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ORIGINAL PAPER

Sustainability Benefits of Adopting Geosynthetics in Roadway Design

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Abstract
The world's roadway system is so extensive that its total length would encircle the Earth over 1,600 times if combined. Geosynthetics have provided sustainable alternatives in roadway projects, representing a significant portion of the total usage of geosynthetics in civil infrastructure. Yet, considering the significant extension of roadway projects worldwide, geosynthetic products are only utilized in a small fraction of them. Consequently, the opportunities to achieve sustainability goals by making more extensive use of geosynthetics in roadways are massive. The objective of this paper is 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 using geosynthetics. Each roadway project involved one of six different applications involving the use of geosynthetics. Specifically, they involved the use of geosynthetics to (1) mitigate reflective cracking in structural asphalt overlays, (2) stabilize unbound aggregate layers, (3) reduce layer intermixing, (4) reduce moisture in structural layers, (5) stabilize soft subgrades, and (6) mitigate distresses caused by expansive clay subgrades. The sustainability benefits were quantified by conducting carbon audits for the alternative designs for each roadway project. The results of 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 (or 11.6 to 50.11% decreased footprint in relation to conventional design alternatives). Overall, while the rationale for adopting geosynthetics in different roadway applications has generally focused on the benefits that they offer to improve the project's performance or reduce its costs, the evaluations in this study reveal that an additional reason to adopt geosynthetic solutions in roadway applications is their potential to provide significant sustainability benefits.

Keywords Geosynthetics · Sustainability · Roadways · Separation · Reinforcement · Stabilization · Stiffening · Filtration · Drainage

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Introduction

Roadways' performance can significantly benefit from adopting geosynthetics as part of their design for a number of specific applications that benefit from specific mechanical or hydraulic geosynthetic functions. The geosynthetic products most commonly used in roadway systems include geotextiles (woven and non-woven) and geogrids (biaxial and multiaxial). However, erosion-control products, geocells, geonets (or geocomposite drainage products), and geomembranes have also been incorporated into a number of applications. The multiple types of geosynthetics can be used to fulfill one or more specific functions in several roadway applications. For example, geosynthetics have been in use since the 1970s to improve the performance of unpaved roads on soft subgrade soils. Since the 1980s, geosynthetics

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have also been utilized to minimize reflective cracking in asphalt overlays as well as to improve the performance of base aggregate layers.

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 1600 times if combined. Geosynthetics have provided sustainable alternatives in roadway projects, which currently represent 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 of them. 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. The sustainability benefits that may result when selecting a design alternative involving geosynthetics have not been clearly documented in the technical literature, partly because it has been difficult to establish the proper equivalence in performance between alternatives that adopt geosynthetics or not. However, with the increasing understanding of the mechanisms that lead to increased roadway performance, the sustainability benefits of adopting geosynthetics can be quantified by conducting carbon audits for alternative designs in actual roadway projects.

This paper 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 consists of the use of geosynthetics were evaluated by conducting carbon audits for the alternative designs for each roadway project. While geosynthetics have been generally selected in different roadway applications because of the benefits that they offer to improve the project's performance or reduce its cost, the evaluations in this study were conducted to assess the potential benefits of using geosynthetics to reduce the project's carbon footprint.

The paper was organized to facilitate differentiation among the different geosynthetic applications, as follows: Sect. "Sustainability benefits and quantification in roadway projects involving the use of geosynthetics" includes background information on sustainability benefits related to using geosynthetics in roadway projects. Section "Carbon audit methodology adopted in this study" describes the carbon audit procedure adopted to evaluate different design alternatives and details the approaches adopted for analysis parameters in the presented roadway projects. In the succeeding sections, six roadway projects involving different geosynthetic applications in roadways are presented with discussions related to geosynthetic functions and benefits. The carbon audit of the different cases is quantified to illustrate the sustainability benefits achieved through the use of geosynthetics. Lastly, Sect. "Conclusions" summarizes the findings and concluding remarks from this study.

Sustainability Benefits and Quantification in Roadway Projects Involving the Use of Geosynthetics

Roadway projects can be deemed sustainable if they manage not only to improve safety and mobility in society but also to maintain cost-effectiveness and environmental protection. Thus, environmental, economic, and social values (the triple bottom line of sustainability) compete in the decision-making process and must be balanced when different design alternatives are evaluated for a sustainable roadway project [3]. Traditionally, the economic aspect of a roadway project has generally dictated the final choice among technically viable design alternatives, followed closely by social needs. With the global effort to reduce greenhouse gas emissions, government agencies have focused on identifying areas to decarbonize their economy. This includes the environmental impacts of pavement construction, which are becoming increasingly important in the decision-making process. In the US, the "Buy Clean Initiative" (Executive Order 14,057) and the "Inflation Reduction Act (IRA)" promote the use of low-carbon footprint construction materials at the federal level, while several states (e.g., California, Colorado, Minnesota, Oregon) have passed Buy Clean legislation to mandate the use of environmentally sustainable materials in construction.

This paper aims to assess the potential of enhancing environmental sustainability by using geosynthetics to provide various functions as an alternative to the conventional design for different roadway applications. The sustainability benefits of incorporating geosynthetics in the design of a roadway project can be quantified by performing carbon audits of both the conventional design alternative (without geosynthetics) and the alternative design incorporating geosynthetics, thereby quantifying the total mass of greenhouse gases as CO_2 equivalent (CO_2e) emitted in association with the construction and maintenance of the two design alternatives. The assessment of the CO_2e emitted is carried out using Embodied Carbon (EC) values at various stages of roadway construction and maintenance.

The concept of EC is helpful in quantifying the cumulative CO_2e emissions during the various stages (e.g., extraction, production, transportation, installation, operation, and disposal) of the product under evaluation. For example, the carbon embodied in the asphalt mix produced at a plant includes the emissions from the extraction, processing, transportation, and mixing of asphalt binder and aggregates. However, the carbon embodied in the same asphalt mix, but after being placed and compacted on a roadway, would also include the emissions from transportation (plant to site) and installation (placing and compacting) in addition to the EC of the asphalt mix at the plant. Thus, the EC of a product is a cumulative function of the concerned phase in the product's life cycle.

The sustainability benefits of using geosynthetic solutions in roadway construction can be quantified in two different ways. The first and the most straightforward approach is to compare the embodied carbon of two equivalent pavement structures at the end of construction. Equivalent pavement structures involve structures with different structural components but the same (equivalent) expected performance and maintenance over the design period. For instance, in the case of base stabilization, a traditional pavement system (without geosynthetics) could be equivalent to a system with a geosynthetic-stabilized, thinner base layer. Both structures would be equivalent if they were expected to handle a specific volume of traffic over a certain period while maintaining a desired level of serviceability. However, the embodied carbon of the two equivalent structures is expected to differ owing to the different types and volumes of materials adopted for each alternative. In many cases, roadway maintenance may be assumed to be the same for the two equivalent structures. In these cases, the difference in embodied carbon between the two alternatives at the end of their design life is still dictated by the difference in embodied carbon at the end of construction. Such difference in embodied carbon between two alternative designs for the same roadway project quantifies the sustainability benefit of using geosynthetic solutions in pavement projects where the use of geosynthetics aims primarily at reducing the thickness of the structure's cross-section.

A second approach to quantify the sustainability benefits can be adopted when maintenance data is available for both the traditional and geosynthetic design alternatives. This scenario requires monitoring the maintenance required to keep a desired level of serviceability over the design period of the pavement structure, with and without the geosynthetic (all other factors remaining the same). The emissions from maintenance operations are added to the embodied carbon values at the end of construction to determine the end-of-design-life embodied carbon. This evaluation may be particularly valuable if the only difference between the two alternative designs is the presence of the geosynthetic layer (with all other materials and dimensions remaining the same). Since the level of maintenance required to sustain the desired serviceability is different between the traditional pavement structure and that involving geosynthetics, the embodied carbon of the two pavement structures at the end of the design life will be different. This difference in embodied carbon at the end of design life quantifies the sustainability benefit of using geosynthetic solutions in pavement projects where the use of geosynthetics aims primarily at extending the structure's design life.

In addition to roadway systems, geosynthetics are routinely used to enhance the performance of many other types of civil, transportation, hydraulic, and environmental infrastructure. For many of these structures, recent studies have been reported that estimate the reduced carbon footprint that may occur in design alternatives involving geosynthetics compared to other design options involving conventional construction materials. Such studies have reported carbon audits when incorporating the use of geosynthetics in projects such as retaining structures [4–7], bridge abutments [8, 9], slope stabilization systems [10, 11], load transfer platforms [12, 13] and waste closure systems [12]. The carbon audits reported in the studies for these various infrastructure projects have concluded that the use of geosynthetics generally led to a reduced carbon footprint in addition to improved performance.

Several studies have also reported carbon audits in projects involving roadway construction, although they have primarily involved roadway projects that do not involve the use of geosynthetics. Such studies were often performed to develop reliable life cycle assessment methodologies to determine the environmental impacts. In an early effort, Stripple [14] conducted an extensive inventory analysis for stages including extraction and production of materials, construction, operation, maintenance, and disposal. In addition, Dorchies [15] and White et al. [16] developed processes to quantify the environmental impact of pavement construction in terms of greenhouse gas emissions. Similarly, Chehovits and Galehouse [17] studied pavement preservation processes, illustrating their effectiveness in reducing energy consumption and greenhouse gas emissions compared to traditional rehabilitation and reconstruction approaches. Barbieri et al. [18] evaluated the energy consumption and emissions released during the use stage of asphalt pavements in their analyses, accounting for factors such as maintenance, lighting, albedo effect, and vehicle energy loss due to rolling resistance. In addition, Reza et al. [19] integrated energy synthesis into their life cycle assessment framework to evaluate the environmental and socioeconomic impacts to facilitate decision-making for pavement projects. Along these lines, Zheng et al. [20] proposed a life cycle assessment methodology that integrates economic and social aspects along with environmental impact assessment. Finally, Kraus [21] provides an overview of the geosynthetics' potential to offer sustainability benefits, highlighting initiatives such as that of the World Bank regarding adopting geosynthetic products.

Although in a rather limited number, some studies have evaluated carbon audits of roadway projects in which geosynthetics had been incorporated in their design. For example, Whitty et al. [6] produced a white paper that illustrated differences in the carbon footprint of multiple types of geotechnical structures involving the use of geosynthetics. Some of the illustrations in the white paper involved using geosynthetics in roadway applications such as stabilization of soft subgrade and asphalt reinforcement. They reported that incorporating geosynthetics in civil projects, including roadway projects, may significantly reduce the overall embodied carbon. On the other hand, an Indian perspective on the design and sustainability aspects of geogrid-reinforced flexible pavements was provided by Goud et al. [22]. They reported that the inclusion of geogrid in a granular base layer resulted in a base thickness reduction ranging from 28 to 45% while also leading to a reduction in carbon footprint ranging from 58 to 85 tCO_2e/km reduction in the carbon footprint in relation to conventional roadway design alternatives. Finally, Leite-Gembus et al. [23] highlighted the economic and environmental benefits of roadway rehabilitation involving the use of geogrids using recycled polyester material. Specifically, they reported that the polymeric reinforcing geogrid retarded the development of asphalt reflective cracks, thereby extending the service life by three times and, consequently, resulting in a reduction in carbon footprint of about 61% in relation to a conventional rehabilitation program involving the adoption of a comparatively thick asphalt overlay.

In summary, there is significant evidence that incorporating geosynthetic products in various infrastructure projects, other than roadways, has improved their performance and reduced their carbon footprint. On the other hand, while information is available on the carbon footprint estimation of various roadway projects not involving geosynthetics, such carbon footprint estimation for roadway projects involving geosynthetic products is very limited. Thus, this study aims to evaluate and quantify the sustainability aspects of adopting geosynthetic products in roadway projects, with a particular focus on doing so for a wide range of roadway applications involving the use of geosynthetics.

Carbon Audit Methodology Adopted in This Study

The global warming potential of any product can be assessed by performing a carbon audit at various stages of the product life cycle. A holistic Life Cycle Assessment (LCA) shall include the emissions associated with the product from producing the raw materials required to the end of its useful life when the product is recycled and discarded. In the case of roadways, it is often difficult to determine the outcome (repair, rehabilitation, or replacement) at the end of the project design life, and thus, assessing the End-of-Life emissions is challenging because it includes a high degree of uncertainty. Studies have been recently conducted to assess emissions during the use stage of pavements, with a particular focus on the operational energy requirements [24]. In this study, the authors show that the emissions depend on the roadway condition (roughness, texture, and structural stiffness), and propose theoretical models [25–30] that estimate excess fuel consumption from the hysteretic loss in the vehicular components and in the pavement layers. While these emissions are estimated to make up a significant portion of the emissions over the pavement life, they cannot be directly measured using current technology. This imposes severe limitations on their use to estimate the total life-cycle emissions of the pavement. However, if the objective is to estimate differences in carbon footprint between alternative designs (rather than estimating the total life-cycle emissions), calculating the total emissions may not be necessary. For example, the roadway design alternatives compared in this study (with and without the use of geosynthetics) were deemed technically equivalent as they were designed using the same performance criteria. Hence, the use-stage emissions in the two alternative designs associated with excess fuel consumption can be assumed to be similar.

Figure 1 summarizes the various stages of a pavement life cycle analysis, as adopted in conventional Environmental Product Declarations (EPDs). Unlike the emissions in the use stage and at the end-of-life, the emissions during the material production (A1: Raw material extraction + A2: Transport + A3: Plant production), transportation (A4), and construction/installation (A5) can be directly measured. In fact, with several US states focusing on incentivizing decarbonization of the construction industry through "buy clean" legislation, manufacturers of pavement construction materials (such as concrete, asphalt, lime, geosynthetics, and aggregates) have been conducting carbon audits of their manufactured materials specific to the production plant and publishing EPDs with a "Cradle-to-Gate" scope for their products (Fig. 1). The information from these EPDs can be combined with the emissions associated with transporting the geosynthetic material from the factories to the project site and those associated with construction/installation at the project site to determine the "Cradle-to-Built" carbon emissions. As previously mentioned, the use-stage and end-of-life emissions are challenging to estimate and involve a comparatively high degree of uncertainty, so the scope of the environmental sustainability audit in this paper involves predicting the "Cradle-to-Built" emissions for the

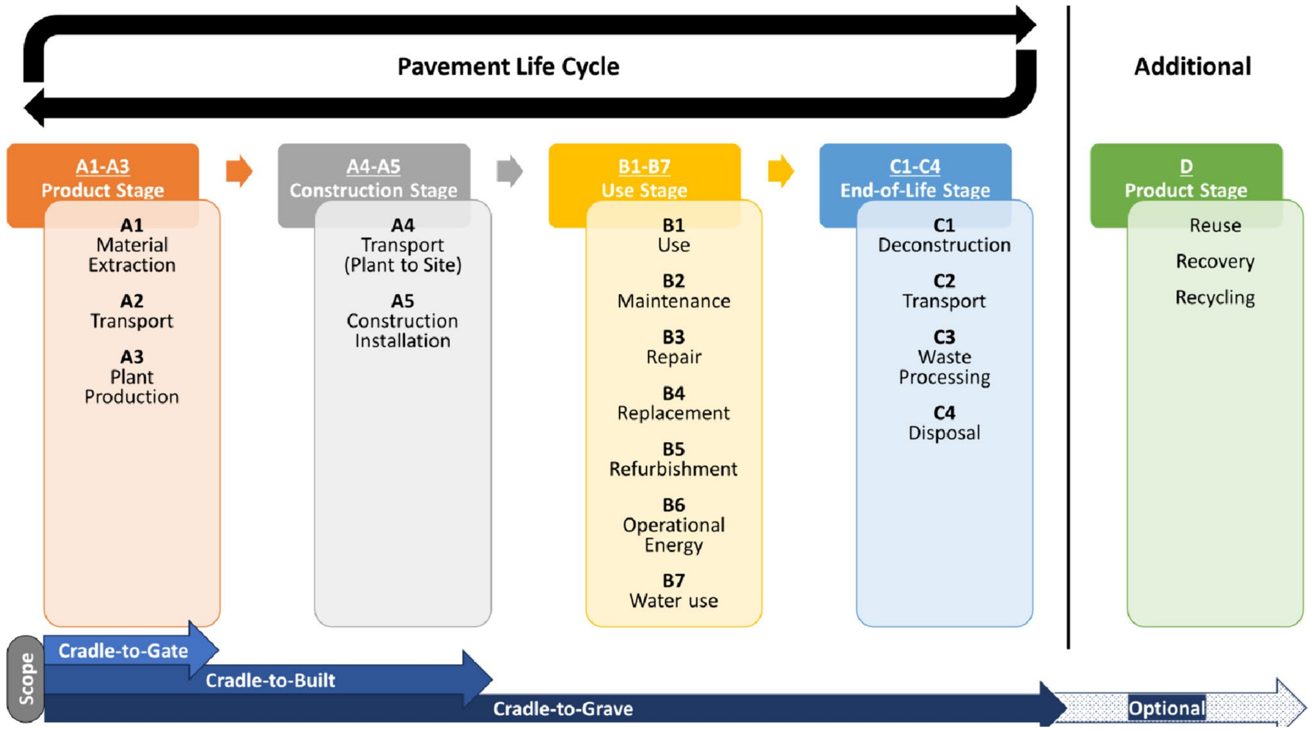

Fig. 1 Environmental Product Declaration (EPD) scopes based on the included life-cycle stages

six case studies discussed in the following sections. In fact, while three of the cases evaluated in this study (comprising geosynthetic applications for mitigation of asphalt reflective cracking, reduction of layer intermixing, and mitigation of distress caused by expansive clay subgrades) also involve constructing an asphalt overlay to improve pavement performance during the design life (use stage), the carbon audit of these overlays was estimated following an approach similar to that for new pavement construction. That is, the emissions were determined by combining the emissions from the production (A1-A3), transportation (A4), and construction (A5) of the materials required for the overlay.

For the construction material production (product stage), the EPDs published by individual manufacturers of various construction materials constitute probably the best estimate of their "Cradle-to-Gate" carbon emissions and global warming potential. However, most of the case studies discussed in the paper pre-date the era of manufacturer-published EPDs, and thus, limited project-specific information is available. Therefore, in this paper, the product stage (A1–A3) emissions associated with the construction materials other than the geosynthetics were assumed to be the same across the various case studies and were obtained from the Inventory of Carbon and Energy (ICE) 2019 database [31]. This approach allows for comparing the sustainability benefits among the various applications of geosynthetics in pavements. Table 1 summarizes the unit embodied carbon (EC) values used in calculating carbon emissions of common materials as adopted across all six case studies.

For geosynthetic products, the unit EC values were assumed based on the type of material used to manufacture the geosynthetic adopted in each project. The unit EC values reported by Raja et al. [32] were adopted for polypropylene geogrids and geotextiles. On the other hand, for interlayer products (asphalt embedded-polyester geogrid) used in the case study involving mitigation of asphalt reflective cracking (Case 1), the unit EC values were obtained from the EPD published by the manufacturer. In cases where the specific type of geosynthetic used had not been reported by Raja et al. [32], similar products in terms of production method (i.e., needle punching, thermal bonding, extrusion, weaving) were considered to provide the unit EC values. Table 2

Table 1 Summary of the unit embodied carbon (EC) values for roadway construction materials

Material	EC (kgCO_2e/kg)
Asphalt	0.0563
Concrete	0.138
Aggregate	0.00438
Bitumen Emulsion	0.222
Lime	0.780

Unit EC values were adopted from ICE [31] summarizes the unit EC values adopted for the geosynthetics used in each case study. Inspection of the unit EC values reveals they are similar in all case studies except Case 1 (interlayer product). Consequently, the approach of adopting a close match to define the EC for some geosynthetics is not expected to significantly affect the results of the overall analysis.

To estimate the emissions related to the transportation of construction materials from production plants to the project site, the unit emission value reported in the US Environmental Protection Agency (EPA) 2022 inventory [33] was adopted. The carbon audit calculations were performed assuming "Medium- and Heavy-Duty Truck" vehicle class (described as "Combination trucks and single frame trucks with two axles and at least six tires or a gross vehicle weight rating exceeding 10,000 lbs." in the EPA inventory) for the transportation of construction materials from the production facilities to the project site in all case studies. This classification was adopted for all materials involved in the case histories. The EPA recommended conversion factors of 25 for CH_4 and 298 for N_2O were used to convert their respective emissions to equivalent CO_2 (CO_2e) emissions. The unit CO_2e for long-distance hauling was determined as 0.869 kg CO_2e/vehicle-km. The maximum payload capacity per truck was assumed to be 15 tons, except for sprayer trucks, for which it was assumed to be 1,500 gallons (5.7 m^3), and for trucks carrying geosynthetics, for which the payload was determined based on the size of the individual roll. The haulage from local production plants to project sites was assumed to be a roundtrip for the case of construction materials. This is because materials such as asphalt, concrete, bitumen, and aggregates are transported with specialized and designated vehicles such as dump trucks and sprayer trucks. On the other hand, one-way trips were assumed for trucks carrying geosynthetics from the factory to the project site (comparatively longer distances) since these are conventional trucks that usually haul different goods from their destinations.

In order to determine the emissions due to construction activities, emission factors reported by Chappat and Bilal [34] were adopted for the various construction stages, along with the quantity of the various materials being constructed. The typical emission factors used in all the case studies for construction-related emissions are summarized in Table 3. The emission factor for undercut/excavation processes was not identified in the literature. Therefore, it was assumed to be half the value corresponding to unbound layer construction. For geosynthetics, emissions associated with the installation were assumed as 10% of the product stage emission for the interlayer geogrid based on its EPD and as 1% of the product stage emission for all other geosynthetics since only interlayers require specialized installation equipment and materials.

The case studies did not include information about the rate of application of the tack and prime coats. Therefore, typical values [35] were adopted for the application rates, as shown in Table 4. The reported values correspond to the volume of asphalt binder in liters per square meter and do not include the volume of water in the emulsion. Tack coats were assumed to be 100% binder, while the prime coats were assumed to be an emulsion of 50% water and 50% binder. Therefore, for the prime coats, the additional volume (for the water content not included in

Table 3 Unit EC values for typical construction stages

Process/material	Construction emission factor ($kgCO_2$/ton)
Bituminous concrete	0.6
PC Concrete	0.2
Unbound layers	0.4
Soil treated in situ (cement + lime)	1.1
Undercut	0.2[a]

Unit EC values were adopted from Chappat and Bilal [34]

[a] Unit EC value for undercut construction was assumed to be half that of the construction of unbound aggregate layers

Table 2 Summary of the unit EC values used for geosynthetics in each case study

Case number	Geosynthetic type	Polymer type	Roadway application	Unit weight (kg/m^2)	EC ($kgCO_2e/kg$)
1	Geogrid	PET	Mitigation of asphalt reflective cracking	0.287	3.74[a]
2	Geogrid	PP	Stabilization of unbound aggregate layers	0.282	2.36
3	Geotextile	PP	Reduction of layer intermixing	0.315	2.35
4	Geotextile	PP	Moisture reduction in structural layers	0.493	2.36
5	Geogrid	PP	Stabilization of soft subgrades	0.220	2.97
	Geotextile	PP	Reduction of layer intermixing	0.271	2.28
6	Geogrid	PP	Mitigation of distress caused by expansive subgrades	0.210	2.97

[a] Unit EC value of the product was adopted from the available EPD. Unit EC values of the rest of the products were adopted from Raja et al. [32]

the application rate) that needs to be transported to the site was accounted for in the transportation emission calculations.

Tack and prime coat-related construction emissions were estimated by assuming a sprayer truck makes a slow pass along the application area. Tsukui et al. [36] reported the relationship between average speed and CO_2 emissions. Based on their observations, it was considered that CO_2 emissions generated during slow passes are twice the volume of emissions generated during long-distance hauling, i.e., 1.738 $kgCO_2e$/vehicle-km, which is used to determine the construction emissions associated with spraying tack and prime coats.

Stripple [14] reported on the energy consumption associated with the milling of asphalt and concrete surfaces and the emissions of various gases during the milling process. These values were converted into equivalent CO_2 values using the EPA-recommended conversion factors. The resulting unit embodied carbon for asphalt milling was estimated to be 0.00075 $kgCO_2e/m^2$. In addition, in cases involving milling operations, it was assumed that the milling depth was 12 mm, and the milling width was equal to the width of a single lane. Milling machines are coupled with a slow-moving truck, with unit emissions of 1.738 $kgCO_2e$/vehicle-km during milling and 0.869 $kgCO_2e$/vehicle-km during transportation of milled material back to the asphalt plant.

Some of the case studies involve the construction of test sections that were relatively short compared to typical pavement projects. Consequently, the actual construction of the test section involved very low quantities of materials and partial truckloads that would need to be estimated to have the same emissions as a full truckload. To mitigate the impact of partial truckloads, the length of the pavement project in all case studies was normalized, with projects assumed to have involved the construction of a lane with a length of 10 km in all cases. Also, calculations of the quantity of materials used for the construction of projects involving asphalt milling were based on a project length of 10-lane-km.

Table 4 Tack and prime coat application rates

Coat type	Application rate (liters/m^2)
Tack without geosynthetic	0.36
Tack with geosynthetic	0.50
Prime	0.54

Application rates were adopted from TxDOT [35]

Carbon Audit in Projects Involving Mitigation of Asphalt Reflective Cracking

Geosynthetics can be used to effectively retard the reflective cracking that occurs when new flexible pavement overlays are constructed over old paved roads with pre-existing cracks. Reflective cracking may be triggered by bending and/or shear stresses induced by repeated traffic loads, as well as by tensile stresses caused by thermal variations [37]. Stress concentration in asphalt overlays may result from lateral movements induced by the flexing of paved roads located directly below the traffic load. Such stresses may end up causing a reflective crack that propagates through the new pavement overlay, making it susceptible to early failure facilitated by moisture intrusion. Geosynthetics have been used to mitigate the early development of reflective cracks through one or a combination of several functions, including reinforcement, separation (including stress relief), and barrier [38].

More specifically, the geosynthetic can act by (1) developing tensile forces near the crack tip, thereby reducing stresses in the bituminous material, (2) providing a layer that allows horizontal deformations so that such movements can develop near pre-existing cracks without being transmitted to the overlay, or (3) providing a hydraulic barrier function to waterproof the roadway structure. Montestruque [39] conducted laboratory tests on reinforced and unreinforced asphalt concrete beams to investigate the use of geosynthetic reinforcements in pavement overlays. Geogrids and a non-woven geotextile were used as reinforcements. Results indicated better performance of the geogrid-reinforced specimens compared to the geotextile-reinforced and unreinforced specimens. Similar results have been reported from laboratory investigations conducted by other researchers investigating asphalt reflective cracking [40, 41]. Recent advances in the use of asphalt reinforcements include their use not only to mitigate the development of reflective cracks but also to increase the structural capacity of paved roads [42–44].

A relevant case study involving the use of geosynthetics in asphalt overlays is the rehabilitation of Texas State Highway (SH) 21. This highway spans approximately 500 km between San Marcos, TX, and the Texas-Louisiana border, connecting about 12 different counties. The project evaluated in this study involves the rehabilitation of SH21 in a portion located in Lee County, Texas, USA. The project involved four lanes, with two lanes in each direction. Each lane was 3.5 m wide, while the width of paved shoulders ranged from 0.9 m to 1.2 m. The pre-existing roadway sections within the project limits included a distressed and oxidized asphalt layer with a thickness of 152 mm, underlain by base and subbase layers with a total thickness of

381 mm. The subgrade soil within the project limits was determined to be an expansive clay with significant swell-shrink potential. Consequently, the environmental loading due to moisture fluctuations in expansive subgrade soil and the repeated traffic loading due to heavy truck traffic along SH21 had resulted in the development of cracks and ruts along the wheel path, deteriorating the ride quality and road-user serviceability.

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 (see Fig. 2a). However, additional considerations led to a revised overlay design involving the use of geosynthetic interlayers. Of particular concern was that the manufacturing, transportation, and construction of a thick HMA overlay would impose particularly high financial costs on the project. Such a rehabilitation program would also lead to comparatively high CO_2 emissions. Consequently, TxDOT developed an alternative solution to incorporate geosynthetic reinforcement in the overlay design that would result in a reduced HMA overlay thickness.

Incorporating geosynthetic reinforcement to mitigate reflective cracking in asphalt overlays is a widespread and effective technique adopted by TxDOT and other agencies across the US. Additionally, more recent investigations [42, 43] have reported that geosynthetic reinforcements placed within the asphalt layers could reduce permanent deflections and strains under traffic loads, which in turn, enhanced the structural capacity of asphalt layers. With such background and experience in incorporating geosynthetic reinforcements in Texas roadways, TxDOT eventually adopted the overlay design that involved incorporating a polymeric geosynthetic reinforcement with a reduced (76-mm-thick) HMA overlay thickness (see Fig. 2b). This alternative design resulted in significant cost-saving and sustainability benefits compared to the conventional rehabilitation program with a comparatively thicker HMA overlay. Rehabilitation of SH21 was one of the very few projects in Texas and the US to adopt a geosynthetic reinforcement technique not only to mitigate reflective cracking but also to reduce the design HMA overlay thickness. Construction of the alternative solution included half- or full-depth repairs, application of binder tack coat (see Fig. 3a), installation of polymeric geosynthetic reinforcement (see Fig. 3b), and construction of a thinner (76-mm-thick) HMA overlay (see Fig. 3c).

The global warming potential of the two design alternatives was evaluated by performing carbon audits using the methodology described in Sect. "Carbon audit methodology adopted in this study". The construction sequence for both design alternatives involved surface milling, tack coat application, and two lifts of asphalt overlay constructed to achieve the required thicknesses. The average transportation distance between the asphalt plant and the construction site

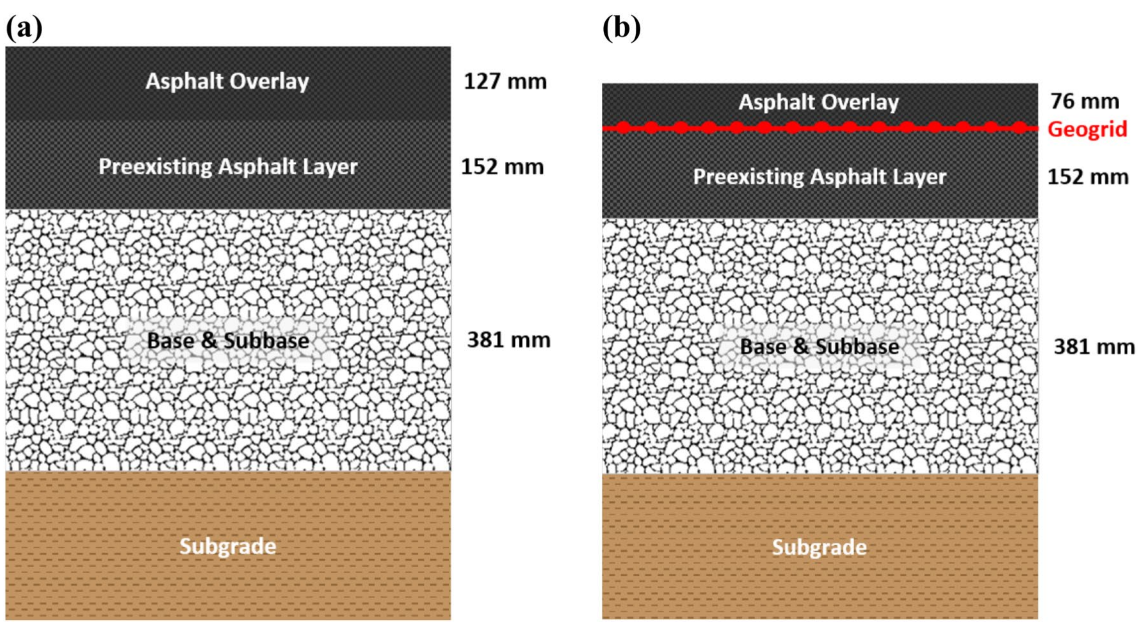

Fig. 2 Cross-section of the case study involving asphalt reinforcement: **a** Section with conventional asphalt overlay; **b** Section with a geogrid-reinforced asphalt overlay

Fig. 3 SH21 rehabilitation: **a** Application of binder tack coat; **b** Installation of polymeric geosynthetic reinforcement; **c** Construction of asphalt overlay

was estimated to be 37 km, and the geosynthetics were procured from a factory located approximately 1800 km from the site. The results of the analysis are summarized in Fig. 4, which includes the EC values related to the different stages (material, transportation, construction) for the two alternative pavement designs as well as the total EC values. As indicated by the results in this figure, most of the emissions are related to the material production phase, which includes the production of asphalt mixtures, bitumen emulsions for tack coat application, and geosynthetics. For the conventional asphalt overlay, the emissions per lane-km were determined to be 60.74 tCO_2e for material production, 5.10 tCO_2e for transportation, and 0.65 tCO_2e for construction—totaling 66.49 tCO_2e. For the geogrid-reinforced overlay, the material production and transportation emissions are reduced to 40.71 tCO_2e and 3.42 tCO_2e, respectively. Meanwhile, the construction emissions are determined to be marginally higher, 0.79 tCO_2e, owing to the requirement of specialized equipment and processes associated with geosynthetic reinforcement installation. The total EC, including all phases of geogrid-reinforced overlay construction, was estimated to be 44.91 tCO_2e. Figure 5 provides a breakdown of EC

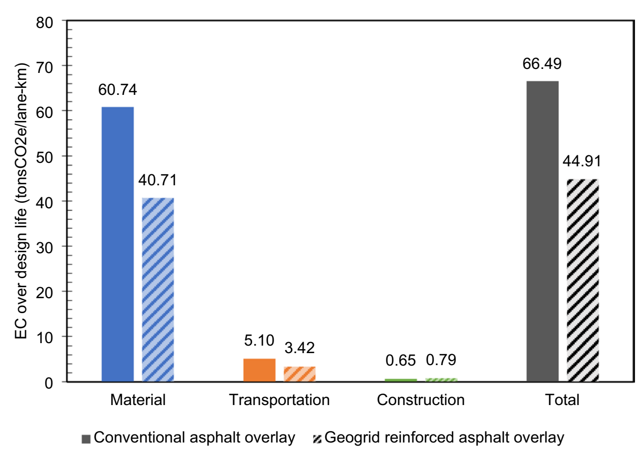

Fig. 4 Carbon audit results for the case study involving mitigation of reflection cracks – Contribution of different phases

for individual pavement layers, illustrating that the carbon footprint of the geosynthetic solution showed a reduction of 32.4% compared to the conventional overlay design. It should also be noted that the EC value of the geogrid layer in

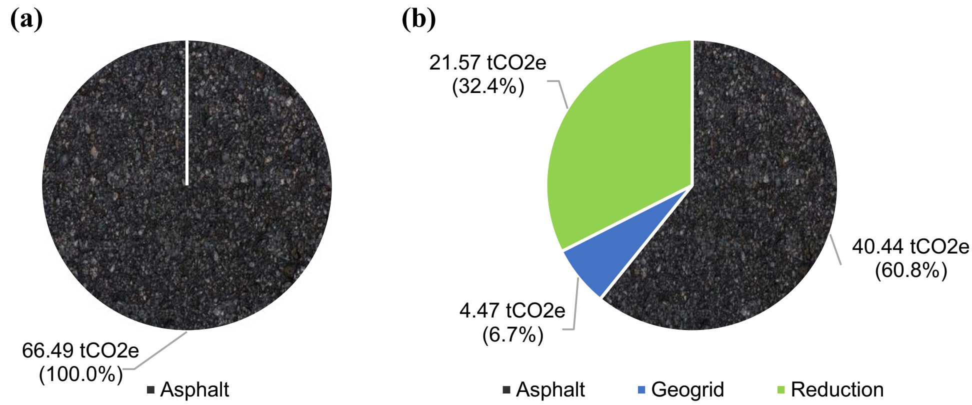

Fig. 5 Carbon audit results for the case study involving mitigation of reflection cracks – Contribution of different pavement layers: **a** Conventional asphalt overlay; **b** Geogrid-reinforced asphalt overlay

the reinforced overlay design is 4.47 tCO_2e, which is about 11% of that of the 76 mm-thick asphalt overlay (i.e., 40.44 tCO_2e), i.e., the "Cradle-to-built" EC of the geogrid reinforcement is equivalent to that of an asphalt overlay with a thickness of 9 mm. Thus, under similar conditions, as long as the asphalt overlay thickness reduction exceeds 9 mm, adopting geogrid reinforcements would lead to a more environmentally sustainable solution for the conditions of the SH21 project. In this project, the asphalt overlay thickness reduction was about 51 mm.

The scenario described in this case study is typical of an asphalt overlay project with the asphalt mix, binders, and emulsions locally available (within 40 km). At the same time, the interlayers are generally shipped from the manufacturer's factory from distant locations (e.g., over 1500 km). With overlay constructions being the most commonly adopted method for DOTs to extend the pavement service life, the use of asphalt reinforcement interlayers not only aids in mitigating reflective cracking and decreases the asphalt overlay thickness but, in addition, also provides significant reduction (over 30% in this case) in the carbon footprint of the overlay structure.

Carbon Audit in Projects Involving Stabilization of Unbound Aggregate Layers

The stabilization of unbound aggregate layers (e.g., base and sub-base) in flexible pavements involves the use of geosynthetics to maintain or possibly increase the stiffness of the aggregate materials over their design life. Stiffening is the primary function leading to decreased lateral displacements within (and increased confinement of) the aggregate-geosynthetic composite. While the geosynthetic could be placed within the unbound aggregate layer, the typical placement location to facilitate constructability is at the interface between the layer being stabilized (e.g., base or sub-base) and the underlying layer.

Lateral displacement of aggregate particles occurring under repeated traffic loading is a mechanism that degrades the mechanical properties of the base aggregate. Such displacement is particularly significant in the lower portion of the base layer, directly below the wheel path, where tensile stresses are more prone to develop. The displacements result in decreased lateral stresses (i.e., decreased confinement) of the aggregate, significantly impacting its modulus. In a multi-layer pavement system, the main characteristic of the base layer is its comparatively high modulus, which widens the distribution of vertical loads and ultimately decreases the maximum vertical stresses acting at the interface between unbound aggregates and the underlying subgrade. Traffic-induced degradation of the original modulus of the aggregate (i.e., the modulus at the time of construction) results in increasing contact pressures at the top of the subgrade and, eventually, in high rutting depths in the roadway structure.

Interaction between the unbound aggregate and the geosynthetic results in the transfer of shear stresses from the base material into tensile stresses in the geosynthetic. As a result, comparatively high interface shear transfer is needed to stabilize the base layer. In addition, the geosynthetic tensile stiffness also contributes to limiting the development of lateral strains. Consequently, a geosynthetic with comparatively high stiffness is also beneficial for unbound aggregate stabilization [45]. The increased confinement provided by the geosynthetic layer in the unbound aggregate material leads to an increase in the mean stresses, also resulting in an increased aggregate shear strength. Both frictional and interlocking characteristics of the interface between the soil and the geosynthetic contribute to lateral restraint. Therefore, when geogrids are used to stabilize a road base, the geogrid aperture and base material particle sizes should be appropriately selected. On the other hand, when geotextiles are selected for base stabilization, proper interface frictional capabilities should be provided.

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) removed the existing pavement structure and layers of subgrade, added additional lanes to the highway in both directions, and reconstructed the entire pavement. The lake-effect snow that results from the project site's proximity to Lake Erie 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 (Fig. 6a) 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 in the project.

Specifically, adopting a biaxial geogrid beneath the AASHTO #2 stone layer would result in a reduced undercut of about 610 mm (Fig. 6b). 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. Ultimately, the contractor could complete the project in two-thirds of the initially anticipated time, which resulted in additional savings in labor, equipment, traffic control, and logistic costs in the project. Figure 7a shows the excavation, various unbound aggregate layers, and geosynthetic layer during the I90 construction. Figure 7b illustrates the installation of the geosynthetic layer covered by AASHTO #2 stones.

The carbon footprints of the two design alternatives for this roadway project (with and without geogrid stabilization of the road base) were quantified using the methodology described in Sect. "Carbon audit methodology adopted in this study". Accordingly, the emissions associated with each construction phase were individually determined and then combined to determine the overall carbon footprints. The construction phases included subgrade undercutting, installation of the geogrid (in the geosynthetic-stabilized alternative), construction of the unbound aggregate layers, application of the prime coat, and construction of the asphalt concrete layers (in three lifts with tack coats between lifts). The transportation emissions were determined considering that the unbound aggregates, asphalt mixtures, tack coats, and prime coat emulsions were transported from the production plant located 50 km from the project site. The geosynthetics were delivered from the manufacturer's factory located 1500 km from the site. The assessed carbon footprints are presented in Fig. 8, which includes the EC values corresponding to different construction phases as well as the total EC values. Based on the original design, the construction of a typical one km-long lane of roadway generates emissions corresponding to 256.56 tCO_2e/lane-km (195.25 tCO_2e for material production, 55.68 tCO_2e for transportation, and 5.62 tCO_2e for construction). The alternative involving the use of geogrids for unbound aggregate stabilization resulted in a reduction in emissions across all stages, totaling 226.69 tCO_2e/lane-km (185.28 tCO_2e for material production, 37.43 tCO_2e for transportation and 3.99 tCO_2e for construction). The most significant reduction in emissions corresponds to the transportation stage, even if the geogrid rolls were hauled over a distance of 1,500 km

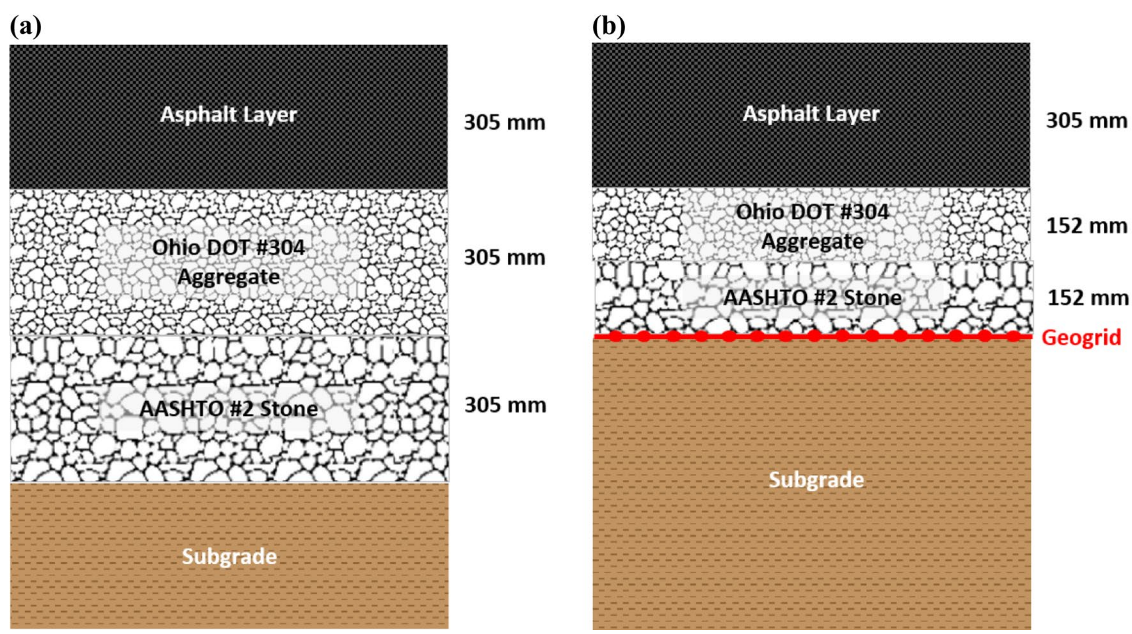

Fig. 6 Cross-sections of the case study involving stabilization of unbound aggregate layer: **a** Conventional design section; **b** Geosynthetic design section (geogrid-stabilized base)

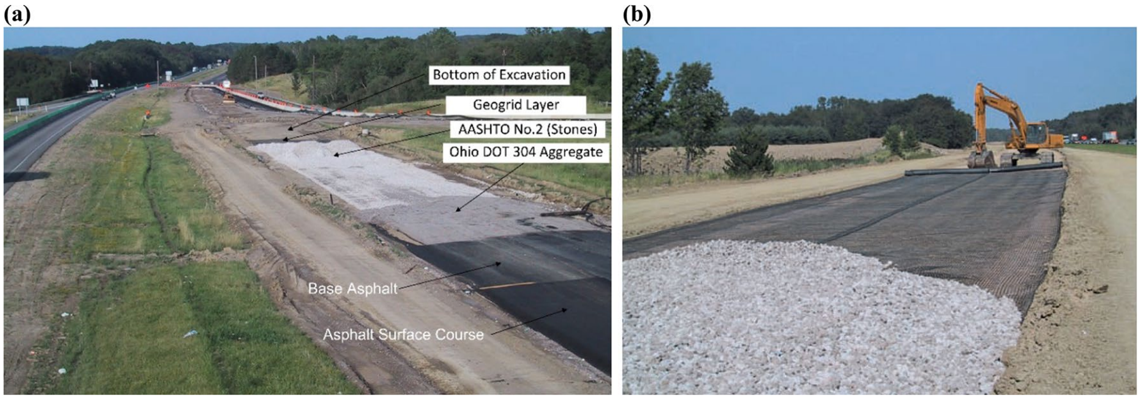

Fig. 7 Case study involving stabilization of unbound aggregate layer: **a** Various roadway layers in I90 reconstruction project; **b** Installation of geosynthetic during reconstruction (Pictures courtesy of Huesker)

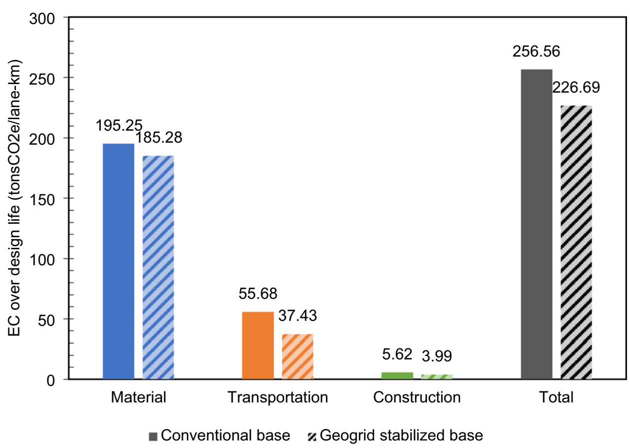

Fig. 8 Carbon audit results for the case study involving stabilization of unbound aggregate layers—Contribution of different phases

from the factory to the project site. This is because the geosynthetics alternative resulted in significant reductions in aggregate layer thickness, significantly reducing emissions related to the transportation of aggregate material. Overall, the geogrid stabilization design showed an 11.6% reduction in emissions compared to the conventional design for the entire pavement structure.

The breakdown of emissions related to different pavement layers is shown in Fig. 9. In the conventional design alternative, the asphalt layer contributes 188.89 tCO_2e emission per lane-km, corresponding to 73.6% of the total emissions. The other components, comprising the undercutting operations and the construction of the unbound layers, contribute 67.68 tCO_2e per lane-km. While the emissions corresponding to the asphalt layer remain the same in the geosynthetic-stabilized base design, significant benefits are observed for

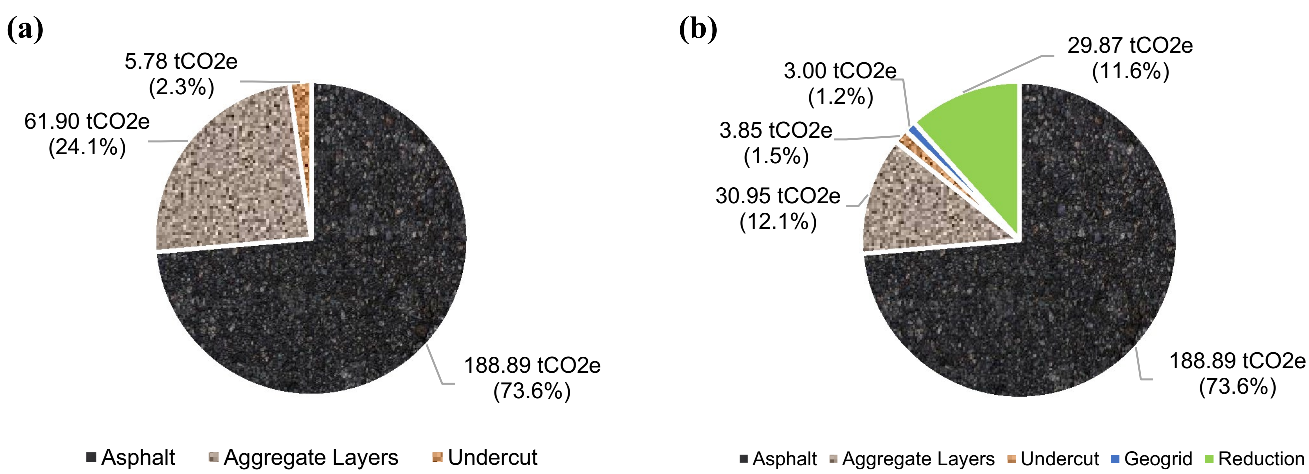

Fig. 9 Carbon audit results for the case study involving stabilization of unbound aggregate layers—Contribution of different pavement layers: **a** Conventional design alternative; **b** Geosynthetic design alternative (geogrid-stabilized base)

the other components. 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. Furthermore, the unit EC values for the geogrid layer and the 305 mm-thick unbound aggregate layers are 3.00 tCO_2e and 30.95 tCO_2e, respectively. The correlation between these unit EC values shows that the geogrid layer is equivalent to a 30 mm-thick aggregate layer from an environmental sustainability standpoint when adopting a "Cradle-to-Built" scope. Considering that a base layer thickness reduction of 305 mm was achieved in this project, the geosynthetic-stabilized design alternative is clearly a more sustainable approach.

This project was designed considering the impact of base stabilization in design and costs, leading to a reduction in the overall pavement thickness of 33%. Although sustainability criteria were not explicitly considered at the time of the design, the geosynthetic design alternative led to an overall carbon footprint reduction of approximately 12%, with the thickness reduction coming from the low EC aggregate base. Considering the results of this carbon audit analysis, a more sustainable alternative would have been achieved by maintaining the base layer thickness but reducing the asphalt layer thickness to compensate for the improved performance of the geogrid-stabilized road base. That is, understanding the EC audit results of the alternatives may lead to exploring less conventional designs such as reducing the thickness of the asphalt layer even if the improved structural capacity due to using geosynthetics is on the base material.

Carbon Audit in Projects Involving Reduction of Layer Intermixing

In this roadway application, a geosynthetic is placed between two soil layers with different particle-size distributions. The objective being to alleviate a common cause of failure of roadways constructed over soft foundations, which is the contamination of unbound aggregate materials with the underlying soft subgrade soil. Contamination occurs due to (1) aggregate penetration into the weak subgrade due to localized bearing capacity failure under stresses induced by wheel loads, and (2) intrusion of the fine-grained soils into the aggregate because of pumping or subgrade weakening due to excess pore water pressure. Subgrade contamination results in inadequate structural support, which often leads to premature failure of the roadway. A geosynthetic placed between the aggregate and the subgrade can act as an effective separator by preventing the intermixing of the subgrade and aggregate base particles.

Even a small volume of fines contaminating a granular layer would negatively affect its structural response, causing a reduced shear strength, decreased hydraulic conductivity, and increased frost susceptibility. Ultimately, a mix involving base aggregate material contaminated with fine-grained soils may essentially behave as the fine-grained soil itself. Consequently, the contamination effectively leads to a reduced base layer thickness and, ultimately, to a decreased road life. Using a geosynthetic separator is comparatively inexpensive and may result in significant cost savings over the design life of a roadway. Among the different types of geosynthetics, geotextiles have generally been used to achieve the function of separation. Design methodologies for the use of geosynthetics in separation applications are provided by Koerner [46] and Holtz et al. [47, 48].

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 (Fig. 10). This is because the main differences in performance between a conventional roadway design and a design incorporating a geotextile separator will be realized by differences in maintenance costs. Consequently, difficult-to-obtain performance data are needed for the proper evaluation of alternatives. As part of this VDOT study, nine 15-m-long test sections, including three control sections, three test sections with a geotextile separator, and three test sections with a geogrid, were constructed [49–53]. The geosynthetic layer (geotextile or geogrid) was placed between the subgrade and base layers, with varying thicknesses of the base course layer: 102 mm (in Test Sections 1–3), 152 mm (in Test Sections 4–6) and 203 mm (in Test Sections 7–9). The subgrade was characterized by low California Bearing Ratios (CBR), ranging from 6 to 10%, with soils classifying as ML and CH according to the Unified Soil Classification System (USCS) and as A-7–6 according to the AASHTO classification system. The base course material was a VDOT class 21-B limestone aggregate. The HMA course, placed in two layers, had an average thickness of 95 mm [51].

The test sections were heavily instrumented with earth pressure cells, strain gauges, soil moisture blocks, and thermocouples. Visual inspection, falling weight deflectometer (FWD) tests, and rut measurements were also conducted for 8 years. Analysis of FWD results over the lifetime of the test sections indicated that the use of geotextiles led to enhanced pavement performance. In addition, rutting depth measurements were found to be the highest in sections without geosynthetic. Ground penetrating radar (GPR) measurements were used to create profiles of the base-subgrade interface. Analysis of GPR data showed that sections with geotextiles did not show an intermixed transition layer between subgrade and base. In contrast, such an intermixed layer was observed in the control and geogrid sections.

Figure 11 shows the roadway sections evaluated in this study, including the control sections and sections with

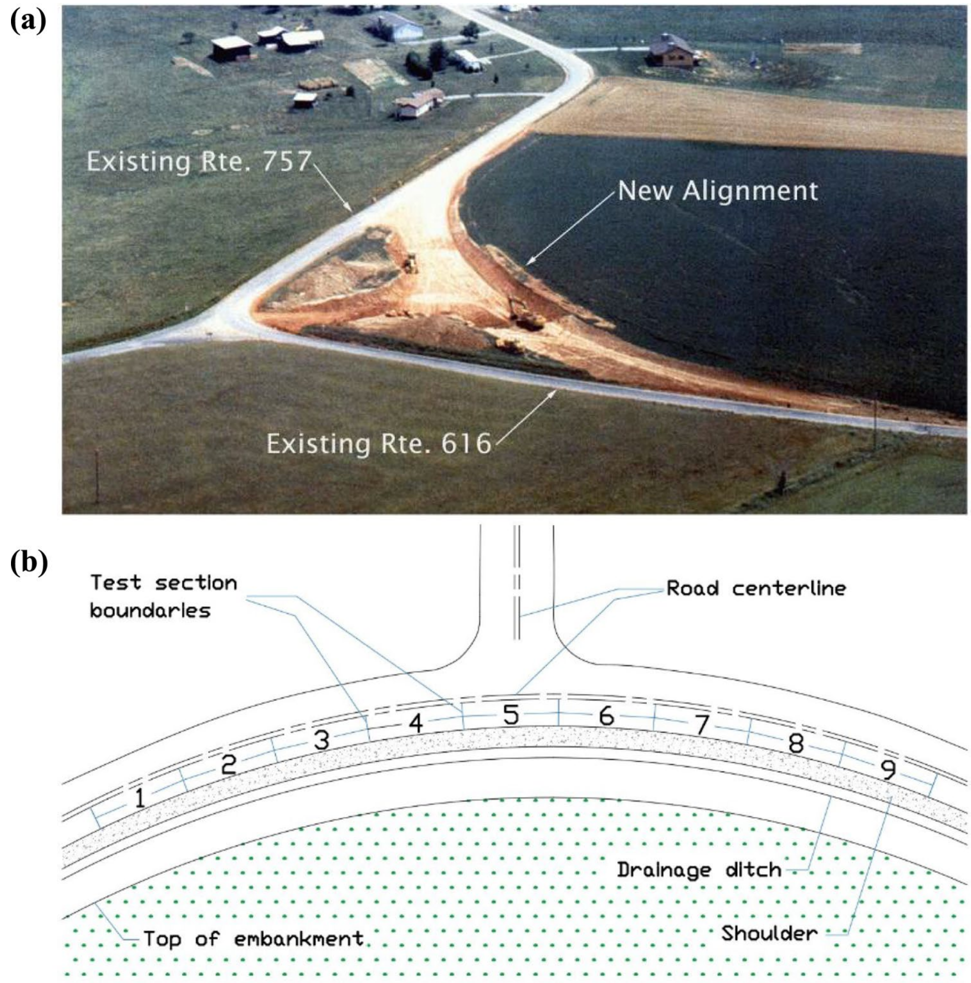

Fig. 10 Case study involving reduction of layer intermixing: **a** Project site aerial view; **b** Layout of the test sections (Figure drawn after Appea [49])

geotextile separators. 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. Specifically, the conventional design section (control section without geotextiles) exceeded the acceptable performance criterion of 20 mm rutting after 55,161 ESALs. Then, two rehabilitation periods were required to achieve an additional 45,000 ESAL [51].

Carbon audits were conducted for both alternative design sections by considering similar initial construction sequences for unbound aggregate layer and asphalt layer construction but by considering the use of a geotextile separator in the alternative design section. The carbon footprint for the two rehabilitation stages required for the conventional design section (without a geotextile separator) considered the emissions corresponding to the asphalt overlays (each having a thickness of 38 mm), asphalt milling operations, and tack coat applications. These rehabilitation emissions were added to the initial construction "Cradle-to-Buil" emissions calculated for the case without geotextile separation. Transportation distances were determined as 38 km for aggregates and asphalt products and 744 km for the geosynthetic. The carbon footprints for the two design alternatives are shown in Fig. 12 in terms of EC values for the individual construction phases, as well as the total EC for each design alternative. For the conventional design alternative, the emissions related to initial construction and rehabilitation are represented in the figure, respectively, with light and dark colors. Instead, rehabilitation is not shown for the design alternative with geosynthetic separation because it was not required over the design life. As expected, the initial construction EC values are slightly higher for the alternative with a geotextile separator since this section includes an additional component (the geotextile layer), while the other layers are the same as in the conventional section. However, when the required rehabilitation operations are considered, the EC values of the traditional design exceed those of the alternative design in all stages, adding to a total of 116.79 tCO_2e /lane-km (100.49 tCO_2e for material production,

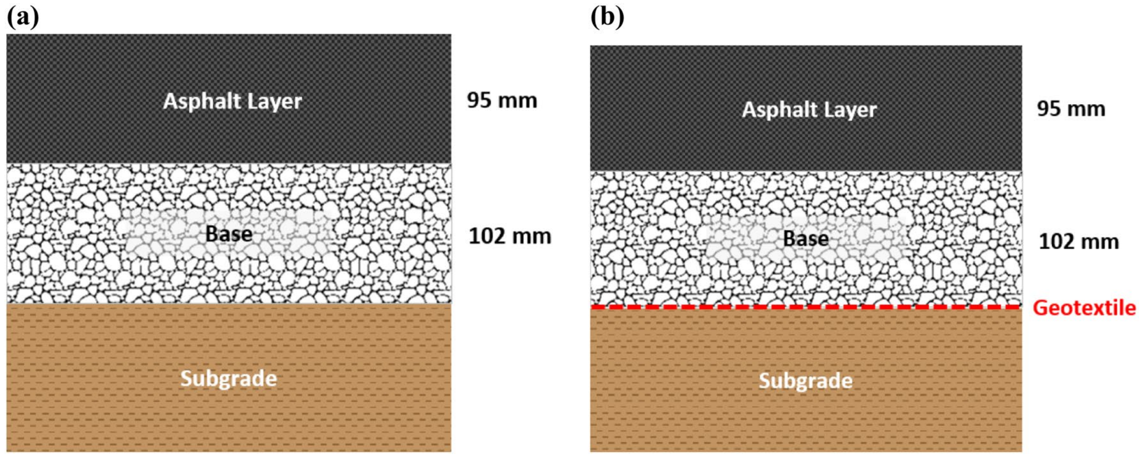

Fig. 11 Cross-sections of the case study involving reduction of layer intermixing: **a** Conventional design section; **b** Geosynthetic design section (geotextile separator)

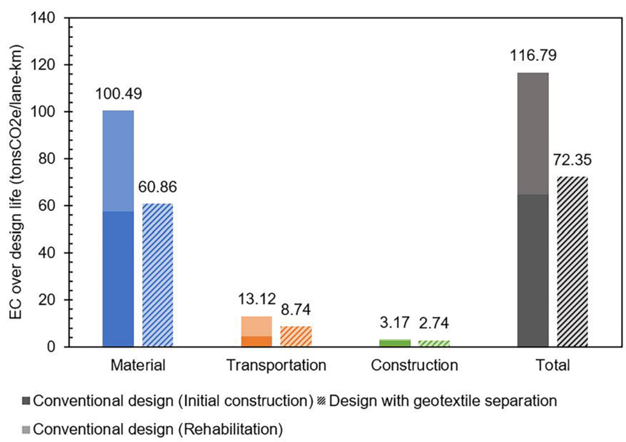

Fig. 12 Carbon audit results for the case study involving reduction of layer intermixing—Contribution of different phases

13.12 tCO_2e for transportation, and 3.17 tCO_2e for construction). Since the design alternative with a geotextile separator requires no rehabilitation, total emissions are reduced to a total EC value of 72.35 tCO2e, i.e., a 38.1% reduction (60.86 tCO_2e for material production, 8.74 tCO_2e for transportation, and 2.74 tCO_2e for construction). Figure 13 shows emissions associated with the individual materials for the two design alternatives. 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. Considering that this enhancement adds a carbon footprint of only 3.26 tCO_2e during construction (corresponding to the geotextile separator), it is clear that incorporating geotextile separators can lead to important sustainability benefits.

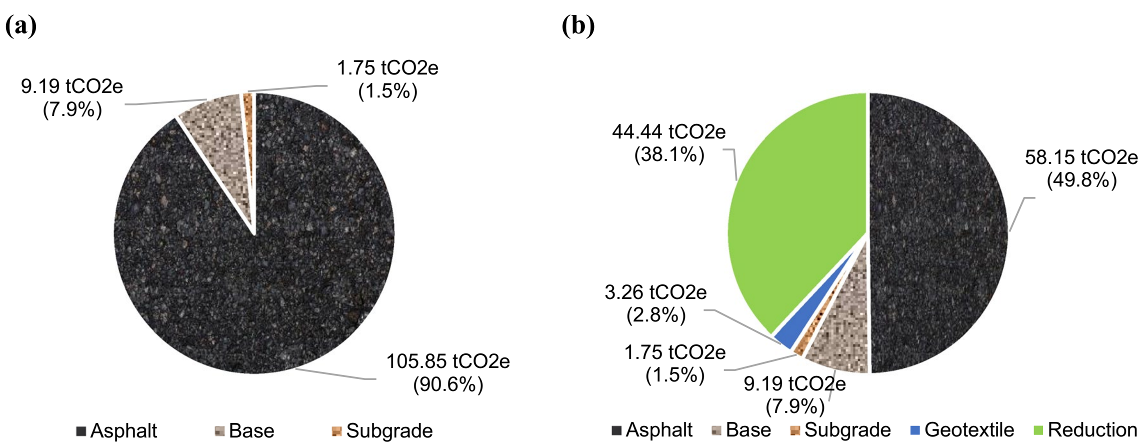

Fig. 13 Carbon audit results for the case study involving reduction of layer intermixing—Contribution of different pavement layers: **a** Conventional design alternative; **b** Geosynthetic design alternative (geotextile separator)

This case study showcases the quantification of the use-stage emissions, B2 and B5 (see Fig. 1), as part of the "Cradle-to-Built" stage by combining the emissions associated with rehabilitation with the initial construction stage to quantify the overall carbon footprint over the design life of the pavement. The scenario discussed here shows a particularly adverse control section that is affected by subgrade pumping and base intermixing issues where the proposed treatment option of mill-and-overlay, which did not address the underlying problem, proved to be an economically and environmentally unsustainable solution. Overall, using a geosynthetic separator resulted in an alternative that proved far more sustainable than the conventional design.

Carbon Audit in Projects Involving Moisture Reduction in Structural Layers

The presence of moisture in any of the various roadway layers is particularly detrimental, compromising their mechanical properties. One way to quantify the impact of increased moisture involves evaluating its effect on the structural number (SN) in the design method proposed by the American Association of State Highway and Transportation Officials (AASHTO) [54]. This method considers the pavement as a multi-layer elastic system, with the overall structural number reflecting the total pavement thickness and its resiliency to repeated traffic loading. The required SN for a project is selected so that the pavement will support anticipated traffic loads and experience a loss in serviceability no greater than that established by project requirements. The SN is penalized by a modifier, *m*, which accounts for the moisture characteristics of each pavement layer. This penalty can be sizable, with values for m ranging from as high as 1.4 for excellent drainage conditions to as low as 0.4 for poor drainage conditions. Or, stated differently, the structural capacity of a roadway with poor drainage conditions is as low as 29% (i.e., the ratio between the extreme modifiers) of that of a roadway with excellent drainage conditions. Designers often overlook the importance of lateral (internal) drainage in a roadway, focusing instead on building thick, high-quality material layers while omitting good drainage features. Unfortunately, moisture trapped under pavement will exacerbate pavement distress by increasing pore pressures and softening the subgrade soil.

Conventional geosynthetic drains include geocomposite drainage products (a combination of geonets and geotextile filters) and geotextiles with comparatively high transmissivity. However, these conventional geosynthetic products can only provide gravity-induced lateral drainage, which is important when the soil adjacent to the geosynthetic has reached saturated conditions. Through advances in geosynthetic manufacturing, such as the development of geotextiles with enhanced lateral drainage (ELD), drainage under unsaturated conditions has also been made possible. These materials have also been referred to as "wicking geotextiles." Zornberg et al. [55] highlight the use of ELD in a number of roadway situations, including (1) enhanced lateral drainage of moisture migrating upward from a high water table, (2) enhanced lateral drainage of moisture infiltrating downward from the surface, (3) control of frost heave-induced pavement damage, (4) control of pavement damage caused by expansive clay subgrades, and (5) enhanced lateral drainage in projects involving soil improvement.

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 (Fig. 14) [55]. This bridge was constructed in 2013 over the Missouri River in St. Louis, Missouri, USA. An existing bridge built in the 1930s had deteriorated beyond repair, and an additional bridge built in the 1980s did not meet traffic requirements. Therefore, the new bridge was built to add capacity for additional traffic. 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 (Fig. 15a). 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. As shown in Fig. 15b, 52 mm of the total regular and drainable base materials were replaced by an in-plane draining geotextile, which also provided separation and subgrade stabilization to the roadway. The geotextile alternative both lowered costs and met drainage requirements. The geotextile extended into the shoulder to an aggregate-covered edge to release moisture. Moisture was either released into trench drains or simply evaporated. Figure 16a illustrates the presence of the geotextile directly over the subgrade and the moisture diversion from the high water table to the edge of the road. Heavy rain occurred several days after the geotextile installation, and moisture was observed to wick to the edge of the roadway, as illustrated in Fig. 16b. The bridge was completed in 2015, and no pavement distress has been observed since then.

The sustainability benefits of using the geotextile drainage design over the conventional aggregate drainage design were evaluated following the carbon audit procedure described in Sect. "Carbon audit methodology adopted in this study". An important difference between the two design alternatives is that the production

Fig. 14 Daniel Boone bridge: Case study involving reduction of moisture in structural layers (Picture courtesy of Tencate/Solmax)

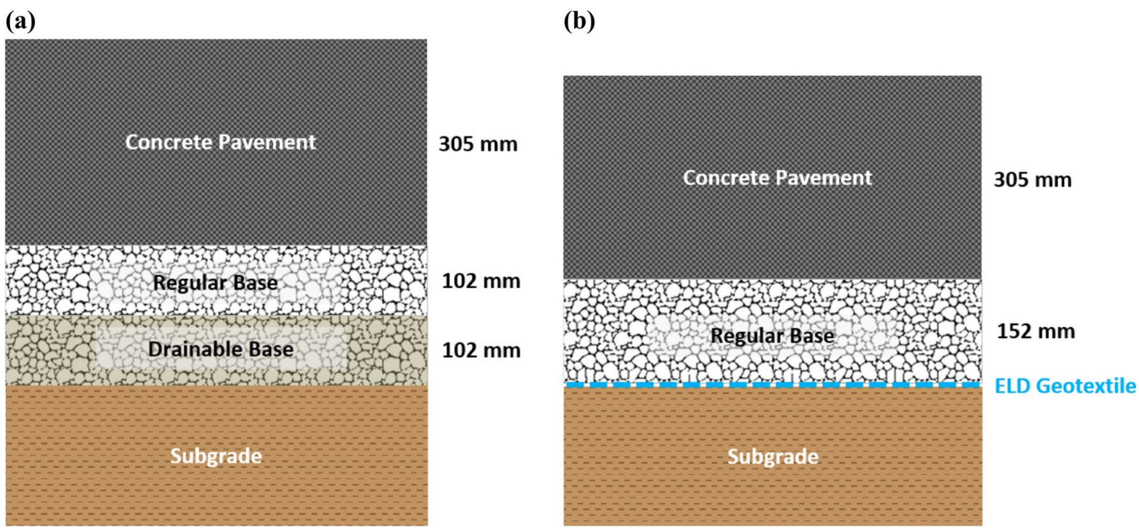

Fig. 15 Cross-sections of the case study involving moisture reduction in structural layers: **a** Conventional design section; **b** Geosynthetic design section (with ELD geotextile)

emissions related to the material identified as "drainable aggregates" are higher than the typical unit value corresponding to regular aggregates due to additional processing (in terms of extraction and screening) necessary to meet the gradation requirements. Furthermore, these aggregates may not be locally available and hence require longer hauling distances, resulting in more fuel consumption for the transportation stage. The average unit prices of drainable and regular aggregates were assumed by considering that they correlate with the energy consumption and the resulting emissions. Therefore, to account for the additional processes required to produce drainable aggregates, the production and transportation emissions of the drainage layer in the conventional (original) design were factored by the unit price ratio between drainable and regular aggregates. The analysis could then be performed considering a transportation distance of 56 km for aggregates and 994 km for the geosynthetics. The results, summarized in Fig. 17, 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 (A4), 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, respectively.

Figure 18 summarizes the contributions of the individual pavement layers, illustrating that the drainable base unit has the highest EC at 27.28 tCO_2e (i.e., 74.7% of the total EC

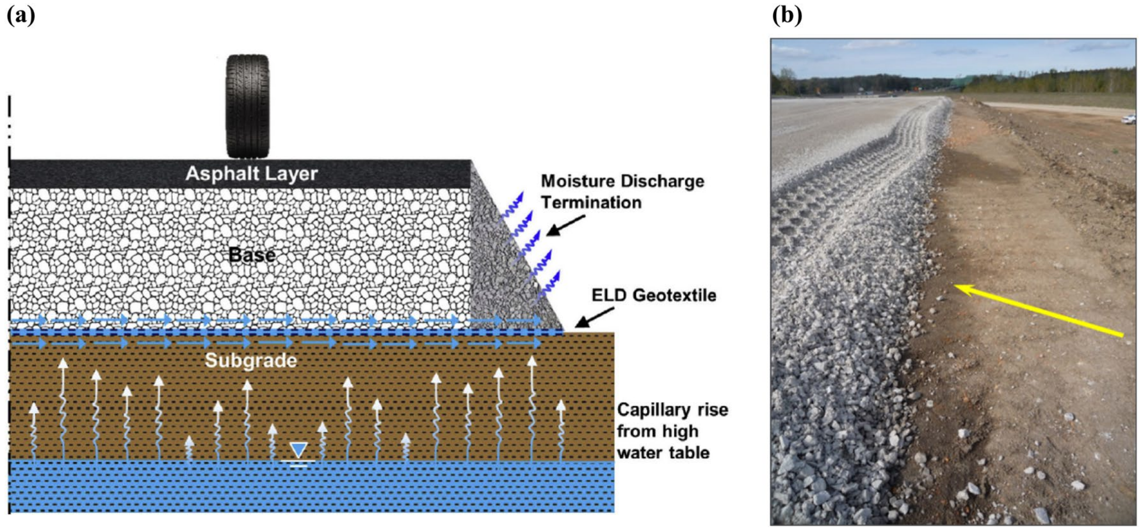

Fig. 16 Case study involving moisture reduction in structural layers: **a** Schematic view of the hydraulic system involving a geotextile with enhanced lateral drainage; **b** View of lateral drainage during construction (Picture (b) courtesy of Tencate/Solmax)

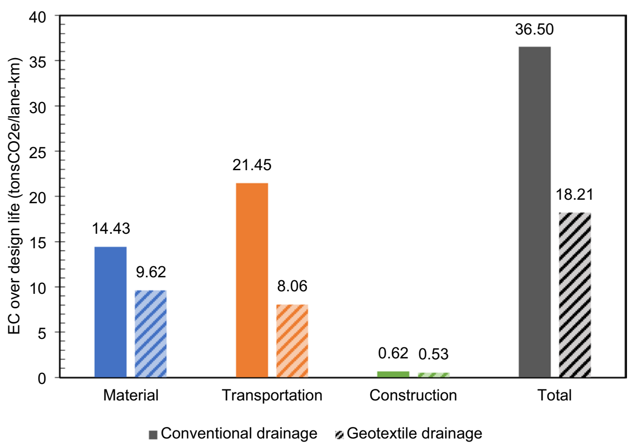

Fig. 17 Carbon audit results for the case study involving moisture reduction in structural layers—Contribution of different phases

of the conventional design), which is a consequence of the high production and transportation emissions required to procure drainable aggregates. The alternative design to a 102-mm drainable base involved a wicking geotextile with an EC of 4.38 tCO_2e and an additional 50-mm-thick layer of regular that increases the total emission by another 4.61 tCO_2e. Overall, the total emissions are reduced by 50.1%, representing a significant improvement compared to the conventional design alternative.

The “Cradle-to-Built" EC of the conventional drainable layer, in this case study, was found to be dominated by the emissions associated with the transportation of the material from the production plant to the site. It should be noted that the analysis presented herein is confined to the drainage system (drainable aggregate vs. wicking geotextile) and does not include the concrete pavement layer, which remained

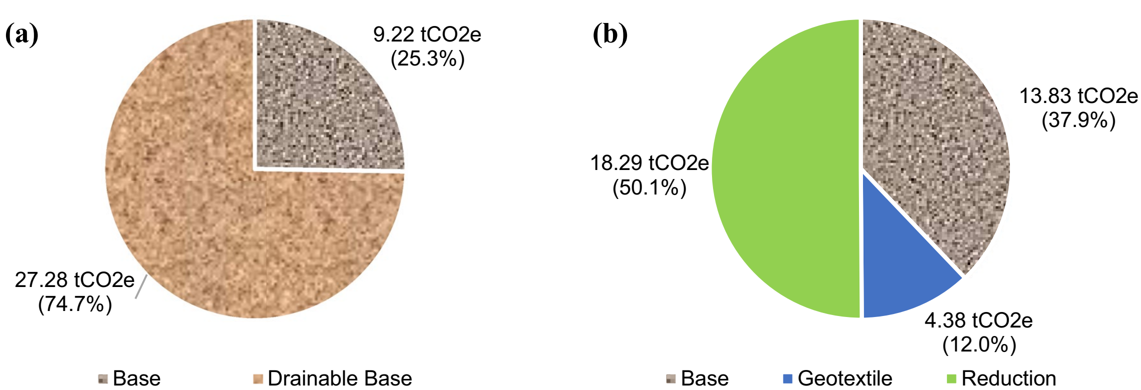

Fig. 18 Carbon audit results for the case study involving moisture reduction in structural layers—Contribution of different pavement layers: **a** Conventional design alternative; **b** Geosynthetic design alternative (geotextile with enhanced lateral drainage)

the same in the two design alternatives. By adopting the alternative design involving the use of ELD geotextiles, the drainable aggregates were no longer necessary, and the subbase aggregate requirements could be met using sustainable local sources.

Carbon Audit in Projects Involving Stabilization of Soft Subgrades

Subgrade stabilization is a relevant roadway application that involves the use of geosynthetics to increase the bearing capacity of soft subgrade soils. The functions of reinforcement, stiffening, separation, and filtration are involved in this application. Among these multiple functions, the reinforcement function leads to an increased bearing capacity of soft foundation soils, while the stiffening function contributes to decreased lateral displacement within the overlying base. The geosynthetic is placed at the interface between the subgrade being stabilized and the overlying granular base. Unlike the stabilization of unbound aggregate layers, the stabilization of soft subgrades involves the mobilization of comparatively large geosynthetic strains and the development of comparatively large rutting depths, which are consistent with those expected in unpaved roads.

The presence of a weak subgrade may lead to the development of localized (punching) shear failure in foundation soils, which creates significant deflections in the various overlying layers of the roadway. This is exacerbated by a stress distribution within the base layer characterized by a comparatively small distribution angle, resulting in a comparatively high contact pressure on top of the subgrade layer [56]. In this application, the geosynthetic acts as a tensioned membrane, at least partly supporting the wheel loads. That is, the geosynthetic develops a concave shape, so the acting tension includes a vertical component that directly resists the applied wheel load. More importantly, the vertical deflection and membrane-induced tension under the wheel path result in the mobilization of soil-geosynthetic interface shear stresses in the portion of the road beyond the wheel path. The tension mobilized by the geosynthetic beyond the wheel path provides control of the subgrade heave between the wheel paths [56]. Ultimately, vertical restraint of the subgrade results in a surcharge that is applied beyond the loaded area. Such surcharge results in vertical restraint that may contribute significantly to an increased bearing capacity in subgrade soils. Subgrade stabilization has been reported to be particularly applicable for projects involving subgrade CBR values below 3 [57]. In addition, stiffening of the base material yields a stress distribution characterized by a comparatively wide angle, leading to relatively low contact pressure on top of the subgrade layer. This is expected to change the shear failure from a localized (punching) shear mechanism in the unreinforced subgrade to a generalized shear mechanism in the reinforced subgrade.

Geosynthetics are often used in subgrade stabilization applications to facilitate initial roadway construction. This is because if the subgrade soils are extremely weak, it may be virtually impossible to begin construction of the embankment or roadway without some form of stabilization. Geosynthetics have proven to be a cost-effective alternative to other foundation stabilization methods such as dewatering, excavation, and replacement with select granular materials, utilization of thicker stabilization aggregate layers, or chemical stabilization [38, 58].

The New International Airport of Mexico City is a major engineering endeavor that was 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. Although there were many components to the design and construction of the airport, this case study focuses on one of the initial construction objectives of the project, which was to prepare and stabilize the ground for construction operations.

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. Clay layer depth extended approximately 80 m, and settlements as high as 1 m were predicted. Figure 19a shows the saturated clay before stabilization, and Fig. 19b illustrates typical hazards during construction on such soft soils.

Construction alternatives included 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 (Fig. 20a), while the geosynthetic-stabilized alternative involved using a geogrid layer overlain by a reduced, 400-mm-thick Tezontle layer (Fig. 20b). In addition, both design alternatives included a non-woven geotextile layer placed directly over the subgrade layer to provide separation and reduce layer intermixing. Figure 19c shows geotextile and geogrid that were laid down to create a construction platform and stabilize soft subgrade, and Fig. 19d shows construction operations proceeding on stabilized ground.

Fig. 19 Case study involving stabilization of soft subgrade: **a** View of the saturated clay at the New International Airport of Mexico City before construction; **b** Evidence of significant problems with low bearing capacity; **c** Placement of geotextile and geogrid to create a working platform and stabilize soft subgrade; **d** construction operations (Pictures courtesy of TDM/Tensar)

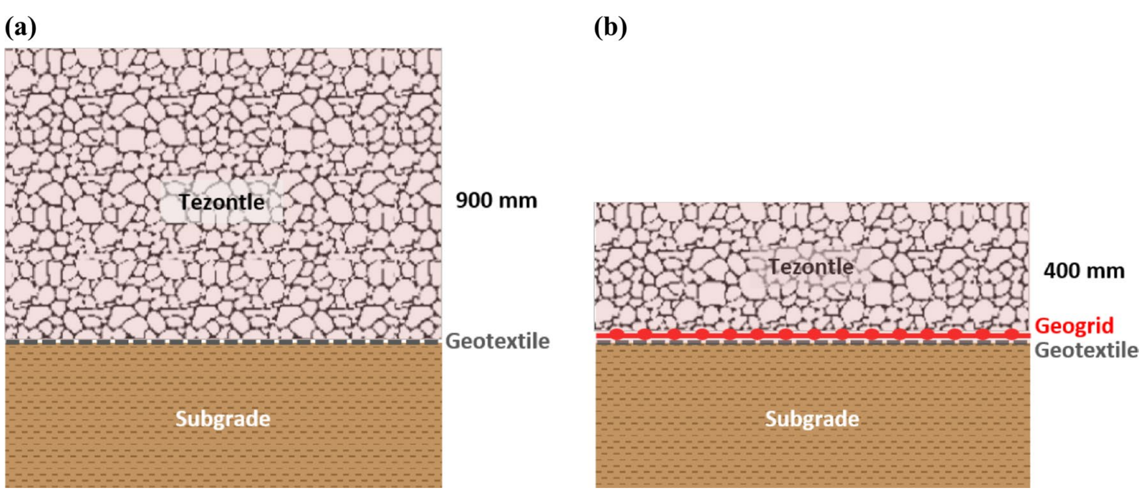

Fig. 20 Cross-sections of the case study involving stabilization of soft subgrades: **a** Non-stabilized design section; **b** Geogrid-stabilized design section

Stabilization of the subgrade was proven to be a timesaving, low-cost alternative to the original design.

The carbon footprints of the two design alternatives were estimated to quantify the sustainability benefits associated with geogrid stabilization of the subgrade and the reduction of the Tezontle layer thickness. The unit emission for the Tezontle aggregate production was assumed to be similar to that of a typical aggregate. The average transportation distance from source to site was determined to be 40 km for Tezontle aggregates and approximately 2969 km for the geosynthetic materials. The results of the carbon audit, presented in Fig. 21, 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%. The main difference, which is associated with the reduction of the Tezontle layer thickness, is shown in Fig. 22. The thickness of the Tezontle layer in the conventional design is reduced by 500 mm, equivalent to a reduction of 23.0 tCO_2e in emissions, with the geogrid application for an increase in emission of 2.90 tCO_2e, resulting in a net EC reduction of 21.09 tCO_2e. Thus, it was found that the geogrid installation was sustainably equivalent to the construction of a 60 mm-thick Tezontle layer, which further highlights the low environmental impact of geosynthetics compared to conventional construction materials.

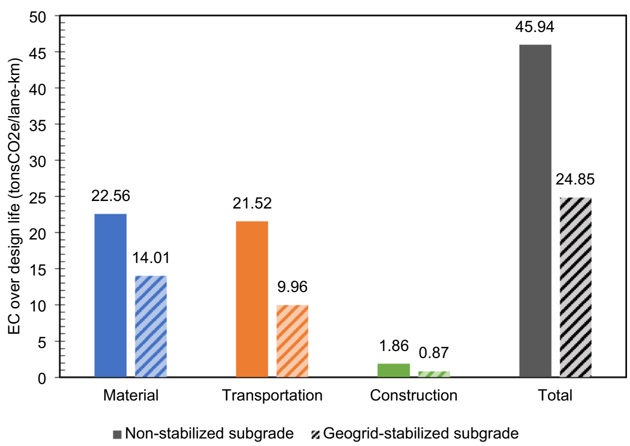

Fig. 21 Carbon audit results for the case study involving stabilization of soft subgrades—Contribution of different phases

As previously discussed in Sect. "Carbon audit methodology adopted in this study", when evaluating a case study involving base stabilization, the inclusion of geosynthetics to stabilize unbound pavement layers such as base, sub-base, or subgrade is expected to be particularly attractive from the sustainability point of view in applications involving unpaved roads. Unpaved roads are characterized by higher stresses and designed for more significant deformations within the unbound aggregate layers, allowing for greater mobilization of the stabilizing geosynthetic. For the same required performance, this results in a substantial reduction in pavement layer thickness when a stabilizing geosynthetic is utilized, resulting in a more sustainable design alternative.

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

Basal stabilization of pavement systems, as previously discussed in Sect. "Carbon audit in projects involving stabilization of unbound aggregate layers", has been used for (i) increasing the lifespan of the pavement while maintaining the thickness of the base course and/or (ii) decreasing the

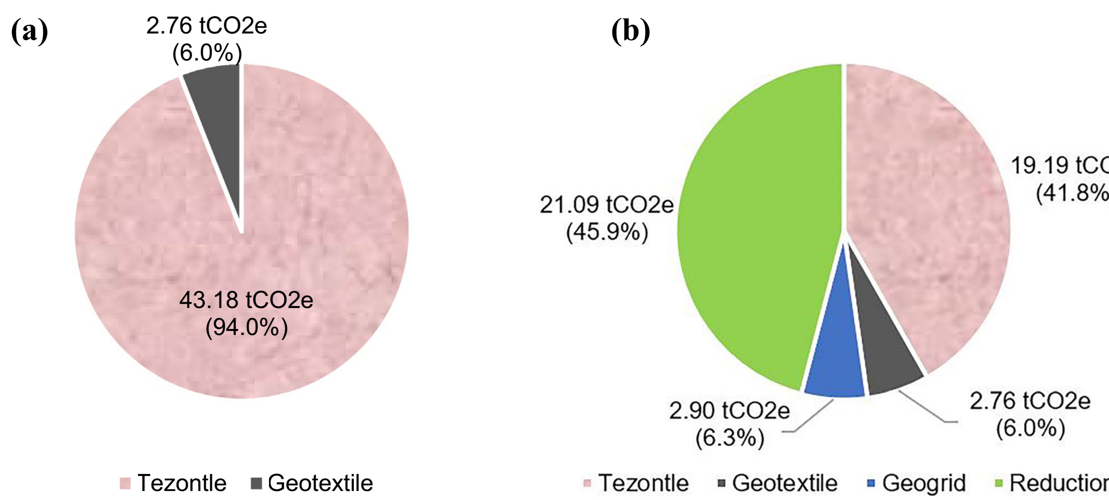

Fig. 22 Carbon audit results for the case study involving stabilization of soft subgrades—Contribution of different pavement layers: **a** Non-stabilized design alternative; **b** Geogrid-stabilized design alternative

thickness of the base course while maintaining the lifespan of the pavement. Another benefit that derives from mechanisms similar to those leading to improved performance of roadways when adopting basal stabilization is the mitigation of longitudinal cracks induced in pavements constructed over highly plastic, expansive clay subgrades [59, 60].

The mechanisms leading to the development of the classical longitudinal cracks are expected to be due to tensile stresses induced by flexion of the pavement during settlements caused during dry seasons. During the dry season, there is a decrease in the moisture content of the soil in the vicinity of the pavement shoulders. This leads to settlements in the shoulder area but not in the vicinity of the central line of the pavement, where the moisture content remains approximately constant throughout the dry season. On the other hand, during the wet season, the moisture content in the soil in the vicinity of the pavement shoulder increases. In this case, the heave occurs in the vicinity of the shoulder area but not in the vicinity of the pavement's central line.

The cracks develop in the region where the moisture front advancing and retreating from the shoulders reaches its maximum penetration under the pavement. Longitudinal cracks have been reported to occur towards the end of dry seasons, which is consistent with this envisioned mechanism. The construction of pavements over expansive clays in regions such as central Texas has often led to poor performance due to the development of longitudinal cracks induced by moisture fluctuations. These environmental conditions are generally not thoroughly evaluated as part of the pavement design, which focuses more directly on traffic conditions. In this application, stabilization of roadways over expansive clay subgrades is accomplished by maintaining integrity of their base and avoiding the conditions leading to crack development.

Farm-to-Market Road 1915 (FM 1915) extends over approximately 32 km from Yarrelton to Davilla 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 at the interface between their subbase and base. Figure 23 shows the cross-sections of the two alternative designs, indicating that 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. While the performance of these and additional test sections constructed in FM 1915 has been discussed by Zornberg and Roodi [61], the focus of this paper is on the evaluation of the carbon footprint and sustainability implications.

The long-term performance of the test sections was documented using data obtained through visual condition surveys. Specifically, the severity and extent of the environmental longitudinal cracks were documented in each condition survey. Geosynthetic-stabilized test sections performed significantly better than the control test section. Pictures illustrating roadway conditions in geosynthetic-stabilized and control test sections are presented in Fig. 24a and b,

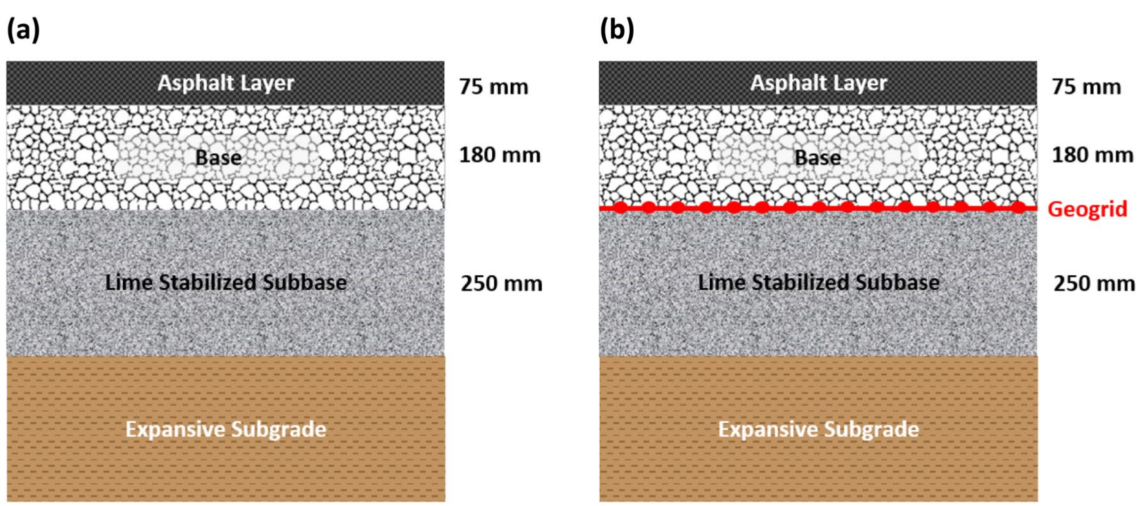

Fig. 23 Cross-sections of the case study involving mitigation of distress caused by expansive clay subgrades: **a** Conventional design section; **b** Geosynthetic design section (geogrid-stabilized base)

respectively. Figure 24c provides the development of longitudinal cracks in the two test sections, which are the type of distress triggered by volumetric changes in the expansive clay subgrade originated by changes in moisture content.

A comparison of the performances of sections constructed using the conventional design and the geogrid-stabilized base revealed that the improved performance of the latter section could easily offset the additional construction cost incurred by incorporating a geogrid layer. Specifically, using a geogrid to stabilize the base layer led to reduced maintenance costs and extended roadway service life. For the purposes of the evaluation presented herein, a percentage of longitudinal cracks of 15% was considered as the design criterion triggering the need for rehabilitation by the construction of an asphalt overlay. This is because the percentage of longitudinal cracks corresponds to the most relevant performance measure for roadways founded on expansive clay subgrades [60, 61]. As indicated by the performance data in Fig. 24c, 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 carbon footprints of the alternative designs shown in Fig. 23 were calculated following the procedure outlined in Sect. "Carbon audit methodology adopted in this study". Transportation distances of 97 km for asphalt materials, 70 km for aggregates, and 1400 km for geosynthetics were considered. For the conventional design alternative (without geogrid stabilization), the emissions resulting from the rehabilitation stage, involving the milling of the initial surface and the construction of a 38-mm-thick asphalt overlay, were added to the initial "Cradle-to-Built" emissions. The results of the carbon audit are presented in Fig. 25 in terms of total emissions, along with the contribution of the various construction stages. For the conventional design alternative, the emissions related to initial construction and rehabilitation are represented in the figure, respectively, with light and dark colors. Instead, rehabilitation is not shown for the geogrid-stabilized alternative, as it was not required during the design life. In addition, it should be noted that the lime-stabilized subbase layer was considered a part of the initial structure, so the emissions corresponding to this layer are not included

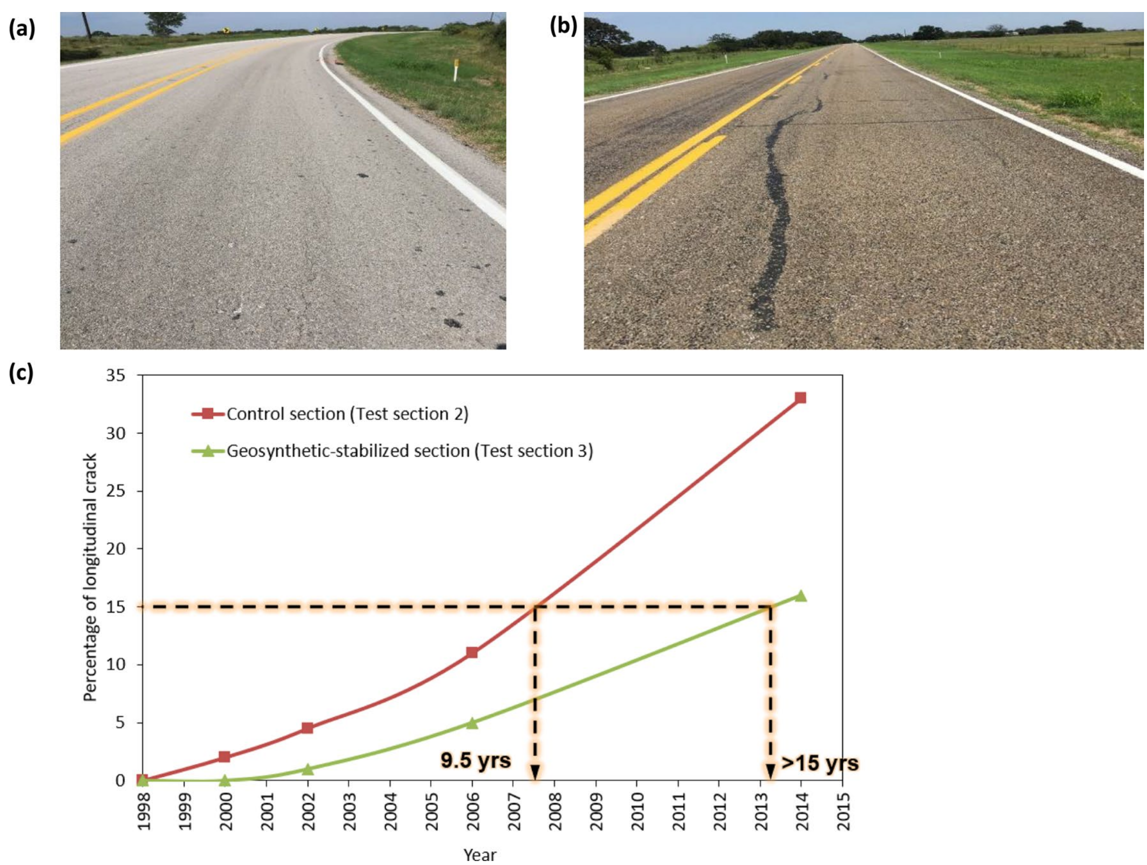

Fig. 24 Case study involving mitigation of distresses caused by shrink/swell subgrades: **a** View of conditions in geosynthetic-stabilized section; **b** View of conditions in control section; **c** Long-term test sections performance data

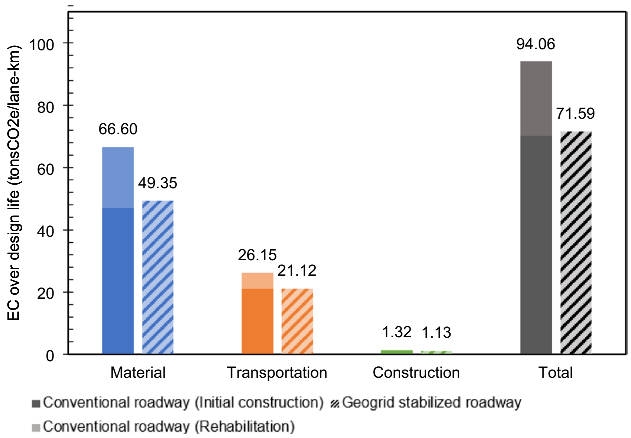

Fig. 25 Carbon audit results for the case study involving mitigation of distresses caused by shrink/swell sub-grades—Contribution of different phases

in these calculations. 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. The comparison between final EC values (i.e., including the rehabilitation stage) for a design life of 15 years shows that geogrid stabilization resulted in reduced EC values. Specifically, the emissions were reduced from 66.60 tCO_2e to 49.35 tCO_2e in the material production stage, from 26.15 tCO_2e to 21.12 tCO_2e in the transportation stage, and from 1.32 tCO_2e to 1.13 tCO_2e in the construction stage. Among these, the most significant reduction is observed in the material production phase, which can be expected considering that geogrid stabilization eliminated the requirement of an overlay consisting of high-EC asphaltic materials. 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. Figure 26 shows the relative contribution of the individual pavement layers for both design alternatives. These results show modest emissions of 2.64 tCO_2e that are attributed to the geogrid layer, with the geogrid alternative ultimately providing a substantial reduction in total emissions by avoiding rehabilitation, resulting in a total EC reduction of 22.47 tCO_2e.

Consistent with the previous discussion on the case study involving the reduction of layer intermixing, this case study also involves the quantification of use-stage emissions since the main impact of adopting a geosynthetic alternative is on the reduced maintenance, requiring evaluation of the design alternatives over the design life period. Using geosynthetics to mitigate the development of longitudinal cracks translates into reduced pavement maintenance and rehabilitation needs. Ultimately, while the original motivation of the alternative design using geosynthetics was to reduce maintenance costs, such geosynthetic alternative design also resulted in substantial savings in carbon emissions over the life of the pavement structure.

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, the comparison between conventional design alternatives and geosynthetic design alternatives evaluated in this study showed that the geosynthetic design

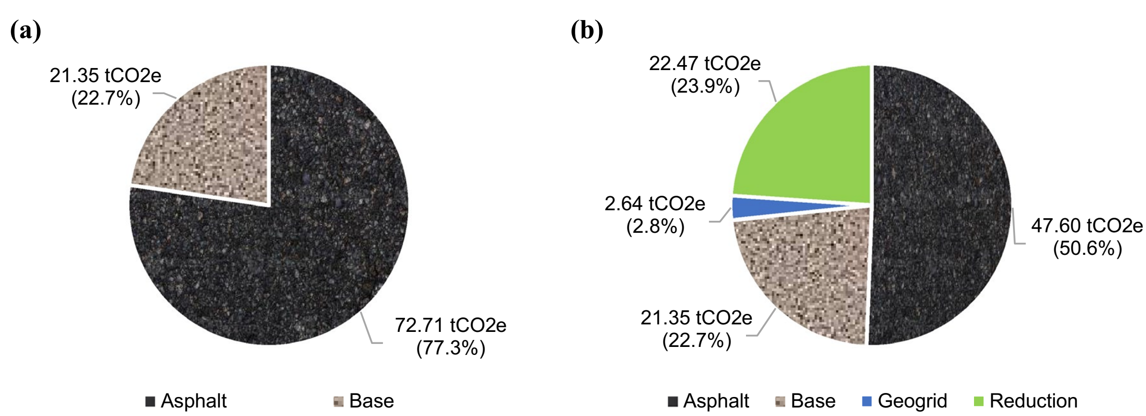

Fig. 26 Carbon audit results for the case study involving mitigation of distresses caused by shrink/swell sub-grades—Contribution of different pavement layers: **a** Conventional design alternative; **b** Geosynthetic design alternative (geogrid-stabilized base)

alternatives consistently provided a lower carbon footprint for six different roadway applications, as follows:

- The use of geosynthetics to mitigate reflective cracking in structural asphalt overlays resulted in a reduced carbon footprint of *21.57* tCO_2e per lane-km (or 32.4% of the carbon footprint for the conventional design alternative).
- The use of geosynthetics to stabilize unbound aggregate layers resulted in a reduced carbon footprint of *29.87* tCO_2e per lane-km (or 11.6% of the conventional alternative carbon footprint)
- The use of geosynthetics to reduce layer intermixing resulted in a reduced carbon footprint of *44.44* tCO_2e per lane-km (or 38.10% of the carbon footprint for the conventional design alternative)
- The use of geosynthetics to reduce moisture in structural layers resulted in a reduced carbon footprint of *18.29* tCO_2e per lane-km (or 50.10% of the carbon footprint for the conventional design alternative)
- The use of geosynthetics to stabilize soft subgrades resulted in a reduced carbon footprint of *21.09* tCO_2e per lane-km (or 45.9% of the carbon footprint for the conventional design alternative)
- The use of geosynthetics to mitigate the distress caused by expansive clay subgrades resulted in a reduced carbon footprint of *22.47* tCO_2e per lane-km (or 23.9% of the carbon footprint for the conventional design alternative)
- 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* based on EPA 2022 inventory [33]—or a forest 2.5 times the area of California. With such potential to reduce carbon footprint, the adoption of geosynthetics in roadways is among the most promising uses of geosynthetics to address the world's sustainability needs.

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Author Contributions The study was conceptualized by Jorge G. Zornberg. Material preparation, data collection, and analysis were performed by S Subramanian, Gholam H. Roodi, Yagizer Yalcin, and Vinay Kumar and supervised by Jorge G. Zornberg. The first draft of the manuscript was written with contributions from all authors and finalized by Jorge G. Zornberg. All authors read and approved the final manuscript.

Data Availability Data sets generated during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of Interests No financial or non-financial interests that are directly or indirectly related to the work submitted for publication.

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