Geosynthetics in roadways: Impact in sustainable development

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ABSTRACT: The world's roadway systems are so extensive that if combined, their total length would encircle the Earth over 1,600 times. Geosynthetics have provided sustainable alternatives in roadway projects, which currently represent a significant portion of the total geosynthetics market. Yet, geosynthetics are still employed in a small fraction of roadway projects worldwide. Accordingly, the opportunities to achieve sustainability benchmarks by increasing the presence of geosynthetics in roadways are, simply, enormous. This paper focuses on six types of applications that can be identified where geosynthetics can be used to improve roadway performance. Each application uses one or more of the various geosynthetic functions, including separation, filtration, reinforcement, stiffening, drainage, barrier, and protection. The applications include the mitigation of reflective cracking in asphalt overlays, separation, stabilization of road bases, stabilization of road soft subgrades, mitigation of environmental loads, and and lateral drainage. This paper illustrates the mechanisms as well as key advances in each one of these multiple applications. In addition, the paper illustrates relevant case histories for each application, which illustrates the relevance their relevance in roadway engineering. The impact of selection of geosynthetics in sustainability for each case history can be quantified by conducting a quantification of the carbon footprint. In addition to address key technical aspects, the solutions provided by geosynthetics also provided significant sustainability benefits.

Keywords: Geosynthetics, roadways, separation, reinforcement, stiffening, filtration, drainage

1 INTRODUCTION

The geosynthetic products most commonly used in roadway systems include geotextiles (woven and nonwoven) and geogrids (biaxial and multiaxial), although erosion-control products, geocells, geonets (or geocomposite drainage products) and geomembranes have also been incorporated in a number of applications. These various types of geosynthetics can be used to fulfill one or more specific functions in a variety of roadway applications. For example, geosynthetics have been in use since the 1970s to improve the performance of unpaved roads on soft subgrade soils. Beginning in the 1980s, geosynthetics were utilized to minimize reflective cracking in asphalt overlays as well as to improve the performance of base aggregate layers.

The terminology used in the technical literature to describe the various applications of geosynthetics in roadway systems and the functions of geosynthetics incorporated into roadway design has not been consistent. This is understandable, as the mechanisms that lead to roadway improvement in each application are complex and often intertwined. Consequently, a framework is presented in this paper that is expected to minimize inconsistencies regarding the terminology used when designing roadways using geosynthetics.

While strongly based on frameworks currently used for geosynthetic design (Koerner 2012), the refined framework proposed herein follows two key premises: (1) Different geosynthetic functions unequivocally correspond to different geosynthetic properties, and (2) Geosynthetic applications correspond to the different types of projects that can be implemented to achieve specific design goals. Each geosynthetic application may involve a single geosynthetic function or a combination of such functions to develop mechanical or hydraulic mechanisms aimed at enhancing the roadway performance.

Fig. 1 shows a paved road section with the location of possible geosynthetic layers and the various functions that these geosynthetics can fulfill. These functions include:

- Separation: The geosynthetic, placed between two dissimilar materials, maintains the integrity and functionality of the two materials. It may also involve providing long-term stress relief. Key design properties to perform this function include those used to characterize the survivability of the geosynthetic during installation.
- Filtration: The geosynthetic allows liquid flow across its plane, while retaining fine particles on its upstream side. Key design properties to fulfill this function include the geosynthetic permittivity (cross-plane hydraulic conductivity per unit thickness) and measures of the geosynthetic pore-size distribution (e.g. apparent opening size).
- Reinforcement: The geosynthetic develops tensile forces intended to maintain or improve the stability of the soil-geosynthetic composite. A key design property to carry out this function is the geosynthetic tensile strength.
- Stiffening: The geosynthetic develops tensile forces intended to control the deformations in the soil-geosynthetic composite. Key design properties to accomplish this function include those used to quantify the stiffness of the soil-geosynthetic composite.
- Drainage: The geosynthetic allows liquid (or gas) flow within the plane of its structure. A key design property to quantify this function is the geosynthetic transmissivity (in-plane hydraulic conductivity integrated over thickness).

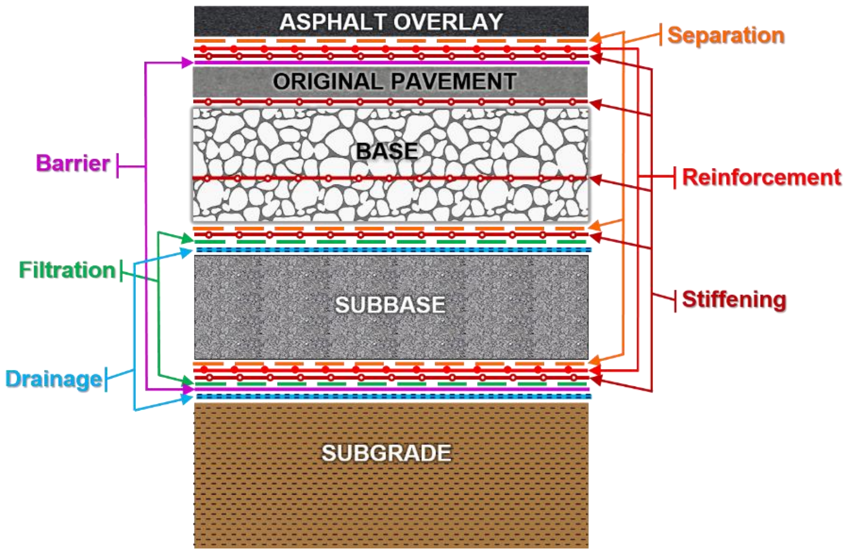

Fig.2. Multiple functions of geosynthetics in roadway applications.

While comparatively less common in roadway applications, additional geosynthetic functions include:

- <u>Hydraulic/Gas Barrier:</u> The geosynthetic minimizes the cross-plane flow, providing containment of liquids or gasses. Key design properties to fulfill this function include those used to characterize the long-term durability of the geosynthetic material.
- <u>Protection:</u> The geosynthetic provides a cushion above or below other material (e.g. a geomembrane) in order to minimize damage during placement of overlying materials. Key design properties to quantify this function include those used to characterize the puncture resistance of the geosynthetic material.

Six of the seven functions listed above have traditionally been reported in the technical literature (Koerner 2012, Zornberg and Christopher 2006). However, a seventh function – stiffening – is additionally considered in this paper. This addition is deemed appropriate to make a clear distinction on whether the mechanical inclusion (i.e. the geosynthetic) is used to develop tensile forces for the purposes of improving system stability or of controlling deformations. While both functions involve mechanical improvements, the properties required to fulfill them are distinctively different.

One or more of the seven aforementioned geosynthetic functions are used to enhance the roadway performance in the following five roadway applications: (1) mitigation of reflective cracking in asphalt overlays; (2) separation; (3) stabilization of road base; (4) stabilization of road subgrade; (5) mitigation of environmental loads-induced distress; and (6) lateral drainage. This list is limited to applications of geosynthetics within a roadway section. Consequently, it does not include transportation applications aimed at enhancing the roadway performance but that involve components that are beyond the roadway section. Such applications, including trench drains, erosion control elements and surface water management features, are discussed by Holtz et al. (2008) and Zornberg and Thompson (2010).

Table 1 identifies a total of five roadway applications involving geosynthetics. For each of the five roadway applications, the table identifies the design objectives, relevant mechanisms, the primary and secondary geosynthetic function(s) involved in the application and the implications in roadway performance. A summary is provided next in this paper regarding each one of these roadway applications.

Table 1. Summary of roadway applications involving geosynthetics.

Application	Objective	Mechanism	Geosynthetic Functions		Implications in Roadway Performance
			Primary	Secondary	
Mitigation of reflective cracking in asphalt overlays	Retard or eliminate reflective cracking in asphalt overlays	Reduction of stress concentration in asphalt overlays in the vicinity of pre-existing cracks	Reinforcement	Stiffening Barrier Separation[1]	Reduced impact of degradation mechanisms in asphaltic layers that are caused (or accelerated) by water intrusion
Separation	Avoid contamination of aggregate base material with fine-grained subgrade soils	Minimized loss of aggregate particles into the subgrade and migration of fine-grade particles into the base layer	Separation	Filtration	Minimized time-dependent decrease in base layer thickness and in the quality of the aggregate base material
Stabilization of road bases	Minimize a time-dependent decrease in the modulus of the aggregate base material	Lateral restraint, which involves minimizing the time-dependent lateral displacements of aggregate base material	Stiffening		Minimized lateral displacements in the base aggregate material. This facilitates maintaining the original (comparatively high) aggregate confinement and, consequently, maintaining the original (comparatively high) aggregate modulus that results in a comparatively wide distribution of vertical loads and decreased base-subgrade contact stresses
Stabilization of road soft subgrades[2]	Increase the bearing capacity of subgrade soils	Development of membrane-induced tension under the wheel path and of soil-geosynthetic interface shear transfer beyond the wheel path	Reinforcement[2]	Stiffening Separation Filtration	Decreased vertical stresses in the subgrade under the wheel path, and beneficial redistribution of shear and normal stresses beyond the wheel path
Mitigation of environmental load-induced distress	Minimize the development of longitudinal cracks due to differential volumetric changes induced by conditions such as the presence of expansive clays	Differential movements occurring along the transversal section of the road	Stiffening	Separation	Minimized generation of longitudinal cracks induced during dry seasons due to often significant settlements of the road shoulders in relation to the road centerline. This in turn avoids moisture infiltration and subsequent degradation of the roadway materials
Lateral drainage	Minimize the accumulation of moisture within the base and subgrade materials	Gravity-induced lateral drainage (for saturated conditions) and suction-driven lateral drainage (for unsaturated soil conditions)	Drainage (in-plane)	Filtration Separation	Minimized generation of positive pore water pressures (for saturated conditions) and decreased soil moisture content (for unsaturated conditions). This in turn avoids moisture-induced reduction of shear strength and modulus, both in the aggregate base and in the subgrade materials

Notes: [1] The "stress relief" reported as a possible mechanism in some applications is considered herein as a "separation" function.
[2] The same geosynthetic used for the application of "stabilization of road soft subgrades," with reinforcement as primary function, also results in "stabilization of road bases." Note that "stiffening" is the primary function of the geosynthetic in the latter application.

2 SUSTAINABILITY BENEFITS AND QUANTIFICATION IN ROADWAY PROJECTS INVOLVING THE USE OF GEOSYNTHETICS

In roadway projects involving geosynthetics, sustainability of the roadway structure can be determined by measurement of the total mass of greenhouse gases as CO_2 equivalent (CO_2e) emitted in association with the construction and maintenance of the roadway. The assessment of the CO_2e emitted is carried out using Embodied Carbon (EC) values.

The concept of EC provides a measure of the cumulative CO_2e emissions during the various phases (extraction, production, transportation, installation, operation and disposal) of the product concerned. 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 compacted asphalt mix placed on a roadway would 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, EC of a product is a cumulative function of the concerned phase in the life cycle of the product.

The sustainability benefits of using geosynthetic solutions in roadway construction can be quantified in two different ways. The first, and the more straight-forward, approach is to compare the embodied carbon of equivalent pavement structures at the end of construction. Equivalent pavement structures are those structures that have different structural components but the same expected performance and maintenance over the design period. For instance, in the case of base stabilization, a traditional unreinforced pavement structure could be equivalent to a reinforced structure with a thinner base layer. Both structures are expected to handle a certain volume of traffic, over a certain period, while maintaining a desired level of serviceability and are hence equivalent. However, the embodied carbon of the two equivalent structures is different owing to the different type and volume of materials used. Since maintenance is expected to be the same between the equivalent structures, the difference in embodied carbon value remains constant from the end of construction to the end of design life and is quantified as the sustainability benefit of using geo-synthetic solutions in pavements.

The second approach, to quantify the sustainability benefits, can be used when maintenance data is available for the traditional and geosynthetic solutions. In this scenario, the maintenance required, to maintain a desired level of serviceability over the design period of the pavement structure, with and without the geosynthetic (all other factors remain the same) is monitored. The emissions from the maintenance operations is added to the embodied carbon values at the end of construction (which are quite similar between the two pavement structures), to determine the end of design life embodied carbon. Since, the level of maintenance required to sustain the desired serviceability is different between the traditional and reinforced pavement structures, the embodied carbon of the two pavement structures at the end of design life is different. This difference is quantified as the sustainability benefit of using geo-synthetic solutions in pavements.

Some of key areas that contribute to the reduced carbon footprint of geosynthetic-enhanced pavements are:

- Material Volume – Geosynthetic-enhanced pavements tend to have a reduced profile than their traditional counterparts. The lesser volume of material used results directly in lesser embodied carbon of the constituent materials in the final structure
- Material Type – Geosynthetic-enhanced pavements usually allow the use of poorer quality in-situ materials while traditional systems require higher grade construction aggregates which may not be locally available and have higher embodied carbon.
- Haulage – Because of the use of lower volumes of construction materials or locally available poorer quality materials, the total haulage of all materials for the project is usually lower in the case of geosynthetic-enhanced pavements.
- Maintenance – In case of equal structures with and without geo-synthetics, the enhanced structure is often less maintenance intensive than the traditional structure, resulting in reduced overall embodied carbon at the end of the design life of the structure.

3 MITIGATION OF REFLECTIVE CRACKING IN ASPHALT OVERLAYS

The prevention of reflective cracking in asphalt overlays was one of the earliest applications involving geosynthetics in paved roads. Reflective cracks can occur in new flexible pavement overlays where pre-existing cracks are located within the old paved road. 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 (Button and Lytton 2003).

Fig.3(a) shows the development of stresses resulting from lateral movements induced by flexing of the paved road 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 functions, including reinforcement, separation (or protection) and barrier (Perkins et al. 2010). Accordingly, the geosynthetic can act:

- By developing tensile forces in the vicinity of the crack tip, thereby reducing stresses and strains in the bituminous material. This reinforcement function has been achieved using polymeric, steel or glass grids.
- By providing a layer that allows horizontal deformations so that potentially large movements can develop without failure in the vicinity of pre-existing cracks. This mechanism has been referred to as

stress absorbing membrane interlayer, often involving bitumen-impregnated non-woven geotextiles and can be characterized as a controlled de-bonding.

- By providing a hydraulic barrier function to waterproof the roadway structure, even after the reappearance of a crack in the road surface. This mechanism has also involved the use of bitumen-impregnated non-woven geotextiles.

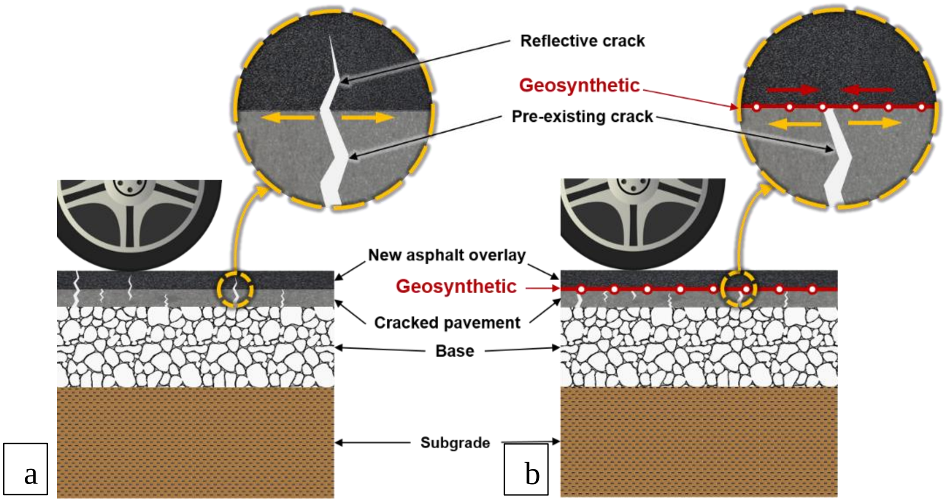

Fig.3. Use of geosynthetics in mitigation of reflective cracking in asphalt overlays: (a) roadway designed without geosynthetics, (b) roadway designed with geosynthetics.

The use of a geosynthetic to fulfill a reinforcement function at the interface between the surface of an old pavement surface and a new overlay is shown in
Fig.3(b). The figure illustrates the geosynthetic tensile forces that can halt the progression of reflective cracking. Montestruque (2002) conducted laboratory tests on reinforced and unreinforced asphalt concrete beams to investigate the use of geosynthetic reinforcement in pavement overlays. Geogrids and a non-woven geotextile were used as reinforcements. Results indicated better performance of the geogrid-reinforced specimens, as compared to the geotextile-reinforced and unreinforced specimens. More recently, Correia and Zornberg (2015) reported that the use of geosynthetics as reinforcement in asphaltic layers can not only mitigate the development of reflective cracks, but can also increase the structural capacity of a paved road.

A relevant case study is presented next, which involves rehabilitation of an airport apron as well as its runway and taxiway. The project location is the Nacala Airport in Nampula Province in Northern Mozambique. After more than 30 years of operation, the condition of the previous pavement had deteriorated and several cracks were observed on the pavement surface (Figure 3a). In addition, a comparatively higher and heavier traffic had been projected at this airport that could exceed the structural capacity of the old runway. The new airport had to be designed for an annual volume of 500,000 passengers and 5,000 tons of air cargo. Specifically, the runway needed to have the load capacity for jumbo cargo and passenger airplanes such as Boeing 747.

Additional financial and sustainability concerns made the new pavement design particularly challenging. Specifically, due to unavailability of local sources for suitable material for the base course, procurement and transportation of off-site aggregates not only could impose particularly high financial costs to the project, but also could result an environmental toll in terms high CO_2 emission. An alternative solution was to use a locally available soil in the region such as red sands, which is widespread across Mozambique, with chemical treatment. Availability of two cement factories in the city of Nacala made this alternative particularly suitable. However, the comparatively high load bearing capacity required for the airport pavement, needed the red sand to be treated with relatively high percentage of cement (6 %). The high percentage of cement in the cement-treated base layer associated with a high risk for formation of post-treatment (shrinkage) cracks in the base, which could then be reflected into the asphalt concrete surface layer.

Eventually, a geosynthetic reinforcement was adopted in the asphalt concrete layer (Figure 3b) to mitigate the risk of reflective cracking into the pavement surface and also to strengthen the asphalt layer. A comprehensive evaluation of this alternative design revealed significant cost saving and sustainability benefits as compared to other alternative solutions. Reconstruction of Nacala airport was one of the first projects in the African continent to adopt geosynthetic reinforcement technique in a new pavement construction.

Fig.3. Case study involving mitigation of reflection cracks: (a) Cracks in the Nacala airport runway before remediation; (b) Installation of geosynthetic reinforcement over asphaltic concrete layer

4 SEPARATION

Geosynthetics were first used in roadway applications solely to fulfill the function of separation. In this application, a geosynthetic is placed between two layers of soil with different particle-size distributions. Indeed, a major cause of failure of roadways constructed over soft foundations is the contamination of aggregate base material with the underlying soft subgrade soil (4(a)). Contamination occurs due to: (1) penetration of the aggregate into the weak subgrade due to localized bearing capacity failure under wheel-load induced stresses, 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 mixing of the subgrade and aggregate base course.

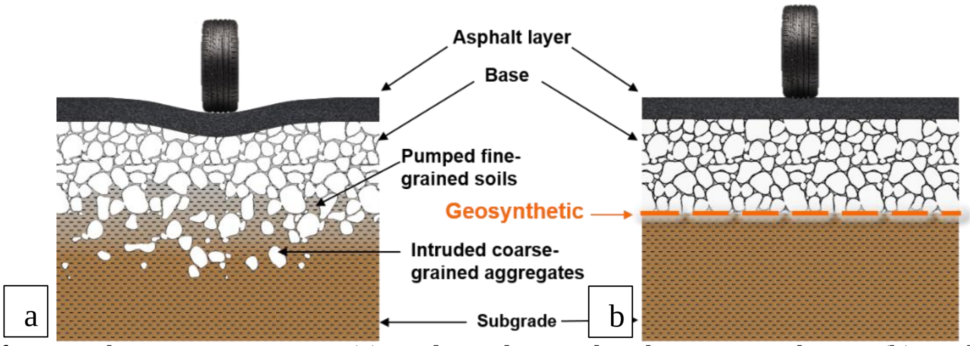

Fig. 4. Use of geosynthetics in separation: (a) roadway designed without geosynthetics, (b) roadway designed with geosynthetics.

Even a small amount of fines contaminating a granular layer can negatively affect its structural response, including 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. Use of a geosynthetic separator is comparatively inexpensive and may result in significant cost savings over the design-life of the roadway (4 (b)). 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 (2012) and Holtz et al. (1997, 2008).

Al-Qadi et al., (1997) investigated the separation application of geosynthetics by constructing full scale test sections. Nine different test sections were constructed, three unreinforced control sections (1, 4, 7), three reinforced with geosynthetic (2, 5, 8), and three reinforced with geogrid (3, 6, 9). Geosynthetic reinforcement was placed between subgrade and base layers, and base course thicknesses varied: sections 1-3 were 10 cm, sections 4-6 were 15 cm, and sections 7-9 were 20 cm. Test sections were heavily instrumented with earth pressure cells, strain gauges, soil moisture blocks, and thermocouples. The subgrade was classified as an ML and CH according to the USCS classification scheme, and an A-7-6 by the AASHTO classification scheme. The base course material was a VDOT class 21-B limestone aggregate, and a chip seal layer was placed and compacted over the base course before two HMA layers were placed.

Over the lifetime of the test sections rut depth measurements were taken and falling weight deflectometer (FWD) tests were performed. FWD results indicated that geotextiles enhanced the pavement performance. Furthermore, rut depth measurements were found to be highest for unreinforced sections (which failed) and substantially lower for geotextile and geogrid reinforced sections. Ground penetrating radar (GPR) was used to create profiles of the base-subgrade interface. GPR data indicated lighter areas consistent with higher reflections, and higher reflections may result from higher moisture content or from soil migration.

The moisture content was the same in the three sections and in turn it is reasonable to conclude lighter areas are representative of a transition intermixing layer. Visual inspection of GPR profiles of the different test sections indicates geotextiles did not possess transition layers like those observed in control and geogrid sections. It may be concluded that geotextile separation inhibits the formation of a transition intermixing layer which may compromise the structural integrity of the pavement.

5 STABILIZATION OF ROAD BASES

Base stabilization can be defined as the roadway application where geosynthetics are used to maintain the stiffness of the base aggregate materials. Stiffening is the primary (and sole) function leading to decreased lateral displacements within (and increased confinement of) the aggregate-geosynthetic composite. As stated previously, key design properties to fulfill this function involve those quantifying the stiffness of the soil-geosynthetic composite.

While the geosynthetic could be placed within the base layer, the typical placement location to facilitate constructability is at the interface between the base being stabilized and the underlying subgrade. As will be discussed in the subsequent section, this is also the location where geosynthetics are placed for subgrade stabilization. Consequently, it is possible that a geosynthetic used for base stabilization may also serve for subgrade stabilization. However, base stabilization can be achieved for a wide range of roadway deformations, including comparatively small levels consistent with those in paved roadways, while base stabilization requires mobilization of comparatively large roadway deformations, consistent with those that develop in unpaved roads.

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 of particular significance in the lower portion of the base layer, directly below the wheel path, where tensile stresses are more prone to develop. 5(a) illustrates the lateral displacements that may develop within the base layer. The displacements result in decreased lateral stresses (i.e. decreased confinement) of the aggregate, which significantly impact the modulus of the base material. 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 base-subgrade interface. Traffic-induced degradation of the original modulus in the aggregate results in increasing contact pressures at the base-subgrade interface and eventually high rutting depths in the roadway structure.

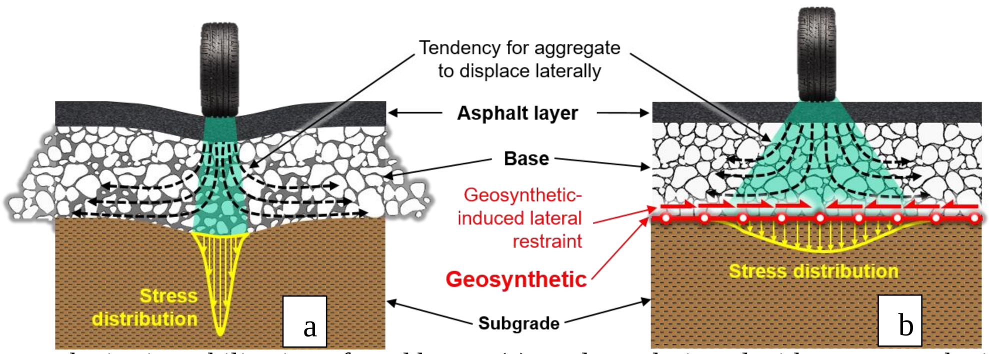

Fig. 5. Use of geosynthetics in stabilization of road bases: (a) roadway designed without geosynthetics, (b) roadway designed with geosynthetics.

Fig. 5(b) illustrates the restrain to lateral displacement provided by the geosynthetic inclusion. Interaction between the base aggregate and the geosynthetic results in 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 achieve stabilization of the base layer. In addition, the geosynthetic's own tensile stiffness also contribute to limit the development of lateral strains. Consequently, a geosynthetic with comparatively high stiffness is required to achieve stabilization of the base. Zornberg and Gupta (2010) identified a parameter, the stiffness of the soil-geosynthetic composite, which accounts for both the interface shear strength at the soil-geosynthetic interface and the geosynthetic stiffness. The increased confinement provided by the geosynthetic layer in the base course material leads to an increase in the mean stresses, leading also to an increase in the shear strength of the aggregate. 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 properly selected. On the other hand, when geotextiles are selected for base stabilization, proper interface frictional capabilities should be provided. As also illustrated in Fig. 5(b), the comparatively higher modulus of the geosynthetic-stabilized base results in a wide distribution of vertical traffic loads and in comparatively smaller vertical stresses acting at the base-subgrade interface.

The reconstruction of Interstate 90 near Ashtabula, Ohio, USA, represents a good example illustrating a base stabilization application. The project involved reconstruction of a section of the Interstate Highway 90 (I90), located in Ashtabula, Ohio, US. The Ohio department of transportation (ODOT) had to remove the existing pavement structure and layers of subgrade, add additional lanes to the highway in both directions, and reconstruct the entire pavement. The lake-effect snow that had resulted from proximity of the project site to Lake Erie made the construction window particularly short. Thus, an innovative design that could minimize the construction time was significantly important. The original design by ODOT involved an undercut of 900 mm (36 inches) to be replaced by 300 mm (12 inches) of AASHTO #2 stone overlain by 300 mm (12 inches) of smaller size aggregate and 300 mm (12 inches) of asphalt section. However, incorporation of a geosynthetic layer in the design led to significant sustainability and construction benefits in the project.

Specifically, installation of a biaxial geogrid beneath the AASHTO #2 stone layer reduced the undercut to 450 mm (18 inches) (Figures 6a and 6b). Therefore, the amount of aggregate used on the project was cut in half resulting in significant saving as well as sustainability benefits. In addition, replacement of 18 inches of aggregate by a geosynthetic stabilization layer resulted a significantly shorter construction time. Specifically, the contractor could complete the project in two thirds the time originally anticipated, which resulted additional savings in labor, equipment, traffic control, and logistic costs in the project.

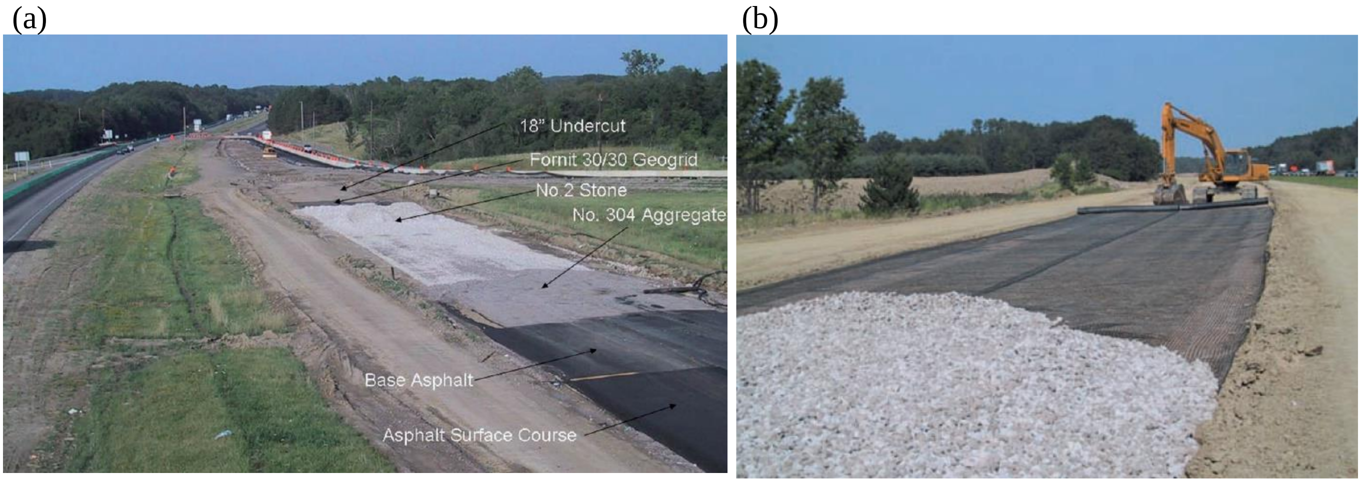

Fig.6. Case study involving based stabilization: (a) Various roadway layers in I90 reconstruction project; (b) Installation of geosynthetic during reconstruction

6 STABILIZATION OF ROAD SUBGRADES

Subgrade stabilization is defined herein as the roadway application involving 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 base. Accordingly, a key design property for the reinforcement function is the geosynthetic tensile strength. It should be noted, though, that the stiffening function, which requires quantification of the rigidity of the soil-geosynthetic composite, is also relevant to complement stabilization of the subgrade with that of the base.

The geosynthetic is placed at the interface between the subgrade being stabilized and the overlying granular base. As previously indicated, it is then the case that a geosynthetic used for subgrade stabilization also provides stabilization to the overlying base material, as discussed in the previous section of this paper. This exemplifies use of a single geosynthetic for two applications: subgrade stabilization (to increase the subgrade bearing capacity) and base stabilization (to control lateral displacement of base material and consequently maintain a comparatively high base stiffness). However, subgrade stabilization 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. In contrast, base stabilization is mobilized for comparatively small geosynthetic strains and the corresponding small rutting depths, which are in line with those expected for paved and unpaved roads.

As illustrated in Fig. 7(a), 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 comparatively narrow angle in the stress distribution within the base layer, which in turn results in a comparatively high contact pressure on top of the subgrade layer (Giroud and Han 2004). Fig. 7(b) illustrates the impact that incorporating a geosynthetic reinforcement can have on the bearing capacity of subgrade soils. 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 results in 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 (Giroud and Han 2004). 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. High deformations (i.e. high rutting depth), which are consistent with those acceptable only in unpaved roads, are required to mobilize this mechanism. Subgrade stabilization has been reported to be particularly applicable for projects involving subgrade CBR values below 3 (Barksdale et al. 1989). 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.

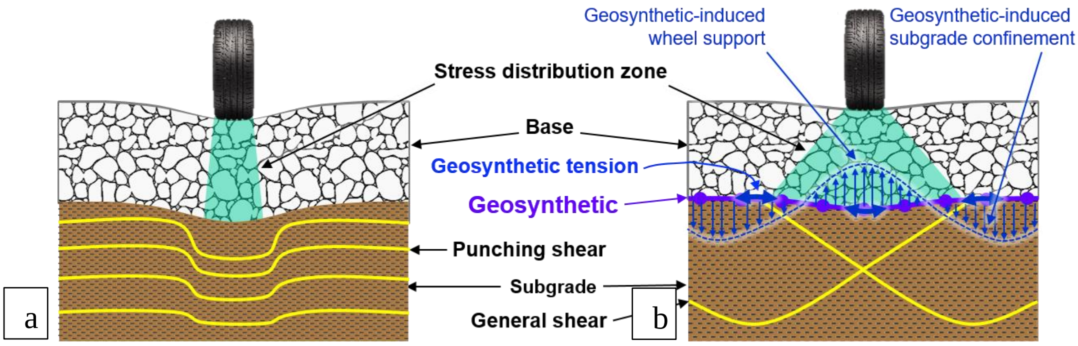

Fig. 7. Use of geosynthetics in stabilization of road subgrades: (a) roadway designed without geosynthetics, (b) roadway designed with geosynthetics.

Geosynthetics have often been used in subgrade stabilization applications to facilitate construction. 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 de-watering, excavation and replacement with select granular materials, utilization of thicker stabilization aggregate layers, or chemical stabilization (Perkins et al. 2010, Christopher 2014). The use of stabilizing geosynthetics enables contractors to meet minimum compaction specifications for the first few aggregate lifts. Even in cases where the stabilization application is primarily selected for initial construction, geosynthetics will provide long-term benefits and improve the performance of the road over its design-life.

The New International Airport of Mexico City is a major engineering endeavor that seeks to construct an airport capable of sustaining 70 million passengers and 540,000 landings and take-offs yearly. The airport will be located 15 km from city center over the former lake Texcoco and will occupy over 40 million square meters of surface area. Because of the presence of soft lacustrine clay, the soil is saltier than seawater and sinking at a rate of 1.5 to 2 cm a month. Chemical stabilization is not a viable alternative because of the presence of volcanic basalt, and other traditional methods to stabilize the ground have not succeeded. Preliminary trials using geosynthetics however have shown to be a technically feasible low-cost alternative to stabilize the subgrade.

Although there are many components to the design and construction of the airport, this case study will focus on the first construction objective of the airport: to prepare and stabilize the ground for construction operations. Clay extends roughly 80 m into the ground from the surface, and settlements as high as 1 m are expected. Initial construction will place a combination of geomat, geotextile, and tezontle (a local volcanic rock often used in construction in Mexico) to stabilize the ground.

To achieve proper stabilization, substantial amounts of geosynthetics are required including upwards of 10 million square meters of geotextile. Figure 8a shows the saturated clay before stabilization, and Figure 8b shows the hazards to construction it poses. Figure 8c shows geotextile that has been laid down to create a platform from which construction may proceed, and Figure 8d shows construction operations proceeding on stabilized ground. Although the airport is nowhere near completed, geosynthetics have proven to be a time-saving low cost alternative to the construction of the New International Airport of Mexico City.

(a) (b) (c) (d)

Fig.8. Case study involving subgrade stabilization: (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 to create a working platform; (d) construction operations

7 MITIGATION OF ENVIRONMENTAL LOAD-INDUCED DISTRESS

Basal stabilization of pavement systems has been used for the purposes of: (i) increasing the lifespan of a pavement while maintaining the thickness of the base course, and (ii) decreasing the thickness of the base course while maintaining the lifespan of the pavement. Another benefit that derives from mechanisms similar to those leading to an improved performance of roadways when adopting basal stabilization is the mitigation of longitudinal cracks induced in pavements constructed over highly plastic, expansive clay subgrades has been proposed (Zornberg et al. 2010).

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. Figure 9 illustrates the envisioned mechanism that leads to the development of longitudinal cracks. During the dry season, there is decrease in the moisture content of the soil in the vicinity of the pavement shoulders (Figure 9a). 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 (Figure 9b). In this case, heave occurs in the vicinity of the shoulder area, but not in the vicinity of the pavement central line.

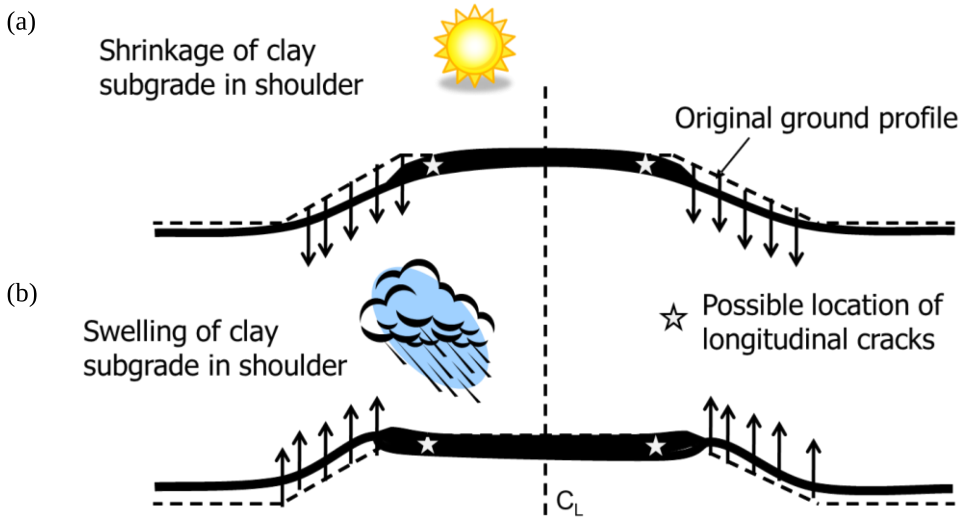

Figure 9: Mechanism of longitudinal crack development on pavements over expansive clays

The cracks are developed 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 development of longitudinal cracks induced by moisture fluctuations. These environmental conditions are generally not fully evaluated as part of the design of pavements, which focuses more directly on traffic conditions. In this application, stabilization of roadways over expansive clay subgrades is accomplished by rigidizing their base and avoiding the conditions leading to crack development.

Farm-to-Market Road 1915 (FM 1915) is extended for approximately 32 km from Yarrelton to Davilla in Milam County, Texas. A section of this road has been founded on a high expansive clay subgrade and had been reported to have extensive damages particularly in form of longitudinal cracks. As part of the efforts conducted by the Texas Department of Transportation (TxDOT) in 1996 to rehabilitate the damaged section of FM 1915, three 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 begin at the Little River Relief Bridge, approximately 9.8 km south of the intersection with highway 190, and extend south for 4 km. As presented in Figure 1, the test section located in the middle (Section 2) was constructed as a control section (without geosynthetic) and test Sections 1 and 3 were constructed using a biaxial geogrid at the interface between their subbase and base. Test Sections 2 and 3 had the same base thickness of 180 mm, however, test Section 1 had a reduced base thickness of 130 mm.

Long-term performance of the three test sections has been documented using data obtained through visual condition surveys. Specifically, severity and extent of the environmental longitudinal cracks were documented in each condition survey. Overall, both geosynthetic-stabilized base test sections (i.e., test Sections 1 and 3) were found to perform significantly better than the control test section (i.e., test Section 2). Example pictures from road conditions in test Sections 1 and 2 that have been taken during condition surveys are presented in Figures 2 and 3. TxDOT construction and maintenance database was also explored to determine the initial construction cost as well as the lifetime maintenance costs corresponding to each test section.

This case study provided a unique opportunity for evaluating the benefits from geosynthetic inclusion from two perspectives. Comparison between the performances of the test Sections 2 and 3, which were constructed using the same design profiles but without and with geosynthetic, respectively, provided relevant information on how additional cost for including geosynthetic could be offset by the improved performance of the roadway, thus, reduced maintenance costs and extended service life of the roadway. On the other hand, comparison between test Sections 1 and 2, provided insight into how reduction of the base course thickness due to the inclusion of the geosynthetic (in test Section 1) could affect the initial cost of construction for this section as well as corresponding future performance and maintenance costs.

(a)

(b)

(c)

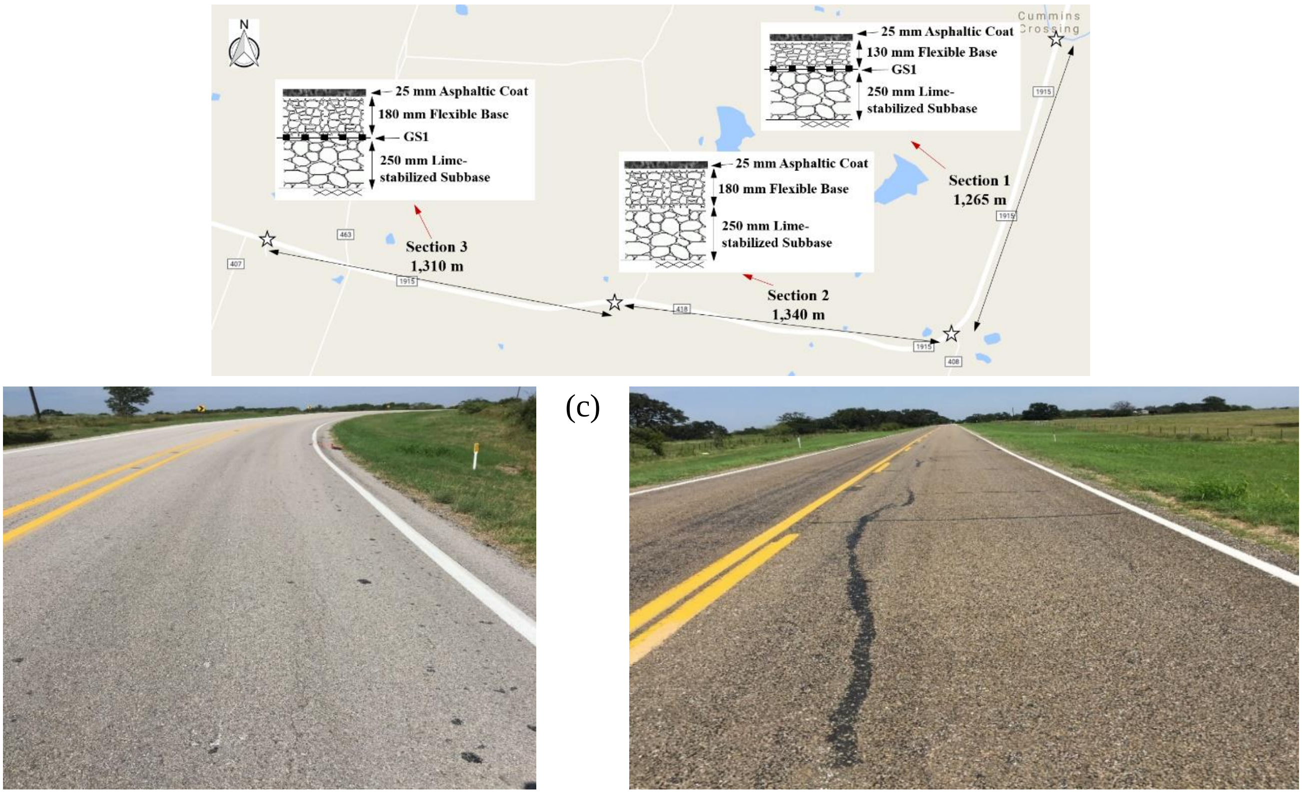

Figure 10: Mitigation of environmental load-induced distress: (a) Layout and design of the test sections at FM1915; (b) View of conditions in geosynthetic-stabilized section with reduced thickness; (c) view of conditions in control section

8 LATERAL DRAINAGE

The presence of moisture in both the base and subgrade layers of a pavement is detrimental, compromising the mechanical properties of these soils. Fig. 11(a) shows the impact on road performance of a moisture-induced decrease in modulus in both the base and subgrade layers. One way to quantify the impact of increased moisture is to evaluate its effect on the structural number (SN) in the design method proposed by the American Association of State Highway and Transportation Officials (AASHTO 1993). 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 more precisely, 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 a pavement will exacerbate pavement distresses by increasing pore pressures and softening the subgrade soil.

Fig. 11(b) illustrates the use of a geosynthetic with in-plane drainage capabilities. In this illustration, a horizontal geosynthetic drain was placed directly beneath the pavement, laterally diverting moisture that may have reached the base layer through downward infiltration, which may result from the presence of cracks in the pavement surface. The geosynthetic can also minimize moisture in the underlying subgrade soils, which may have reached high degree of saturation, for example, through capillary rise from a comparatively high water table.

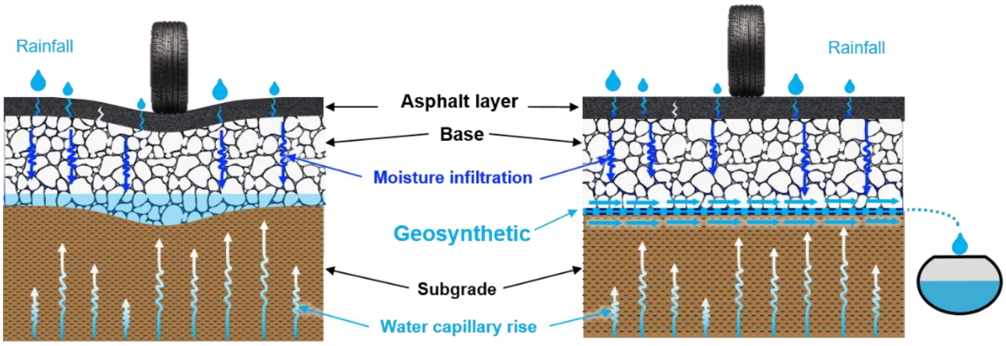

Fig. 11. Use of geosynthetics in improved internal drainage: (a) roadway designed without geosynthetics, (b) roadway designed with geosynthetics

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. Zornberg et al. (2017) highlights the use of with 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 Daniel Boone bridge in St. Louis, Missouri was constructed in 2013 over the Missouri River. The objective of the project was to replace an existing bridge built in the 1930s which had deteriorated beyond repair and did not meet traffic requirements. A new pavement approaching the bridge was also needed. However, the presence of the river resulted in a high-water table beneath the pavement, and a way to remove moisture and avoid upwards infiltration into the pavement base was required.

To address the high-water table, several alternatives were considered. One pavement alternative considered a 4 in. thick layer of drainable aggregate to be placed beneath 4 in. of aggregate base layer (Figure 12a). However, drainable base costs on average $\$40/ton$ whereas regular base aggregate costs $\$12/ton$. In turn, another alternative which used an in plane draining geotextile was considered.

As shown by Figure 12b, 2 in. of base material 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. To release moisture, the geotextile extended into the shoulder to an aggregate covered edge. Moisture was either released into trench drains or it simply evaporated. Figure 12c below presents the placement of the geotextile in the roadway and the diversion of moisture from the high-water table to the edge of the road. Several days after geotextile installation heavy rain occurred and moisture was wicked to the edge of the roadway (Figure 12d). The bridge was completed in 2015 and no pavement distress has been observed since then.

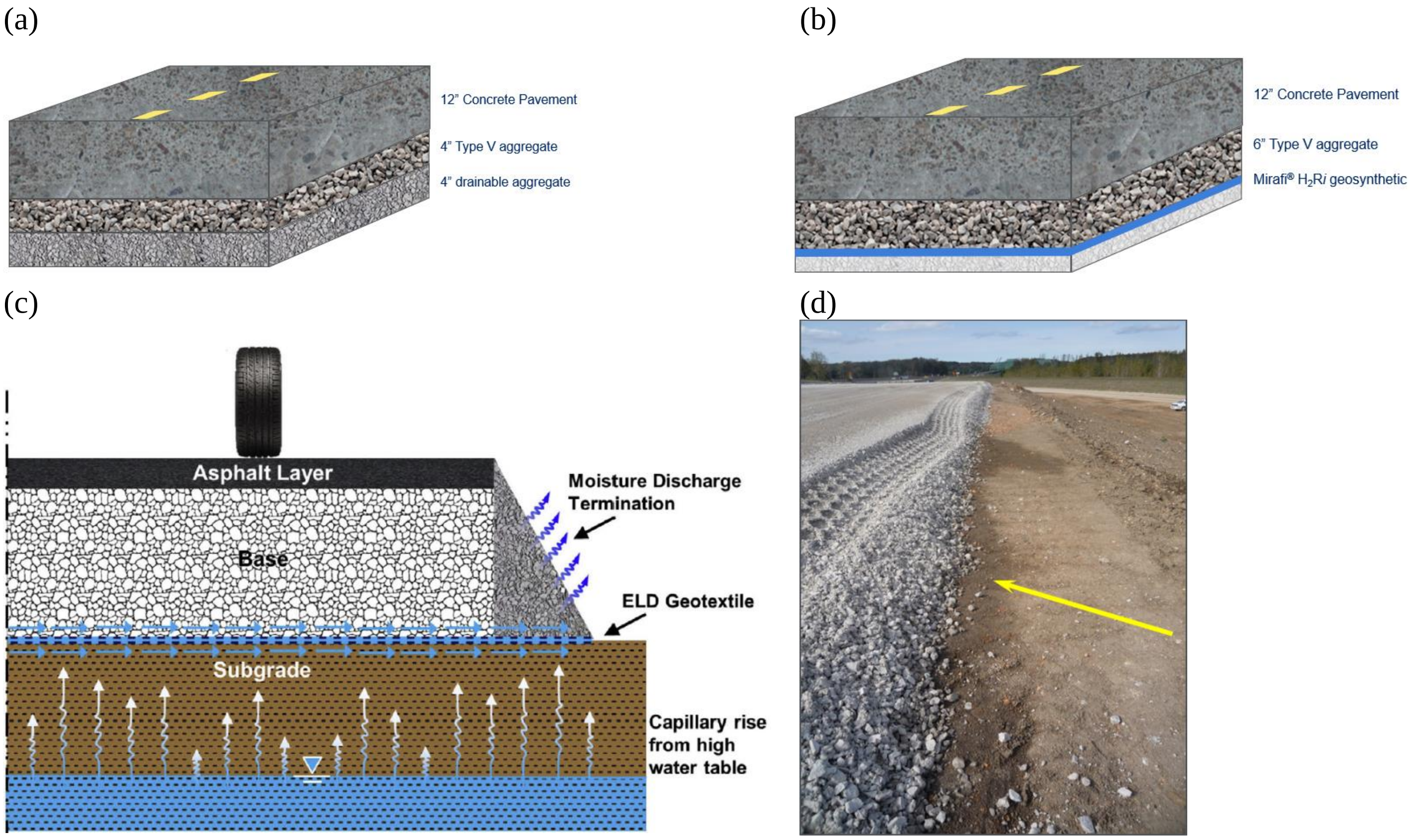

Fig.10. Case study involving enhanced lateral drainage: (a) Originally proposed design at the Daniel Boone Bridge; (b) Revised design involving geosynthetics; (c) Schematic view of the hydraulic system involving a geotextile with enhanced lateral drainage; (d) View of lateral drainage during construction

9 FINAL REMARKS

The world's roadway systems are so extensive that if combined, their total length would encircle the Earth over 1,600 times. Geosynthetics have provided sustainable alternatives in roadway projects, which currently represent a significant portion of the total geosynthetics market. Yet, geosynthetics are still employed in a small fraction of roadway projects worldwide. Accordingly, the opportunities to achieve sustainability benchmarks by increasing the presence of geosynthetics in roadways are, simply, enormous. This paper presents recent advances in two groups of roadway applications involving geosynthetics. The first group involves already established applications for which selection of geosynthetics has been challenged by the need to identify relevant serviceability-based properties. This includes geosynthetics applications such as the mitigation of reflective cracking in asphalt overlays, separation, base stabilization for base course thickness reduction, and subgrade stabilization for increased road design life. The second group involves new applications where geosynthetics have been found to result in significantly enhanced roadway performance. This includes the use of geosynthetics in base stabilization to mitigate problems with expansive clay subgrades, and enhanced lateral drainage in sites where the water table is high. The advantages of these roadway applications are ample, and the overall impact of geosynthetics on sustainable development is probably unmatched when considering the significant extension of roadways that could benefit from their use.

ACKNOWLEDGEMENTS

The authors are grateful to the information provided by many colleagues regarding the case histories presented in this paper. This includes Flavio Montez, Lizeth Vergara, Erick Sanchez, Sven Schroer, John Herrmann, James Robbins, and Darlene Goehl.

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