than the traditional flex base material. The unit cost of 0.15 m height geocell was $6.40/$m^2$, including the material, transportation, and installation cost.
- The deterministic approach showed that the overall agency cost for the GRRB layer was 10% lower than the flex base layer; however, the user cost for the GRRB layer was marginally higher due to the construction-induced traffic delay.
- Probabilistic approaches showed that the average agency cost for the GRRB layer was 13.7% lower than the flex base layer, and no significant differences were observed for the user cost.
- LCSA study suggested that applying geocells with RAP in the pavements also provided a sustainable solution by replacing the traditional flex base layer with GRRB and will reduce the CO_2 emission by 37 tons for each lane-km.

It should be noted that some of these analyses are performed for the first time on Geocell bases, and one should expect some changes as these analyses and their attributes get developed and validated in the near future. Nevertheless, the analyses and studies provide salient benefits of using these geocells for cost-effective field applications with high sustainability.

CRediT authorship contribution statement

Md Ashrafuzzaman Khan: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Visualization, Writing – original draft. **Anand J. Puppala:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Project administration, Resources, Investigation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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