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SUSTAINABILITY BENEFITS PROVIDED BY GEOSYNTHETIC SOLUTIONS IN ROADWAY APPLICATIONS

Introduction

The world's roadway system has been reported to reach a total length of 64,285,009 km [1]. The extent of the roadway system is so significant that its total length would encircle the Earth over 1,600 times if combined. Geosynthetics have provided sustainable alternatives in roadway projects, representing a substantial portion of the total usage of geosynthetics in civil infrastructure. Yet, considering the significant extension of roadway projects worldwide, geosynthetics are still employed in a comparatively small fraction. Accordingly, the opportunities to achieve sustainability benchmarks by increasing the presence of geosynthetics in roadways are simply enormous.

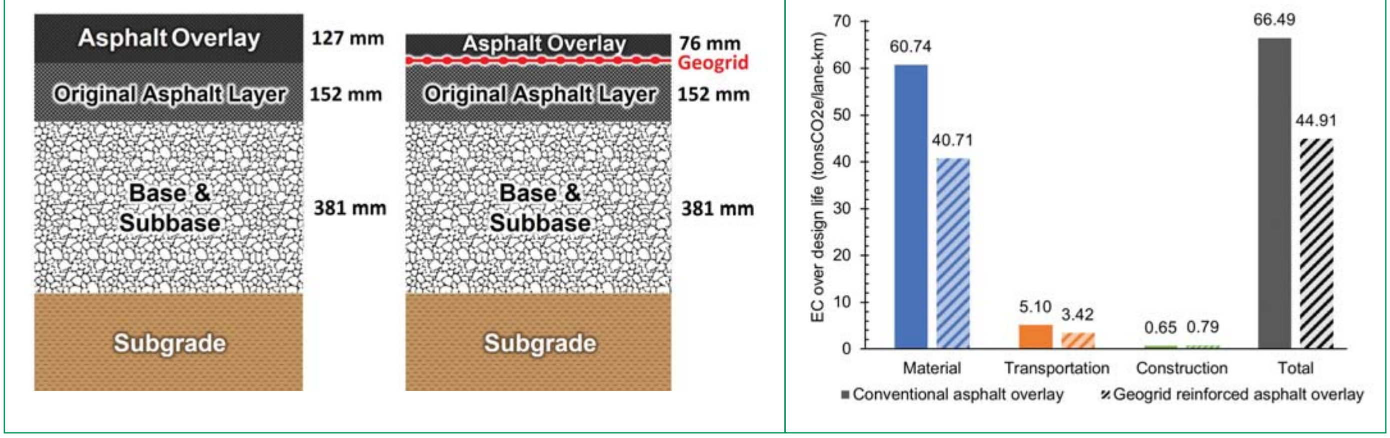
One or more of the various geosynthetic functions have been used in roadway applications for separation, filtration, reinforcement, stiffening, and drainage [2]. Listing the various roadway applications according to the position of the layers in a roadway structural package where the geosynthetics are installed (from top to bottom), they can be summarized as follows: (1) mitigation of reflective cracking in structural asphalt overlays, (2) stabilization of unbound aggregate layers, (3) reduction of layer intermixing, (4) reduction of moisture in structural layers, (5) stabilization of soft subgrades, and (6) mitigation of distresses caused by shrink/swell subgrades. This study focuses on quantifying the carbon footprint for six roadway projects, each involving at least two alternative designs: One with and the other without using geosynthetics. The sustainability benefits of selecting a design alternative that uses geosynthetics were evaluated by conducting carbon audits for the alternative designs for each roadway project. Details on the methodology and various case studies are provided by Zornberg et al. (2024) [3].

Projects involving Mitigation of Asphalt Reflective Cracking

A relevant case study involving the use of geosynthetics in asphalt overlays is the rehabilitation of Texas State Highway (SH) 21. The Texas Department of Transportation (TxDOT) designed and implemented a rehabilitation program to restore the roadway's serviceability and to improve resistance against reflective cracks and other distress that may occur due to the moisture fluctuations in the expansive clay subgrade and the repeated heavy truck loads. TxDOT pavement designers considered an initial rehabilitation solution that included treating the pre-existing distresses with half or full-depth repairs, applying a binder tack coat, and constructing a 127-mm-thick hot mix asphalt (HMA) overlay. However, additional considerations led to a revised overlay design involving the use of geosynthetic interlayers. Specifically, TxDOT eventually adopted the overlay design, which involved incorporating a polymeric geosynthetic reinforcement with a reduced (76-mm-thick) HMA overlay thickness (see figure 1a).
The Embodied Carbon (EC) quantifies the total greenhouse gas emissions that are associated with the production, transportation, construction, and other stages of a product or system's lifecycle, excluding its operational use and end-of-life disposal. The results of the analysis are summarized in figure 1b, which includes the EC values related to the different stages (material, transportation, construction) for the two alternative pavement designs and the total EC values. The carbon audit results are quantified in tonnes of carbon dioxide equivalents per lane-km (tCO_2e / lane-km). This standard unit for measuring carbon footprints allows different greenhouse gases to be expressed in terms of the amount of CO_2 that would have the same global warming potential. By using CO_2 equivalents, the total impact of various greenhouse gases, such as methane (CH_4) and nitrous oxide (N_2O), can be combined and reported as a single figure. A breakdown of EC for individual pavement layers reveals that the geosynthetic solution's carbon footprint showed a reduction of 32.4 % compared to the conventional overlay design.

Carbon Audit in Projects Involving Stabilization of Unbound Aggregate Layers

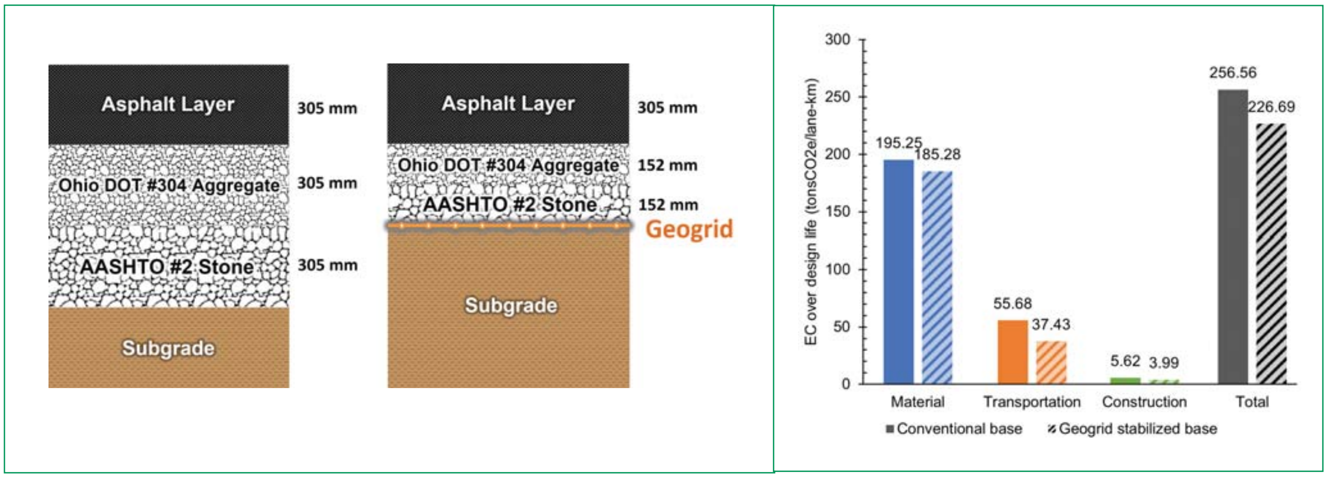
The reconstruction of Interstate Highway 90 (I90) near Ashtabula, Ohio, USA, is a project that illustrates the adoption of geosynthetics to stabilize unbound aggregate layers. Along a section of I90, the Ohio Department of Transportation (ODOT)



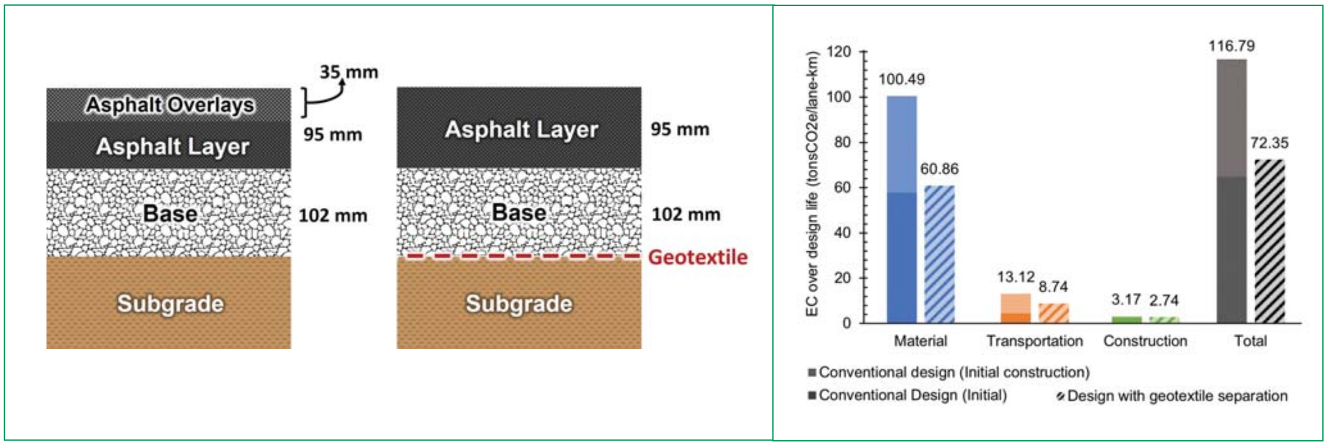
Figures 1a & b – Case study involving mitigation of reflection cracks: (a) Cross-sections of conventional and geosynthetic solutions; (b) Carbon audit results showing contribution of different phases (source: Zornberg et al. 2024).

SUMMARY

The opportunities to achieve sustainability goals by making more extensive use of geosynthetics in roadways are massive. This paper aims to illustrate the sustainability benefits of adopting geosynthetics in roadway design. This is accomplished by quantifying the carbon footprint for six roadway projects, each involving at least two alternative designs: One with and the other without geosynthetics. The analyses indicate that the design alternatives involving geosynthetics always proved more sustainable than the conventional (without geosynthetics) alternatives, resulting in savings in the total carbon footprint that ranged from 16.3 to 44.44 tCO_2e per lane-km.



Figures 2a & b – Case study involving stabilization of unbound aggregate layers: (a) Cross-sections of conventional and geosynthetic solutions; (b) Carbon audit results showing contribution of different phases (source: Zornberg et al. 2024)



Figures 3a & b – Case study involving reduction of layer intermixing: (a) Cross-sections of conventional and geosynthetic solutions; (b) Carbon audit results showing contribution of different phases (source: Zornberg et al. 2024)

removed the existing pavement structure and layers of subgrade, added additional lanes to the highway in both directions and reconstructed the entire pavement. The project site's proximity to Lake Erie results in a weather phenomenon where cold air passes over warmer lake waters, picks up moisture, and then deposits it as snow on the downwind shores (lake-snow effect). This made the available time construction window particularly short. Thus, adopting a design that would minimize construction time was particularly important. The original pavement design by ODOT involved an undercut of 915 mm to be replaced by 305 mm of AASHTO #2 stone overlain by 305 mm of smaller-size aggregate and 305 mm of asphalt layer. However, incorporating a geosynthetic layer in the design led to significant cost-savings and construction benefits. Specifically, adopting a biaxial geogrid beneath the AASHTO #2 stone layer would reduce the undercut by about 610 mm (see figure 2a). Consequently, the amount of aggregate used on the project was cut in half, resulting in significant cost savings. In addition, replacing 305 mm of aggregate with a geosynthetic-stabilized layer resulted in a significantly shorter construction time.

The assessed carbon footprints are presented in figure 2b, which includes the EC values corresponding to different construction phases and the total EC values. The total emission, excluding the asphalt layer, reduces to 37.80 tCO_2e per lane-km, which corresponds to a reduction of 44.1 % in relation to the conventional design.

Carbon Audit in Projects Involving Reduction of Layer Intermixing

The construction of several field test sections in a low-volume road by the Virginia Department of Transportation (VDOT) in Bedford County, Virginia, USA, represents a good opportunity to evaluate the use of geosynthetics to reduce layer intermixing. As part of this VDOT study, nine 15-m-long test sections were constructed, including three control sections, three test sections with a geotextile separator, and three test sections with a geogrid. The roadway sections evaluated in this study include control sections and sections with geotextile separators (see figure 3a). The service life of the test sections was estimated based on the equivalent single axle load (ESAL) corresponding to a rutting depth of 20 mm. While sections constructed with geotextile separators reached a traffic volume of over 100,000 ESALs without rehabilitation, the control sections required two rehabilitation activities to reach such traffic volume.

The carbon footprints for the two design alternatives are shown in figure 3b in terms of EC values for the individual construction phases and the total EC for each design alternative. While the EC components associated with subgrade and base courses are the same for both alternatives, installing a geotextile separator avoids rehabilitation cycles, which would involve additional asphalt overlays. As a result, the EC of the asphalt layers is reduced from 105.85 tCO_2e to 58.15 tCO_2e.

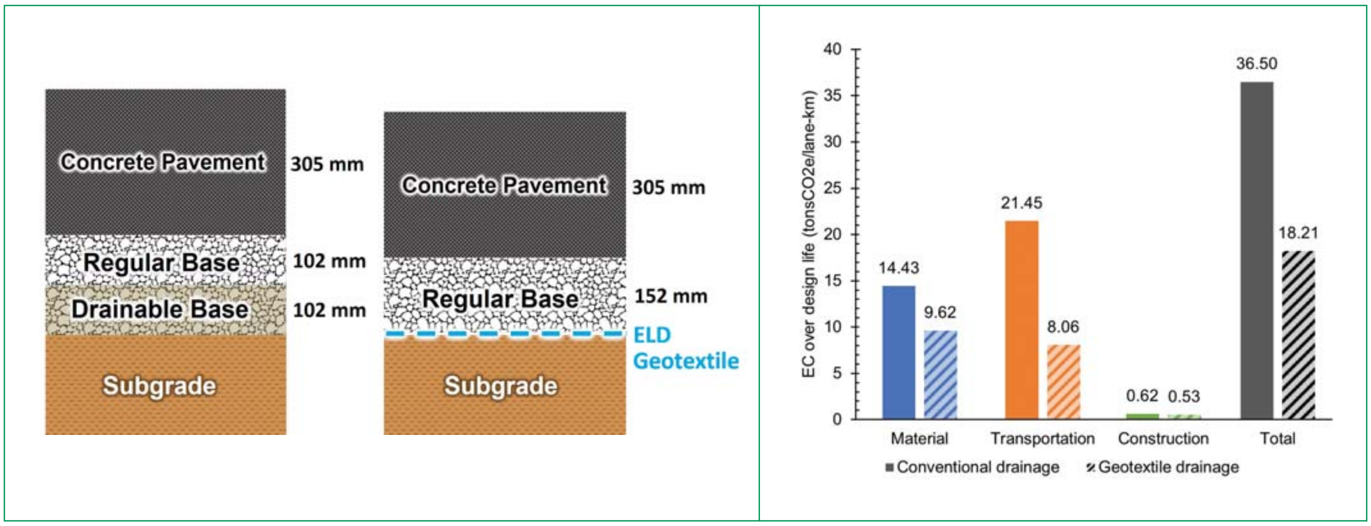
Carbon Audit in Projects Involving Moisture Reduction in Structural Layers

The construction of the Daniel Boone Bridge along Interstate 64 by the Missouri Department of Transportation (MoDOT) represents a good example illustrating the application of geosynthetics to reduce moisture in structural layers. A new pavement approaching the bridge was also needed. However, proximity to the river resulted in a high water table beneath the pavement; thus, reducing moisture in the base course by mitigating upward moisture infiltration was essential. Several alternatives were considered to address the high water table. One pavement alternative considered a 102 mm thick layer of drainable aggregate to be placed beneath a 102 mm aggregate base layer. However, drainable base costs, on average, $40/ton, whereas regular base aggregate costs $12/ton. In turn, another alternative that used an in-plane draining geotextile was considered. Accordingly, 50 mm of the total regular and drainable base materials were replaced by an in-plane draining geotextile, providing separation and subgrade stabilization to the roadway (see figure 4a). The geotextile alternative both lowered costs and met drainage requirements.

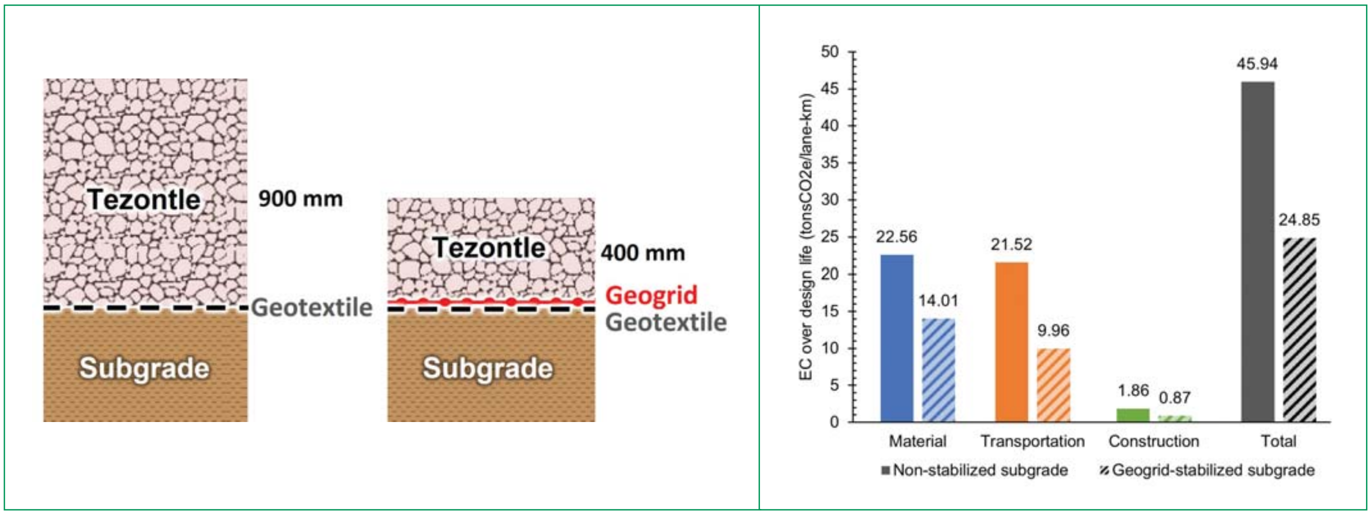
The results, summarized in figure 4b, show a reduction from 14.43 tCO_2e to 9.62 tCO_2e for material production, from 21.45 tCO_2e to 8.06 tCO_2e for transportation, and from 0.62 tCO_2e to 0.53 tCO_2e for construction. Among these components, the most significant change is observed in the transportation stage, which shows a 62.4 % improvement. The total emissions were estimated as 36.50 tCO_2e and 18.21 tCO_2e for conventional and geotextile drainage designs.

Carbon Audit in Projects Involving Stabilization of Soft Subgrades

The New International Airport of Mexico City is a major engineering endeavor initially planned to sustain 70 million passengers and 540,000 landings and take-offs yearly. The airport was planned at a location distanced 15 km from the city center over the former Lake Texcoco and will occupy over 40 million square meters of surface area. Due to the presence of soft lacustrine clay, the subgrade soil was saltier than seawater and settled at a rate of 15 to 20 mm a month. Chemical stabilization was not a viable alternative because of the presence of volcanic basalt, and other traditional methods to stabilize the ground did not succeed. Preliminary trials using geosynthetics, however, proved to result in a technically feasible low-cost alternative to stabilize the very soft subgrade. Construction alternatives included the use of an aggregate locally known as Tezontle (a local volcanic rock often used in construction in Mexico) to stabilize the ground. Specifically, two alternatives were considered in the design to stabilize the soft subgrade, including a conventional and a geosynthetic-stabilized option. The conventional alternative, without geosynthetic stabilization (i.e., non-stabilized alternative), involved placement of a 900-mm-thick layer of Tezontle, while the geosynthetic-stabilized alternative involved using a geogrid layer overlain by a reduced, 400-mm-thick Tezontle layer (see figure 5a).



Figures 4a & b – Case study involving moisture reduction in structural layers: (a) Cross-sections of conventional and geosynthetic solutions; (b) Carbon audit results showing contribution of different phases (source: Zornberg et al. 2024).



Figures 5a & b – Case study involving stabilization of soft subgrades: (a) Cross-sections of conventional and geosynthetic solutions; (b) Carbon audit results showing contribution of different phases (source: Zornberg et al. 2024).

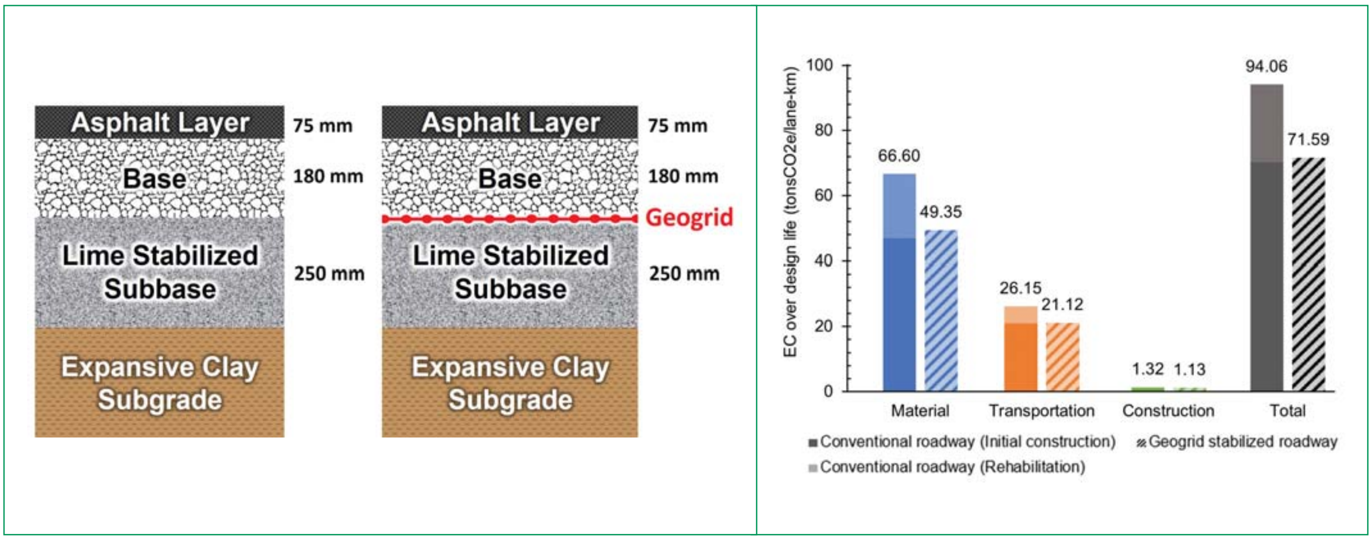


Figure 6a & b – Case study involving mitigation of distress caused by expansive clay subgrades (a) Cross-sections of conventional and geosynthetic solutions; (b) Carbon audit results showing contribution of different phases (source: Zornberg et al. 2024).

The results of the carbon audit, presented in figure 5b, demonstrate that significant benefits can be achieved by including the geogrid layer. The geogrid-stabilized design improves the EC values associated with all construction stages, yielding emission reductions of 37.9 % for material production, 53.7 % for transportation, and 53.4 % for construction. With these improvements, the total EC reduced from 45.94 tCO_2e to 24.85 tCO_2e – yielding an overall benefit of 45.9 %.

Carbon Audit in Projects Involving Mitigation of Distress Caused by Expansive Clay Subgrades

Farm-to-Market Road 1915 (FM 1915) extends approximately 32 km in Milam County, Texas, USA. Sections of this road are founded on highly expansive clay subgrades and have been reported to have extensive distress, particularly in the form of longitudinal cracks. The Texas Department of Transportation (TxDOT) rehabilitated the damaged section of FM 1915 in 1996 when experimental test sections were constructed to evaluate the performance of geosynthetic stabilization of the base course in mitigation of the damages induced by the expansive clay subgrade. The test sections extended for approximately 4 km, including a control (without geosynthetic) section and a test section constructed by placing a biaxial geogrid between their subbase and base. Both sections were constructed using the same base thickness of 180 mm, with the only difference being the presence of the biaxial geogrid in one of the sections (see figure 6a).

Each condition survey documented the severity and extent of the environmental longitudinal cracks. Geosynthetic-stabilized test sections performed significantly better than the control test section. A comparison of the performances of sections constructed using the conventional design and the geogrid-stabilized base revealed that using a geogrid to stabilize the base layer led to reduced maintenance costs and extended roadway service life. The conventional design section (without geosynthetics) exceeded the target of 15% longitudinal cracks only after 9.5 years of service, indicating the need for adding an overlay to extend its service life. However, geosynthetic-stabilized section performance was acceptable for at least 15 years.

The results of the carbon audit are presented In figure 6b in terms of total emissions and the contribution of the various construction stages. While the stabilized design results in slightly higher initial construction emissions for the geosynthetic design alternative (due to the inclusion of the geogrid layer with no pavement thickness reduction), rehabilitation involving the construction of an overlay led to an increased final EC value for the conventional design alternative. Overall, the total EC is estimated to be 71.59 tCO_2e for the geogrid stabilized alternative, which corresponds to a reduction of 23.9 % compared to the conventional design, with a total EC of 94.06 tCO_2e.

Conclusions

This paper presents the results of carbon audits conducted to illustrate the sustainability benefits of adopting design alternatives that involve the use of geosynthetics in roadway applications. While carbon footprint predictions are project-specific, comparing conventional design alternatives and geosynthetic design alternatives evaluated in this study showed that the geosynthetic design alternatives consistently provided a lower carbon footprint for six roadway applications. In all case studies evaluated in this investigation, geosynthetics were adopted as an alternative design to achieve enhanced roadway performance or maximize cost-savings, but without consideration of the potential sustainability benefits. Consequently, the reduction in carbon footprint is expected to be further optimized if designers consider it an additional criterion when selecting alternatives (e.g., by reducing the thickness of high-EC materials such as asphalt or chemically stabilized layers).

Considering for illustration purposes that the case histories evaluated in this study are representative of the six roadway applications discussed in this paper, an average reduction of 26.29 tCO_2e per lane-km in carbon footprint could be expected when adopting a geosynthetic design alternative instead of a conventional design. Assuming that the costs (and carbon footprint) of the roadway projects evaluated in this study are amortized over a typical roadway design life of 15 years, these projects point to an annual average reduction of 1.75 tCO_2e per lane-km-year in carbon footprint. Now, considering the reported world's roadway network of 64,285,009 km (and assuming two lanes per road), this results in a potential annual average reduction of 225 million tCO_2e per year in carbon footprint if the world roadway network were to benefit from designs involving geosynthetics. This is equivalent to the CO_2 sequestered by approximately 100 million hectares of forest in a year – or a forest 24 times the area of the Netherlands. With such potential to reduce carbon footprint, adopting geosynthetics in roadways is among the most promising uses of geosynthetics to address the world's sustainability needs.

References

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[3] Zornberg, J.G., Subramanian, S., Roodi, G.H., Yalcin, Y., and Kumar, V.V. (2024). "Sustainability Benefits of Adopting Geosynthetics in Roadway Design." International Journal of Geosynthetics and Ground Engineering, Springer (in press).