Environmental Design Considerations Using an Equivalency Index between Granular Drainage and Geosynthetic Alternatives

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ABSTRACT

Effective drainage is essential in civil engineering projects, and the design is influenced by the required capacity, inflow rates, and the geometric configuration of the structure. Reduction factors are applied based on material and application. Drainage layers can be granular or geosynthetic, with granular layers using free-draining aggregates and geocomposites comprising non-woven geotextiles and drainage cores or pipes. This study aims to establish equivalency between granular layers and geocomposites in water drainage and gas transport, assuming equal long-term capacity under identical conditions. Despite reduction factors and safety margins, geocomposites significantly reduce drainage layer thickness compared to granular layers. The methodology adopted in this project is to present an equivalency design between granular drainage aggregates and drainage geocomposite and environmental benefit of using geosynthetics as a drainage design solution. This is supported by practical examples and environmental benefits such as reduced aggregate extraction, transportation, greenhouse gas emissions, and construction time for similar or better drainage capacity.

INTRODUCTION

Drainage systems are critical for the effective removal of liquids and gases in various civil engineering projects. These systems offer several benefits, including the dissipation of excess pore pressure from various fluids (such as groundwater or gas), increased soil strength, and accelerated soil consolidation. Drainage applications are important in numerous civil engineering and geoenvironmental applications, including reinforced walls, slopes, embankments, roads, railways, platforms, landfills, and gas evacuation systems in buildings. The design methodology for high permeable granular drainage solutions was established in Giroud's paper (Giroud et al. 2000) and is detailed in the second part of this paper. Given the high permeability and low matrix suction of coarse-grained soils, gravel layers are particularly effective for draining both water and gas.

Due to the scarcity of natural drainage materials such as gravel and sand, and the significant environmental impact throughout their lifecycle: from extraction and manufacturing to transportation, installation, use, and end-of-life management, geocomposite drainage systems are increasingly being used as substitutes for granular materials. These geocomposites notably reduce the overall carbon footprint and total project costs (Durkheim and Fourmont, 2010).

Drainage geocomposites are manufactured composite materials designed for soil drainage. They consist of filtration geotextiles combined with a central core of drainage geomaterial, such as biaxial or triaxial geonets or incorporated corrugated and perforated mini pipes, providing multilinear drainage capabilities. Due to their high permeability and in-plane transmissivity, drainage geocomposites are used in various construction projects to drain water and gas from soils and prevent moisture-related issues, serving as substitutes for granular materials.

The Geosynthetic Sustainability Benefit Calculator, developed by the International Geosynthetics Society (IGS), allows users to measure the sustainability advantages of geosynthetics in various common applications. For drainage application, the tool is based on a comparative analysis of the Carbon footprint of high-quality drainage geocomposite vs. conventional solutions (Gutiérrez and Conesa, 2020). As environmental impact assessments become more prevalent in infrastructure project bids, conducting comprehensive life-cycle analyses of all construction materials, including geosynthetics, is essential and there is a luck of information and real data regarding environmental impact of geosynthetic in sustainable construction compared to traditional materials. Several researches investigated sustainability benefits of adopting geosynthetics especially in roadway design (Zornberg et al., 2024). This was assessed by performing carbon audits on the alternative designs for several roadway project. The results showed that the design options incorporating geosynthetics consistently proved more sustainable than conventional (non-geosynthetic) alternatives. These designs achieved reductions in the total carbon footprint, ranging from 16.3 to 44.44 tCO_2e per km, representing a decrease of 11.6% to 50.11% compared to conventional designs.

This paper underscores the importance of such assessments and provides detailed comparisons of the environmental and economic benefits especially using drainage geocomposite systems over traditional granular materials. Indeed, this paper addresses the equivalency calculations in design between granular drainage materials and drainage geocomposites, emphasizing their environmental benefits. Real project data is utilized to demonstrate the life cycle reduction achievable through the use of geosynthetics, positioning environmental design as a reliable decision-support tool. The first part of the article presents the key design issues of granular drainage materials and their equivalent drainage geocomposite solutions. By understanding these key design issues and conducting a life cycle analysis of embodied Carbon (kg CO_2e/kg) emissions throughout the product's lifetime, the paper illustrates the sustainable benefits of using drainage geosynthetics.

CALCULATION DESIGN ISSUE FOR DRAINAGE THROUGH GRANULAR AND GEOSYNTHETIC SOLUTIONS

Basic equivalent design issue for granular drainage material:

The calculation method for granular drainage layers, based on two technical papers published by Giroud et al. in 2000, ensures the water flow height does not exceed the layer’s thickness. This method considers factors like hydraulic conductivity, slope angle, drainage length, and flow rate per unit area. Giroud’s formula, which includes upstream flow, represents the hydraulic behavior of the drainage layer.

$$q_{req} = F \times L + q_0 = K \times \left(h_{max} \times \sin\alpha + \frac{{h_{max}}^2 \times \cos\alpha}{L}\right) \tag{1}$$

where q_{req} = the required flow rate per unit width ($m^3/s/m$) as obtained from design of the actual system; F=flow rate per unit area ($m^3/s/m^2$); L= Length of drainage (m); q_0= incoming upstream flow per unit width ($m^3/s/m$); K= hydraulic conductivity of the granular layer (m/s); h_{max}= maximum height of water (m); and α = the slope (°).

Based on the site's geometrical characteristics (drainage length, slope, and incoming upstream flow) and drainage conditions (flow rate to be drained), the required granular drainage layer can be designed. Specifically, the minimum required hydraulic conductivity can be calculated, given that the maximum water height (h_{max}) does not exceed the thickness (e) of the granular drainage layer.

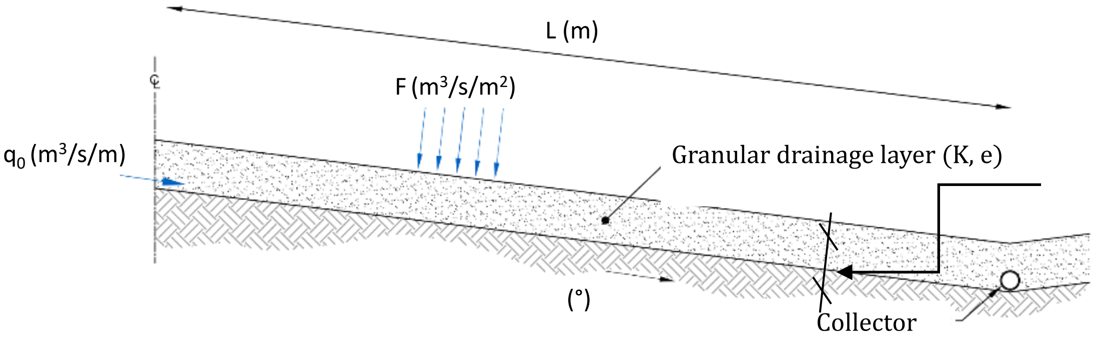

Figure 1. Hydraulic design of a granular drainage layer

Reduction factors for chemical clogging *(RF_{CC})* and biological clogging *(RF_{BC})* can be addressed and applied to the hydraulic conductivity of the granular layer. The factor of safety (FS) is applied to either h_{max} or *K*, whichever gives the most conservative result. Figure 2 gives an example of the flow capacity of a granular drainage layer based on its thickness and the hydraulic conductivity of the granular drainage materials, for a maximum length of drainage equal to 75 m (246 ft) and slope of 3%.

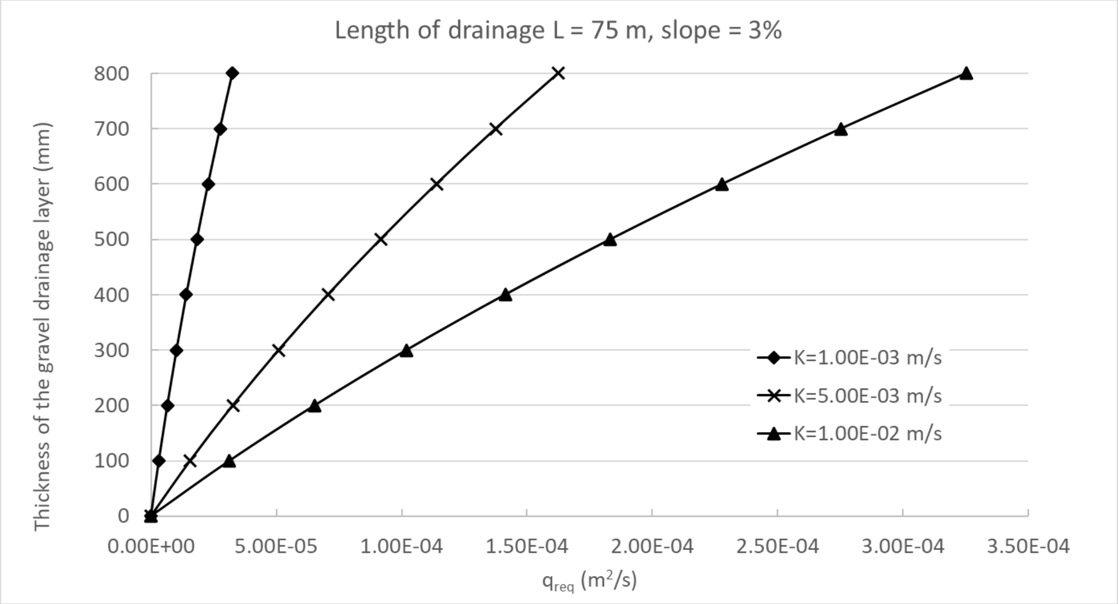

Figure 2. Drainage capacity q_{req} of granular layers with various hydraulic conductivity and thickness

Basic equivalent design issue for drainage geocomposite.

The very essence of the design by function concept is the establishment of an adequate factor of safety (Koerner, 2012). For drainage geocomposites, where the flow rate is the preliminary function, this takes the following form $FS = \frac{q_{allow}}{q_{req}}$ where q_{allow} is the allowable flow rate per unit width obtained from laboratory testing ($m^3/s/m$) including reductions factors to address their long-term performance.

ASTM D7931 (2021) provide a standard equation that can be used to design and specific a drainage geocomposite for most applications. This guide is intended to help designers, purchasers, installers, contractors, owners, operators, and agencies in establishing the minimum criteria to specify drainage geocomposites. Specifically, this guide presents a methodology for determining the allowable flow rate of a candidate drainage geocomposite. The resulting value is then compared to a required (or design) flow rate q_{req} for a product-specific and site-specific factor of safety. The performance of drainage geocomposites is limited by several factors that must be considered when designing (1) geotextile intrusion into the drainage core, RF_{GI}; (2) drainage core crushing, RF_{CR} (i.e., creep in compression); and (3) biological and chemical clogging, RF_{CC} and RF_{BC} (Eq.2). A summary of typical ranges for each of the reduction factors for some common applications of drainage geocomposites is provided in Koerner (2016)

$$q_{allow} = q_{(\sigma,i,100h)} \times \left(\frac{1}{RF_{GI} \times RF_{CR} \times RF_{CC} \times RF_{BC}}\right) = \left(\frac{q_{(\sigma,i,100h)}}{\prod RF}\right) \tag{2}$$

q_{allow} = allowable flow rate per unit width for a drainage geocomposite; $q_{(\sigma,i,100h)}$ = the in-plane flow capacity per unit width performed under a vertical load σ, a hydraulic gradient i and a seating time of 100 h with boundary conditions representative of site conditions; RF_{GI}= reduction factor for geotextile intrusion past the initial 100h seating time, RF_{CR}= reduction factor for creep past the initial 100h seating time; RF_{CC}= reduction factor for chemical clogging; RF_{BC} = reduction factor for biological clogging; . Recommended reduction factors values for the determination of flow rate of the drainage geocomposite for common drainage applications are listed in Koerner (2012) and ASTM D7931 which is a specific guideline for drainage geocomposites with $\prod RF = RF_{GI} \times RF_{CR} \times RF_{CC} \times RF_{BC}$. The reduction factors are product specific and RF values can be obtained also from the manufacturers. To determine reduction factors, the creep reduction factor (RF_{CR}) must be assessed using Test Methods D7406 or D7361 for thickness reduction under compressive stress. The RF_{CR} is not the reduction in thickness but the reduction in drainage capacity due to the reduced thickness. The long-term geotextile intrusion reduction factor (RF_{GI}) can be obtained by first determining the long-term flow rate under representative boundaries, normal load, and service life using Test Methods D7406 or D7361. This long-term flow rate includes both the reduction factor for creep, RF_{CR}, and the reduction factor for long-term geotextile intrusion, RF_{GI}. For chemical and biological clogging reduction factors (RF_{CC} and RF_{BC}) must be specified based on environmental conditions. The in-plane flow capacity test to determine the flow rate, or transmissivity of drainage geocomposites should be performed according to ISO 12958-2 (2020) for the determination of the flow rate per unit width $q_{(\sigma,i,100h)}$ or ASTM D4716 (2022) for the determination of the transmissivity $\theta_{(\sigma,i,100h)}$ performed under a vertical load σ, a hydraulic gradient i and a seating time of 100 h with boundary conditions representative of site conditions. Alternatively, the transmissivity can be used to obtain the equivalent relation $FS = \frac{\theta_{allow}}{\theta_{req}}$. The allowable transmissivity θ_{allow} is the in-plane flow rate per unit width divided by the hydraulic gradient i of the test for a given confining stress and given boundary conditions, expressed as follows:

$$\theta_{allow} = (\ q_{allow}\ )\left(\frac{1}{i}\right) \tag{3}$$

and determined as follows

$$\theta_{allow} = \theta_{(\sigma,i,100h)} \times \left(\frac{1}{RF_{GI} \times RF_{CR} \times RF_{CC} \times RF_{BC}}\right) = \left(\frac{\theta_{(\sigma,i,100h)}}{\prod RF}\right) \tag{4}$$

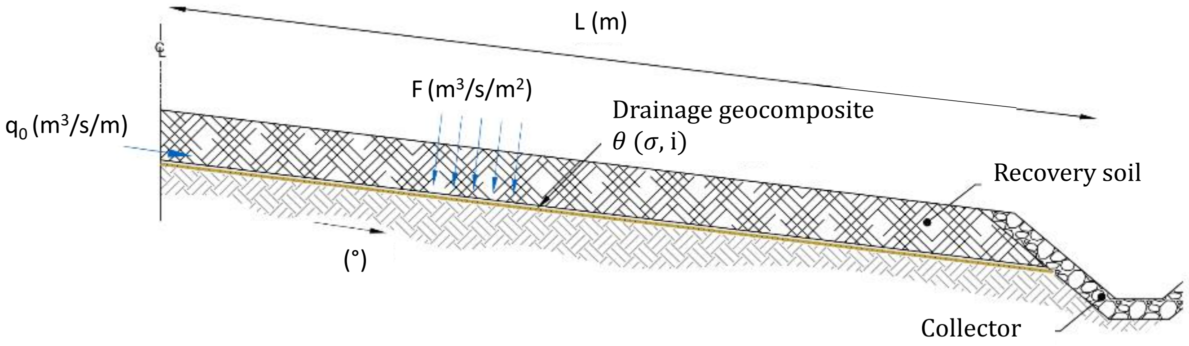

Figure 3. Hydraulic design of a drainage geocomposite

The minimum required flow capacity of the drainage geocomposite $q_{(\sigma,i,100h)}$ or $\theta_{(\sigma,i,100h)}$ is provided using Eq. 5 in an ISO environment and Eq. 6 in an ASTM environment. A potential incoming upstream flow has also been considered as illustrated is Figure 3.

$$q_{(\sigma,i,100h)} = FS \times \prod RF \times (F \times L + q_0) \tag{5}$$

$$\theta_{(\sigma,i,100h)} = FS \times \prod RF \times \frac{(F \times L + q_0)}{i} \tag{6}$$

An example is provided for determining the transmissivity of two different types of drainage geocomposites as replacements for a granular drainage layer. The allowable transmissivity is obtained from the required transmissivity from the gravel layer after applying a factor of safety. Table 1 gives the assumptions and specific reduction factors RFs to calculate the transmissivity for each type of drainage geocomposite. The reduction factors are taken from GSI White paper 4 (Koerner, 2007) and ASTM D7931 standard.

Figure 4 shows the implementation of each set of RFs to obtain the transmissivity of the drainage geocomposite as a function of the type of geocomposite. It shows the importance of the choice of reduction factors or the specific geocomposite type as it can lead to very different transmissivities values. In this example, the geonet geocomposite will need a transmissivity value two times higher than the multi-linear drainage geocomposite, for the same long-term performance (to replace the same granular layer).

Table 1: FS and RFs used to determine the transmissivity of two types of drainage geocomposites

Application	Final cover drainage system				
Hydraulic conductivity of the granular layer (m/s)	1×10^{-3}				
Thickness of the granular layer (mm)	500				
q_{req} (m^2/s)	1.83×10^{-5}				
FS	1.5				
	$\boldsymbol{\theta_{allow}(\frac{m^2}{s})}$	**After $\boldsymbol{RF_{GI}}$**	**After $\boldsymbol{RF_{CR}}$**	**After $\boldsymbol{RF_{CC}}$**	**After $\boldsymbol{RF_{BC}}$**
Geonet geocomposite RFs $\boldsymbol{\theta(\sigma,i,100h)}$	- 9.15×10^{-4}	1.50 1.37×10^{-3}	1.40 1.92×10^{-3}	1.20 2.31×10^{-3}	2.00 4.61×10^{-3}
Multi-linear drainage geocomposite RFs $\boldsymbol{\theta(\sigma,i,100h)}$	- 9.15×10^{-4}	1.00 9.15×10^{-4}	1.00 9.15×10^{-4}	1.20 1.10×10^{-3}	2.00 2.20×10^{-3}

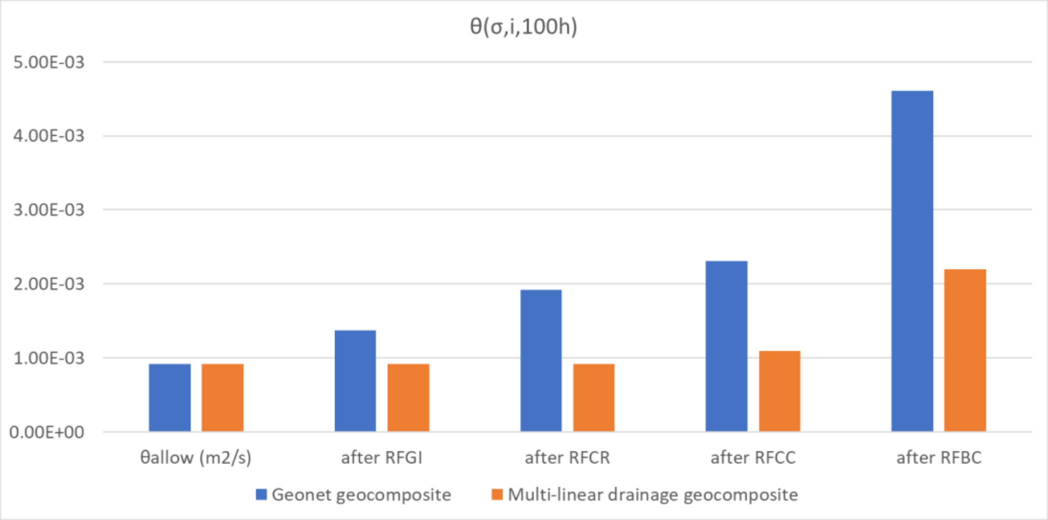

Figure 4: RFs and their impact on the index transmissivity of two types of drainage geocomposite for the same long-term performance

Calculation of $q_{(\sigma,i,100h)}$ or $\theta_{(\sigma,i,100h)}$ for different types of drainage geocomposites and different applications requires many input parameters and calculation steps. A hydraulic software, named Lymphea, assists designers in the hydraulic selection of drainage geocomposites (including multi-linear drainage geocomposites) as well as granular drainage layers using site-specific conditions. The software is based on a previous model developed with LIRIGM university research laboratory at the University of Grenoble (France) and CEREMA (formerly Laboratoire Regional des Ponts et Chaussées de Nancy). It has been updated and improved with the contribution of the SAGEOS (CTT Group, Quebec), the CEGEP of Saint-Hyacinthe (Quebec), and the University of Saskatchewan (USASK) in Alberta. It allows the design of drainage geocomposites for both liquid and gas (Fourmont et al., 2023). The user interface has been developed to represent the engineer’s needs and the design steps as closely as possible. The software is available in several languages (English, French, and Spanish), in SI and US units, and based on ISO and ASTM standards.

EQUIVALENCY CALCULATION BETWEEN GRANULAR AND GEOSYNTHETIC MATERIAL AND LIFE CYCLE ANALYSIS

General overview and consideration

Drainage geosynthetics can significantly contribute to sustainability and carbon emission reduction across various stages of their lifecycle, from cradle to gate, transportation, and installation. The philosophy behind this calculation is based on estimating the embodied carbon (kg CO_2e/kg) of various drainage geosynthetic solutions (including geonet geocomposites, multi-linear drainage geocomposites, cuspated geocomposites, and monofilament geocomposites) compared to an equivalent 300 mm gravel layer thick with a hydraulic conductivity of 10^{-3} m/s. This step, with the definition of the mass per unit area of each drainage solution (kg/m^2) will allow us to estimate the embodied carbon of the total drainage project area.

Comparison of Gas Emissions Between Granular Layer and Equivalent Geocomposite solutions:

Cradle to gate stages (extraction and treatment processes for granular material vs manufacturing of drainage geosynthetic materials

Table 2 presents an estimation of the embodied carbon values per kilogram from literature and manufacturer data for various drainage solutions (kg CO_2e/kg), including geonet geocomposites, multilinear drainage geosynthetics, cuspated geocomposites, non-woven polypropylene geotextiles, as well as granular materials (gravel, sand). The mass per unit area of each drainage solution (kg/m^2) has been included to calculate the embodied carbon per unit area (kg CO_2e/m^2) of the total drainage project area. It is evident from the second column that the embodied carbon value per kilogram is approximately 500 times higher for geosynthetics compared to granular layers. Gravel layers emit 0.0059 kg CO_2e/kg compared to geonet geocomposites which emit 2.9 kg CO_2e/kg. However, the mass per unit area of the drainage geocomposite (ranging from 0.6 to 1.2 kg/m^2) is a critical parameter compared to 720 kg/m^2 for a gravel layer (0.400 m at 1.8 T/m^3), more so than the polymer type, governing the gas emissions (from cradle to gate). Some drainage geocomposites, such as multi-linear drainage geocomposites, offer savings of up to 45% for the same performance compared to other geocomposites, when evaluating the embodied carbon per unit area (kg CO_2e/m^2) of the total drainage project area. Compared to a granular layer, the estimated average embodied carbon per unit area for a multi-linear drainage geocomposite is 2.0 kg CO_2e/m^2, versus 4.8 kg CO_2e/m^2 for an equivalent gravel layer including a separator geotextile. Some of the carbon footprint data of the materials compared in this study is available from Hammond et al. (2011).

This analysis underscores the importance of considering the mass per unit area of the equivalent drainage material, as it results in significant reductions in emissions when using geocomposites. While emissions per kg of material from the manufacture of drainage geocomposites may be higher than those from the extraction and processing of granular materials, the use of geocomposites leads to substantial reductions in emissions because their weight is almost negligible compared to the gravel layer, for the same performances. Consequently, the manufacturing of geosynthetic drainage solutions typically generates fewer greenhouse gases for the same application compared to traditional materials. Geosynthetics also often require less raw material compared to traditional drainage solutions like gravel or sand layers, further reducing the environmental impact associated with extraction. The carbon footprints of the various materials are derived from the data established by Hammond et al. (2011) and from manufacturers established data bases.

Table 2. Embodied carbon value for drainage geocomposites versus granular material during production per m^2 (Cradle to gate stage)

	Embodied carbon kg CO_2e/kg	**Average weight kg/m^2 (oz/sy)**	**Average embodied carbon kg CO_2e/m^2**
geonet geocomposite	2.9	1.2 (35)	3.5
multi-linear drainage geocomposite	3.34	0.6 (18)	2.0
monofilament geocomposite	2.75	1.0 (29)	2.8
cuspated geocomposite	3.1	1.0 (29)	3.1
non-woven polypropylene geotextile	2.75	0.2 (6)	0.6
gravel layer	0.0059	720 (160) (0.400 mm at 1.8 T/m^3)	4.2
gravel layer + separator geotextile	-	-	4.8

Transportation stage

Geosynthetics are typically lighter than traditional materials, leading to lower fuel consumption during transportation. This weight advantage results in a significant reduction (~90%) in carbon emissions for a 2000 km transport from the geosynthetic manufacturing firm to the site, compared to a 20 km transport for granular materials (including a separator geotextile) with equivalent performance, as detailed in Table 3. Specifically, the average embodied carbon for transporting the geonet geocomposite is 0.12 kg CO_2e/m², compared to 1.06 kg CO_2e/m² for the gravel layer and the non-woven geotextile, for the same performances.

Installation stage

The installation of geosynthetics often requires less heavy machinery than traditional materials, resulting in lower fuel consumption and emissions during the installation phase. The faster installation rate of geosynthetics (625 m²/hour) compared to gravel layers (including separator geotextile at 91 m²/hour) significantly reduces the overall carbon footprint, by approximately 90%. Specifically, the average embodied carbon for installing a drainage geocomposite is 0.10 kg CO_2e/m², compared to 1.329 kg CO_2e/m² for a gravel layer (including separator geotextile).

Table 3: Embodied carbon value for drainage geocomposites versus granular material during transportation per m^2

	Transportation ($ton.km/m^2$)	Embodied carbon value Transportation (kg eq.CO_2 / ton.km)	Average embodied carbon (kg CO_2e/m^2)
Geonet geocomposite	2.4	0.049	0.12
Multi-linear drainage geocomposite	1.2	0.049	0.06
Monofilament geocomposite	2.0	0.049	0.10
Cuspated geocomposite	2.0	0.049	0.10
Non-woven polypropylene geotextile	0.4	0.049	0.02
Gravel layer	14.3	0.073	1.04
Gravel layer + separator geotextile	-	-	1.06

Table 4: Embodied carbon value for drainage geocomposites versus granular material during installation per m^2

	Installation	Embodied carbon value Installation (kg eq.CO_2/hour)	Average embodied carbon (kg CO_2e/m^2)
Drainage geocomposite	5000 m^2/day = 625 m^2/hour	-	-
3 workers	-	1.1 (per worker)	0.005
1 engine	-	59 (per engine)	0.094
Total	-	-	**0.10**
Gravel layer + separator geotextile	65 tons/hour =91 m^2/hour	-	-
2 workers	-	1.1 (per worker)	0.024
2 engines	-	59 (per engine)	1.30
Total	-	-	**1.32**

In summary, across various stages—including manufacturing (cradle to gate), transportation, and installation—drainage geocomposites achieve a 50%-70% reduction in total gas emissions compared to a gravel drainage layer with equivalent performance, as shown in Table 5. Specifically, drainage geocomposites generate between 2 to 3.5 kg CO_2e/m^2, thanks to their lightweight and high performance, whereas a gravel layer (including separator geotextile) generates 7.183 kg CO_2e/m^2. Despite being a manufactured product, drainage geocomposites significantly reduce the carbon footprint of the overall construction project compared to natural gravel resources.

Table 5: Summary of total Embodied carbon value for drainage geocomposites versus granular material per m^2

	Average Embodied Carbon (kg CO_2e/m^2)			
Material	**Manufacturing Cradle to Gate**	**Transportation**	**Installation**	**Total**
Drainage geocomposite	2.85	0.1	0.1	**2 - 3.5**
Gravel layer + separator geotextile	4.8	1.06	1.32	**7.18**

CONCLUSION

This paper demonstrates the design rationale and sustainable advantages of utilizing drainage geosynthetic materials instead of granular materials for drainage applications. The ability to achieve the same drainage and flow functions with a thinner product, supported by the proposed equivalence theory, allows for the assessment of the Average Embodied Carbon (kg CO_2e/m^2) for a construction project area. This approach not only significantly reduces construction time and earthwork volumes but also minimizes the associated carbon footprint. Throughout the stages of extraction/manufacturing (cradle to gate), transportation, and installation, the use of drainage geocomposites results in a 50% to 70% reduction in carbon emissions compared to granular materials. This makes drainage geocomposites a viable alternative for selecting drainage products that promote sustainable development and reduce greenhouse gas emissions, offering an environmentally conscious drainage design solution for construction sites. This work is based on carbon footprint of geosynthetics manufacturers, literature, and common field practices for geosynthetic and granular drainage layer transportation and installation.

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