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GSI White Paper #44

Relative Sustainability of Road Construction/Repair: Conventional Materials versus Geosynthetic Materials

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March 16, 2020

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Overview

There are more than four million miles (six million kilometers) of roadways in the United States. These roadways are often crowded, frequently in poor condition, chronically underfunded, and given an overall grade of D+. Roads in the United States are becoming increasing compromised over time. Approximately 20 percent of highway pavements are in poor condition with a significant and increasing rehabilitation backlog. In 2015, driving on roads in need of repair cost motorists annually more than $500 per driver. (ASCE 2017 Infrastructure Report Card).

Paved vs Unpaved Road Comparison

COUNTRY	PAVED		UNPAVED		TOTAL	
	km × 10^3	mi × 10^3	km × 10^3	mi × 10^3	km ×10^3	mi × 10^3
United States of America	4,304	2,675	2,281	1,417	6,585	4,092
India *	243	151	4,455	2,768	4,698	2,919
China	4,046	2,514	531	330	4,577	2,844
Brazil	1,368	850	213	132	1,581	982
Russia	928	576	355	221	1,283	797
Japan	992	616	225	140	1,217	756
France	1,208	751	0	0	1,208	751
Canada	415	258	627	390	1,042	648
Australia	727	452	146	91	873	543
Indonesia	283	176	213	132	496	308
South Africa	158	98	588	365	746	463
Germany	645	401	0	0	645	401
Top 12 Country Total	**15,317**	**9,518**	**9,634**	**5,986**	**24,951**	**15,504**
Other Countries	**26,468**	**16,446**	**12,866**	**7,995**	**39,334**	**24,441**
Grand Total	**41,785**	**25,964**	**22,500**	**13,981**	**64,285**	**39,945**

*Statistics for India are separated by highways vs other roads. (Assumed: highways are paved and other roads are unpaved).

(ref: CIA.gov World Fact book, 2015)

As seen in the chart above, the United States leads the world in total amount of roadways, which is approximately 30% more roadways than China currently has. France's roads are paved and in better condition than U.S. roads, however, with 82% fewer roads, this statistic makes sense.

The huge number of roads in the United States is certainly a contributing factor to the poor maintenance of these roads.

With increased overall traffic, and especially truck traffic volume, road repairs will occur with increased frequency and higher cost due to the larger wheel loading. To reduce the frequency of road repairs, better materials and technologies are needed to help roads become more sustainable. The ASCE 2018 Report Card's recommendations to improve the United States D+ grade included: life-cycle cost analysis, innovative/creative project delivery strategies, and additional research and development (R&D) funding to evaluate new materials and technology.

Sustainability is an additional factor that needs to be considered. Relative sustainability refers to a comparison of the amount of energy (referred to as 'embodied carbon') of a design option to an alternative design option. Embodied carbon is the amount of carbon dioxide (CO_2) energy required to produce, deliver, and use the product through its life cycle (raw material to finished product). With the increasing emphasis on sustainability for civil engineering design and construction projects, geosynthetics are not only viable, but also competitive in road construction and repair applications. Geosynthetics (with specific emphasis on relative sustainability) should be used to reduce or replace conventional construction materials, such as concrete, steel, clay, sand, gravel, graded soil filters, and rip rap.

Geosynthetics are a classification of synthetic materials that have been successfully utilized in geotechnical engineering transportation and environmental applications in the United States and throughout the world, including road construction and repair, for approximately 50 years (Koerner, …). Geosynthetics include a wide range of products such as geotextiles, geonets, geomembranes, geogrids, geosynthetic clay liners, geofoam, geocells, geopipes, and geocomposites. Many of these geosynthetics are used in road construction and repair, but geotextiles and geogrids are the two most frequently utilized.

This White Paper discusses the levels of embodied carbon (EC) generated from conventional construction material design components to the comparable levels generated from equivalent geosynthetic design components as they relate to: (1) walls and embankments, (2) unpaved roads, (3) reflective cracking in paved roads, (4) paved road construction, and (5) slope erosion protection. Embodied carbon is typically presented in terms of Kg of CO_2 produced for the finished product per Kg of raw material (Kg CO_2/Kg). The process to determine that amount of embodied carbon (EC) is not so straight forward due to the many variables. For example, the embodied carbon (EC) in asphalt and concrete is derived from the extraction, processing, and transportation of asphalt, concrete, and aggregate constituents of the finished product to the project site. The EC in steel includes the mining of the iron ore, transportation and manufacture into steel, and transportation and processing of the steel into the final product delivered to the project site. The EC in a geosynthetic component includes the capture of the oil or gas, transportation to a refinery where the polymer is manufactured, subsequent manufacture into a geosynthetic product, and transportation of the finished product to the project site. Lastly, the actual construction activity EC should be included to ensure a complete comparison (conventional construction material vs. geosynthetic material).

Existing Embodied Carbon (EC) Databases

Several organizations have published EC databases for many construction materials as Kg CO_2/Kg. These organizations include: the United States Environmental Protection Agency (USEPA) (2006), the University of Bath (2008 and 2011), and Stucki, et al. (2011). Subsequent authors have provided more product specific EC values– Raja, et al. (2015).

The following EC data was utilized in conventional and geosynthetic material calculations:

Table 1. Listing of Embodied Carbon in Construction Materials

Construction Material	**Embodied Carbon Value (Kg CO_2/Kg)**	**Reference**
Aggregate - Gravel or Crushed Stone	0.048	
Asphalt - 6% Binder Content	0.068	U of B 2011
Bitumen - General	0.38 - 0.43	
Concrete	0.10	
Plastics - General	2.73	
Polyethylene - General	2.04	
HDPE Resin	1.57	
HDPE Pipe	2.02	
LDPE Resin	1.69	
LDPE Film	2.13	
Polypropylene - Orientated Film	2.97	
Polypropylene - Injection Molding	3.93	
Sand - General	0.048	
Soil - General	0.023	
Stone - General	0.073	
	Embodied Carbon Value (t CO_2 e/t)	
Geotextile - NW Needle-punched	2.28	Raja, et al. 2015
Geotextile - NW Heat-bonded	2.42	
Geogrid - Extruded Polypropylene	2.97	
Geogrid - Woven Polypropylene	2.36	

To demonstrate the sustainability and/or cost advantages of incorporating geosynthetic components into road design and construction, the following examples are presented:

- Example 1 - Walls and Embankments
- Example 2 - Unpaved Road on Soft, Compressible Fine-grained Soil
- Example 3 - Reflective Crack Prevention in Asphalt Pavement Overlays
- Example 4 - Paved Road Construction
- Example 5 - Slope Erosion Protection

Each example will compare the impact of conventional construction materials alone versus the substitution of geosynthetics into specific components of the road design in terms of EC and/or overall cost (when cost data is available).

Example 1 - The numeric decrease in embodied carbon using geosynthetics components for walls and slopes was clearly demonstrated in a report titled, "Sustainable Systems in Civil Engineering Applications" by the Waste and Resources Action Program (WRAP) in May, 2009. The report was authored by representatives of 16 U.K. organizations, of which one-third were involved in geosynthetics. Five separate case studies (A through E) are presented, and summarized below. They address both walls and slopes and show that when replacing traditional materials with geosynthetic materials, costs are greatly reduced (as expected) and the embodied carbon is also reduced. The reduced costs verify previous GSI reports (1998-2001) on comparing gravity retaining walls to various geosynthetic retaining walls. See Figure 1.

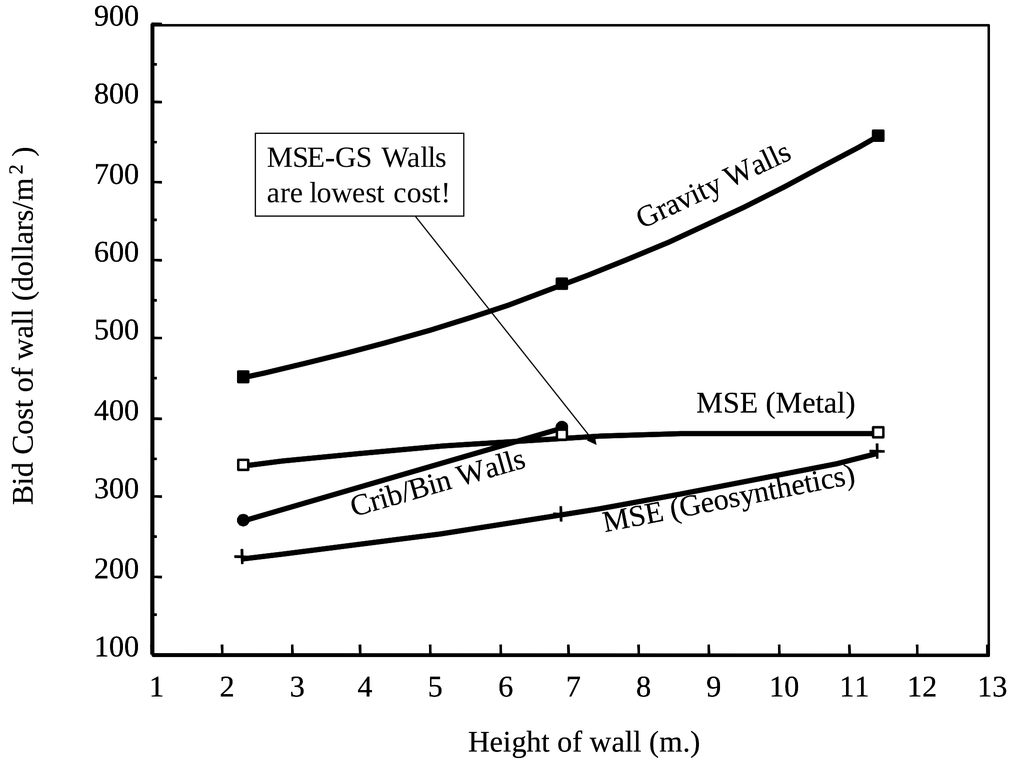

Figure 1.

Table 2. Case Study Results from WRAP Report (May, 2009)

Case History	Traditional Material		Geosynthetic Material		% CO_2 Saving
	Cost (K)	CO_2 Footprint (tons)	Cost (K)	CO_2 Footprint (tons)	
A. Slope Stability	$571	157	$23	21	87
B. Bridge Approach	$1,282	500	$574	346	31
C. Crib Wall	$51	35	$41	11	69
D. Sheet Piling Wall	$246	433	$121	69	84
E. Concrete Wall	$98	107	$20	20	81
				AVE.	70

The average reduction in EC for these 5 case studies is approximately 70%. Detailed calculations for the respective CO_2 footprints for each of the alternate designs were presented in the WRAP report.

Case History A. – Slope Stability

This soil slope stability project compared the original gabion wall design, using quarry imported gravel, to a soil slope reinforced with geogrids. The latter used site available soil in the reinforced soil zone. The above table indicates an 87% decrease in CO_2 footprint using the geosynthetic materials.

Case History B. – Bridge Approach

This new bridge approach embankment was designed with imported gravel fill compared to a locally available fine-grained soil reinforced with geogrids. The above table indicates a 31% decrease in CO_2 footprint using the geosynthetic materials.

Case History C. – Crib Wall

This case concerned the rebuilding of a section from a collapsed brick retaining wall. The alternatives were reconstruction using a reinforced concrete cantilever retaining wall versus a concrete crib wall filled with locally available soil. The above table indicates a 69% reduction in CO_2 footprint using the crib wall.

Case History D. – Sheet Piling Wall

The refurbishing of a deteriorated retaining wall with either an interlocking steel sheet pile wall or a pre-cast concrete faced panel wall with geosynthetic strip reinforcement. The above table indicates an 84% reduction in carbon footprint using panel wall with strip reinforcement.

Case History E. – Concrete Wall

This involved building a new retaining wall to support a parking area. The alternates were a traditional reinforced concrete retaining wall versus a masonry block wall reinforced with geogrids. The above table indicates an 81% reduction in CO_2 footprint using the reinforced masonry block alternative.

Example 2 - Unpaved Road Construction on Soft, Compressible Fine-Grained Soil

An 800 m long, single-lane 4 m wide unpaved road is to be constructed on a soft, compressible fine-grained subgrade. The CBR = 2.0, the ESAL is 1000 and anticipated tire pressure is 480 kPa. How does the EC for an unreinforced unpaved road compare to a geosynthetic-reinforced unpaved road?

Unreinforced Unpaved Option - EC

Based on Koerner (25^{th} GRI Symposium…), the aggregate thickness of an unreinforced unpaved road with a CBR = 2.0 and ESAL = 1000 is 0.3 m The EC associated with this option is as follows [with a unit weight of crushed stone = 20 kN/m^3]:

$$EC = (0.048\ Kg\ CO_2/Kg)(20\ kN/m^3)(101.97\ Kg/kN)(800\ m)\ (4\ m)(0.3\ m)$$

$$= 93{,}976\ Kg\ CO_2$$

Reinforced Unpaved Option - EC

A 400 g/m^2 woven slit-film polypropylene GT is selected as a reinforcement on the soft, compressible, fine-grained subgrade. With a geosynthetic modulus E = 240 kN/m, the aggregate thickness is reduced by 0.23 m. The EC for this option is the sum of the EC for the aggregate plus the EC for the GT:

$$EC_{aggregate} = (0.048\ Kg\ CO_2/Kg)(20\ kN/m^3)(101.97\ Kg/kN)$$

$$(800\ m)(4\ m)(0.07\ m)$$

$$= 21{,}928\ Kg\ CO_2$$

$$EC(GT) = (2.36\ tCO_2e/t)(800\ M)(4\ M)(400\ g/m^2)(t/10^6 g)$$

$$= 3.02\ t\ CO_2 = 3{,}021\ Kg\ CO_2$$

$$EC = EC_{aggregate} + EC_{GT}$$

$$= (21{,}928 + 3{,}021)\ Kg\ CO_2$$

$$= 24{,}949\ Kg\ CO_2$$

The EC reduction by incorporating a woven slit-film FGT into unpaved road option is as follows:

$$EC\ Reduction = EC_{\substack{unpaved\ road\\ section}} - EC_{\substack{paved\ road\\ section}}$$

$$= (93{,}976 - 24{,}949) KgCO_2$$

$$= 69{,}027\ Kg\ CO_2$$

This represents a 73% reduction in EC.

Example 3 - Reflective Crack Prevention in Pavement Overlays

Existing pavement resurfacing with extensive cracking represents an ongoing task for federal, state, local, and private road owners. Historically, pavement resurfacing has been completed with bituminous overlays thickness ranging from 25 to 100 mm. Geosynthetics utilized for this purpose generally serve multiple functions, including reinforcement and waterproofing.

The process includes the following steps: filling cracks with bitumen, an asphalt-based sealant application on the existing pavement, geosynthetic placement over the sealant, and hot-mix bituminous concrete overlay placement.

A two-lane highway carries approximately 4,000 vehicles/day with 10% heavy truck traffic with a 135 kN average mass. The single-axle load limit is 80 kN. The existing pavement consists of 75 mm asphalt pavement and 200 mm of crushed stone base. The CBR was measured to be 5.0. The pavement is showing signs of distress and is in need of an overlay. Calculate and compare an overlay thickness without a geotextile versus incorporating a geotextile, with a Design life of 20 years (per the Asphalt Institute). Then compare the EC for each option.

DTN (Design Traffic Number) = Initial TN × Adjustment Factor

= (90) (1.49)

DTN = 134

Using the CBR = 5, DTN = 134, and the Asphalt Institute design chart for thickness using an unsoaked subgrade CBR, the total depth asphalt pavement thickness for a non-reinforced overly (t_{nr}) = 245 mm. The existing pavement effective thickness incorporates a factor of 0.8 on the existing asphalt pavement and 0.4 on the existing stone base. Therefore, the existing pavement effective thickness (t_e) = (0.8) (75 mm) + (0.4) (200 mm) = 140 mm. The required overlay thickness is the difference between the total pavement section thickness and the effective section thickness, or

$$t_o = (275 - 150)mm = 135\ mm$$

Now, incorporating a geotextile-reinforcement layer, assuming a Fabric Effectiveness Factor (FEF) = 3.0, recalculate the DTN as follows:

$DTN_r = DTN/FEF = 134/3 \approx 45$

Now, revisit Asphalt Institute design chart (using CBR = 5) and DTN_r to get a total thickness of a reinforced pavement (w/reinforced overlay) (t_r) = 215 mm. Therefore, the required thickness of the reinforced overlay t_{ro} = (215 - 140) mm = 75 mm.

The overlay thickness reduction as a result of incorporating a geotextile is:

$$\Delta t = t_o - t_{ro} = (135 - 75)mm = 60\ mm$$

The overall asphalt concrete volumes for a 100 m section are as follows:

For a non-reinforced overlay, $V_o = (0.135\ m)(9\ m)(100\ m)$

$$= 122\ m^3$$

For a reinforced overlay, $V_r = (0.075)(9\ m)(100\ m)$

$$= 68\ m^3$$

The resulting savings in asphalt concrete for a two-lane highway, including shoulders, 9 m (30 feet) wide, per 100 meter length is as follows:

$$Volume = (0.06\ m)(9\ m)(100\ m) = 54\ m^3$$

The EC for the reinforced overlay = $(0.068\ Kg\ CO_2/Kg)(2.24\ Kg/m^3)(122\ m^3)$

$$= 18.6\ Kg\ CO_2$$

The EC for the reinforced overlay = $EC\ (asphalt\ + GT)$

$$= (0.068\ Kg\ CO_2/Kg)(2.24\ Kg/m^3)(68\ m^3) +$$

$$(2.36\ t\ CO_2e_t)\frac{(0.27\ Kg/m^2)(9\ m)(100\ m)}{1{,}000\ Kg/t}$$

$$= 10.36 + 0.57$$

$$= 10.9\ Kg\ CO_2$$

By incorporating a geotextile-reinforcement layer, the EC was reduced by 7.7 $Kg\ CO_2$ or 41%.

Example 4 - Paved Road Construction

A new 1.6 km length × 9 m width section of paved road is planned to connect two existing highways. The designer is considering a pavement section with the following guidelines: ESAL = 100,000, Reliability = 95%, and Subgrade Resilient Modulus = 34,500 kPa. The initial unreinforced pavement section consists of the following components:

asphalt surface course = 50 mm

dense-graded asphalt course = 63 mm

aggregate base course = 200 mm

The resultant ESAL for this unreinforced pavement section is 120,000. What would be the pavement section with a reinforced base course with an equivalent ESAL? Incorporating a triaxial geogrid into the base course results in the following equivalent reinforced pavement section:

asphalt surface course = 38 mm

dense-graded asphalt course = 50 mm

mechanically stabilized layer = 135 mm

The resulting pavement section component reductions by incorporating a triaxial geogrid within the aggregate base course is:

asphalt surface course = 12 mm

dense-graded asphalt course = 13 mm

aggregate base course = 65 mm

The EC for the unreinforced 1.6 km pavement section:

asphalt = $(0.068\ Kg\ CO_2/Kg) \times (2.24\ Kg/m^3)(1{,}600\ m)(9\ m)(0.050 + 0.063)\ m$

$= 248\ Kg\ CO_2$

aggregate = $(0.048\ Kg\ CO_2\ /Kg) \times (2.08\ Kg/m^3)(1{,}600\ m)(9\ m)(0.2\ m)$

$= 288\ Kg\ CO_2$

Total EC = $536\ Kg\ CO_2$

The EC for the reinforced pavement 1.6 km pavement section = EC (asphalt + aggregate + geogrid):

asphalt = $(0.068\ Kg\ CO_2\ /Kg) \times (2.24\ Kg/m^3)(1{,}600\ m)(9\ m)(0.038\ + 0.050)m$

$= 193\ Kg\ CO_2$

aggregate = $(0.048\ Kg\ CO_2/Kg) \times (2.08\ Kg/m^3)(1{,}600\ m)(9\ m)(0.135\ m)$

$= 194\ Kg\ CO_2$

geogrid = $(2.97\ t\ CO_2e/t) \times (1{,}600\ m)(9m)(2.2 \times 10^{-4}\ t/m^2)$

$= 9.4\ t\ CO_2$

Total EC = $(193 + 194 + 9.4)Kg\ CO_2$

$= 396\ Kg\ CO_2$

The geosynthetic-reinforcement pavement has reduced the EC by $140\ Kg\ CO_2$ or 26%.

Example 5 - Slope Reinforcement

Compare the EC of a 460 mm thick rip rap layer with a separation geotextile to a high performance (HP) turf reinforcement mat (TRM) with a unit mass $= 0.68\ Kg/m^2$ on a 5 meter section of a 10 m long 3H:1V slope. Rip rap unit mass $= 2{,}560\ Kg/m^3$.

$EC_{(rip\ rap\ slope)} = EC_{rip\ rap} + EC_{GT}$

$= (0.073\ Kg\ CO_2/Kg)(2{,}560\ Kg/m^3)(10\ m)(5\ m)(0.46\ m) +$

$(2.28\ t\ CO_2e/t)(0.54\ Kg/m^2)(10\ m)(5\ m)(t/1000\ Kg)$

$= 4{,}360\ Kg\ CO_2$

EC (TRM w/100 mm soil layer) $= EC_{TRM} + EC_{soil}$

$$= (2.36\ t\ CO_2e/t)(0.68\ Kg/m^2)(5\ m)(t/1000\ Kg) +$$

$$(0.23\ Kg\ CO_2/kg)(10\ m)(5\ m)(0.15\ m)(1{,}600\ kg/m^3)$$

$$= 356\ Kg\ CO_2$$

By substituting the rip rap with HP-TRM, the overall soil component thickness was significantly reduced (460 mm to 150 mm, based on fully-established vegetation), along with the EC which was reduced by more than 90%.

Summary and Conclusions

Geosynthetics have been utilized in numerous road construction applications for nearly 50 years. With the recent emphasis on resilience, sustainability and life cycle in civil engineering design and construction projects, the use of geosynthetics in road construction should be growing exponentially, although this is not the case. Geosynthetics are often overlooked when it comes to roadway design, but this paper demonstrates why geosynthetics should always be considered. There are many advantages in utilizing geosynthetic components in road design and construction. Reduced embodied carbon values and reduced construction costs are just two of the advantages. Geosynthetics need to be evaluated more frequently in comparison to traditional materials for road construction and repair in order to show their viability. In each of the five example applications presented in this paper (walls and embankments, unpaved roads, reflective cracking in paved roads, paved road construction, and slope erosion protection), incorporating geosynthetic materials significantly reduced the overall embodied carbon (EC). Where data was available, construction costs were significantly reduced as well. Geosynthetics are not new and it is time to start using them to their full potential in roadway applications.

The authors recommend continued research on geosynthetic materials (in support of ASCE's recommendation) that can further reduce EC and cost for unpaved and paved road construction as well as other civil engineering projects. As embodied carbon databases become more product specific and reliable, additional benefits for utilizing geosynthetics in civil engineering projects will be identified.

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