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Performance of high-quality drainage geocomposites and analysis of the carbon footprint vs. conventional solutions

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ABSTRACT
Shortage of natural resources is leading the industry towards an accelerated pace in the use of geosynthetics. However, misconceptions around their properties often obstruct this progression via environment-friendly solutions. Regarding the drainage of fluids, revolutionary products provide not only better hydraulic and mechanical performances than traditional solutions based on granular layers, but also lower installation costs. Moreover, when comparing the volumes and weights surrounding both solutions, the logistic footprint is drastically reduced. Overall, drainage geocomposites emerge as a cost-effective solution against conventional designs and are presented to become a key player within every sector of the industry.

RESUMEN
La escasez de recursos naturales está llevando a la industria hacia un ritmo acelerado en el uso de geosintéticos. Aun así, el desconocimiento de sus propiedades obstruye esta progresión hacia soluciones más sostenibles para el medio ambiente. En referencia al drenaje de fluidos, existen productos revolucionarios que aportan no sólo mejores comportamientos hidráulicos y mecánicos que la solución tradicional basada en capas granulares, sino también inferiores costes de instalación. Además, comparando los volúmenes y pesos correspondientes a estas soluciones, se observa que la huella logística se reduce drásticamente. En general, los geocompuestos de drenaje emergen como una solución económica ante los diseños convencionales y se ofrecen a convertirse en importantes elementos dentro de cada sector de la industria.

1. INTRODUCTION

Drainage geocomposites (GCDs) are three-dimensional polymeric materials designed to create a layer filled with large void spaces through which fluids can be displaced outside a soil mass, even under considerable compressive forces. The term *geocomposite* comes from the fact that these structures result from the combination of at least two typologies of geosynthetics, usually geonets (GNTs) and geotextiles (GTXs) due to the excellent hydraulic and mechanical performance.

The GNT has a high void ratio, which allows the fluid to be displaced downstream. On the other hand, the GTX attached to the core avoids the intrusion of fine particles (filtration and separation) and increases the average puncture resistance (protection). Other layers like a film can also be attached to either side of the GNT to acquire the impermeability function, although this possibility will not be explored in the current study.

Unlike what it might seem, these structures of few millimeters thickness are able to perform even better than most granular layers of some decimeters thickness under the same on-site conditions. In terms of drainage and crush resistance, possibilities of customized solutions are extensive.

Besides the hydraulic analysis, the characterization of the mechanical properties of these polymeric materials is basic to understand broadly their performance under different boundary conditions. To this extent, the compressive resistance and the creep reduction factor play an important role over the stability of the GNT core throughout the system's life cycle and consequently over the transmissivity.

The applicability of GCDs is as broad as the coverage of granular layers. Agents within the civil works, landfill and mining sectors are slowly progressing towards geosynthetic-based approaches under the need of less dependence of natural mineral resources and the industry must be ready to respond with environmentally friendly solutions.

In summary, the applications of GCDs can be transposed and extended from those covered by the conventional solution based on a granular natural layer. This study will explore the benefits of using high-quality geosynthetics in common applications from the performance and environmental viewpoints.

2. FLOW CAPACITY

2.1 Conventional Design

The flow capacity of a granular layer can be estimated using Darcy's Law:

$$q_{granular} = k\ i\ b \tag{1}$$

The in-plane permeability of the granular layer typically lies within the range of 10^{-4} to 10^{-3} m/s.

In the hypothesis of a steady flow, the hydraulic gradient is equal to the geometric gradient:

$$i = \sin\beta \tag{2}$$

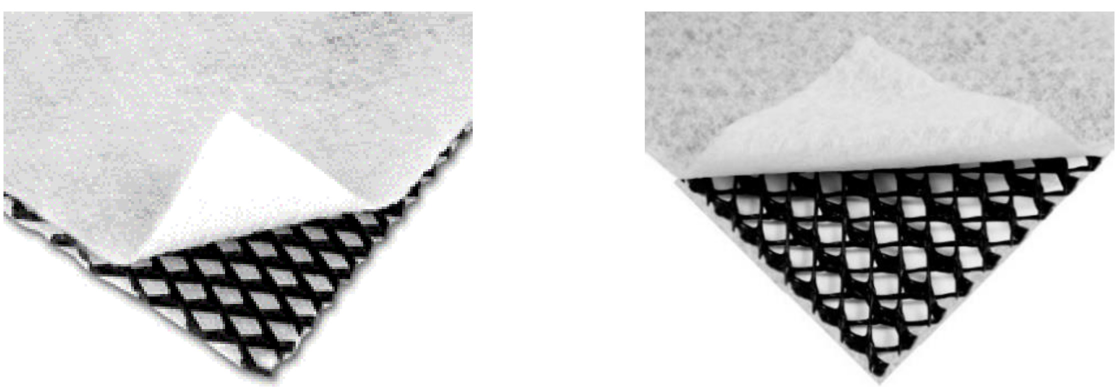
2.2 Geosynthetic Design

As mentioned in Section 1, this study is centered in the definition and analysis of GCDs formed by extruded HDPE GNT (Figure 1) and non-woven PP GTXs thermally bonded over both sides of the GNT (Figure 2), as these structures can cover a broad range of applications thanks to their hydraulic (Figure 3) and mechanical performances (Figure 4).

Figure 1 shows two types of GNT structure: bi-planar and tri-planar. These structures are very different from one another and have been designed to cover different types of applications. That is, the GCD must be designed according to the hydraulic specifications and accounting for all the static and dynamic loads applied throughout the project's life cycle.

a) Bi-planar b) Tri-planar

Figure 1. GNTs structure. Source: Intermas Nets.



a) Bi-planar GNT structure with two GTXs b) Tri-planar GNT structure with two GTXs

Figure 2. GCDs composition. Source: Intermas Nets.

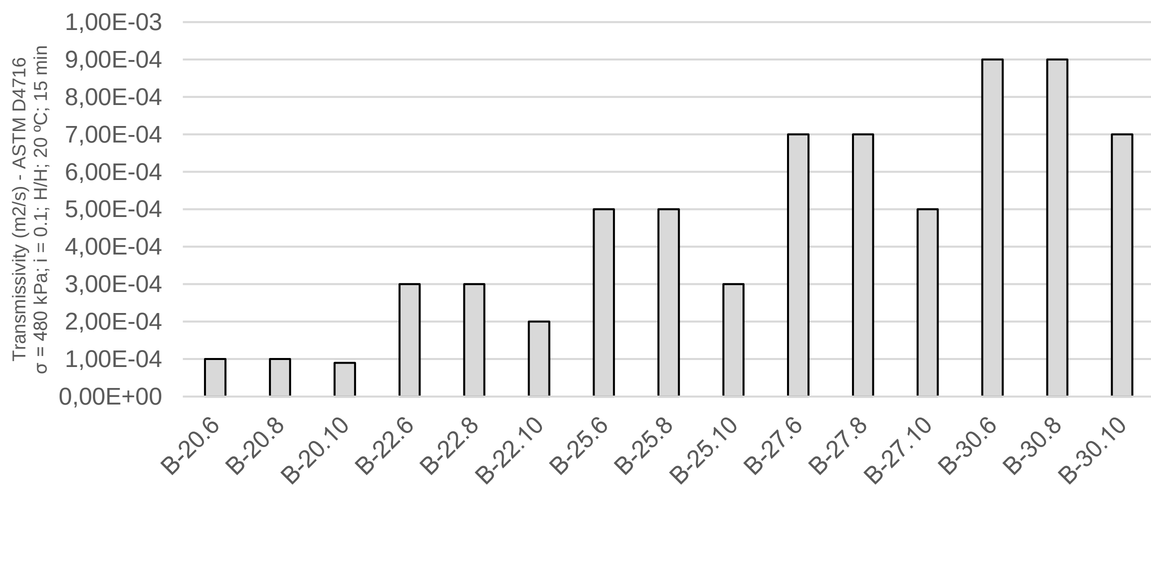
Table 1. List of bi-planar GCDs

GCD	Type of GNT	GNT (mil)	GNT (mm)	GTXs (oz/sy)	GTXs (g/m^2)
B-20.6	Bi-planar	200	5.0	6	200
B-20.8	Bi-planar	200	5.0	8	270
B-20.10	Bi-planar	200	5.0	10	340
B-22.6	Bi-planar	220	5.6	6	200
B-22.8	Bi-planar	220	5.6	8	270
B-22.10	Bi-planar	220	5.6	10	340
B-25.6	Bi-planar	250	6.4	6	200
B-25.8	Bi-planar	250	6.4	8	270
B-25.10	Bi-planar	250	6.4	10	340
B-27.6	Bi-planar	270	7.0	6	200
B-27.8	Bi-planar	270	7.0	8	270
B-27.10	Bi-planar	270	7.0	10	340
B-30.6	Bi-planar	300	7.6	6	200
B-30.8	Bi-planar	300	7.6	8	270
B-30.10	Bi-planar	300	7.6	10	340

Table 2. List of tri-planar GCDs

GCD	Type of GNT	GNT (mil)	GNT (mm)	GTXs (oz/sy)	GTXs (g/m^2)
T-20.6	Tri-planar	200	5.0	6	200
T-20.8	Tri-planar	200	5.0	8	270
T-20.10	Tri-planar	200	5.0	10	340
T-22.6	Tri-planar	220	5.6	6	200
T-22.8	Tri-planar	220	5.6	8	270
T-22.10	Tri-planar	220	5.6	10	340
T-25.6	Tri-planar	250	6.4	6	200
T-25.8	Tri-planar	250	6.4	8	270
T-25.10	Tri-planar	250	6.4	10	340
T-27.6	Tri-planar	270	7.0	6	200
T-27.8	Tri-planar	270	7.0	8	270
T-27.10	Tri-planar	270	7.0	10	340
T-30.6	Tri-planar	300	7.6	6	200
T-30.8	Tri-planar	300	7.6	8	270
T-30.10	Tri-planar	300	7.6	10	340

a)



b)

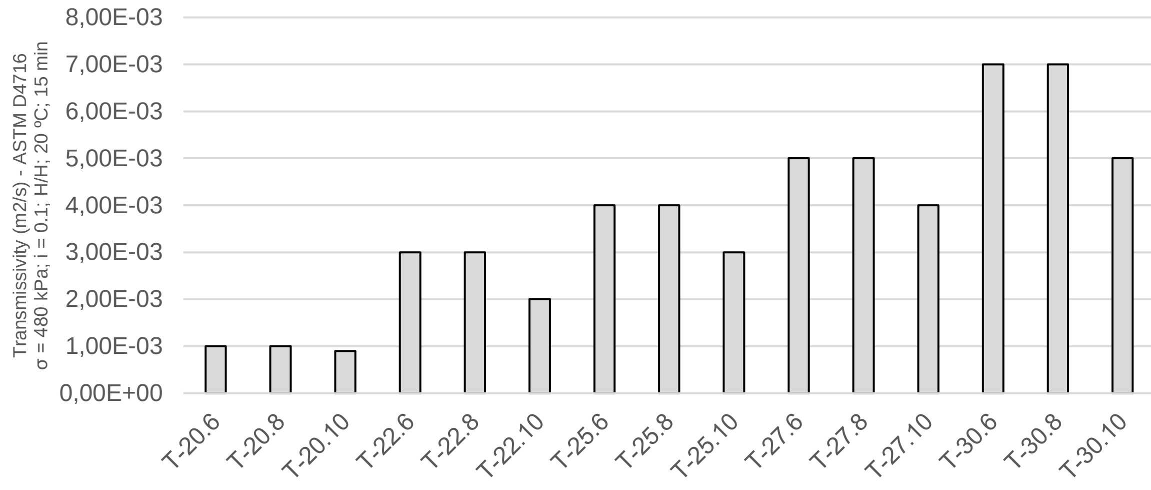


Figure 3. Transmissivity (ASTM D4716) of the bi-planar (a) and tri-planar (b) GCDs listed in Table 1 and Table 2, respectively

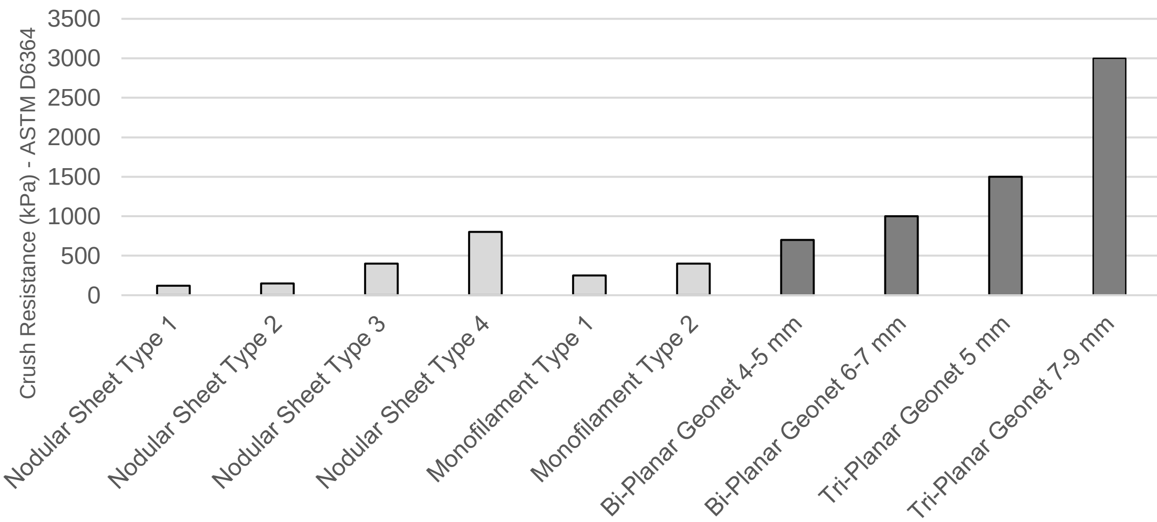


Figure 4. Reference crush resistance (ASTM D6364) values of main geospacers in the market

The drainage capacity of a GCD is experimentally tested based on the ASTM D4716 norm. On-site conditions are reproduced in the laboratory to obtain the short-term behavior:

- Normal stress to the GCD plane or σ_{GCD}
- Hydraulic gradient within the GCD plane or i_p
- Boundary conditions over and under the GCD plane
- Water temperature
- Time elapsed from the beginning until the end of the test

The boundary conditions are defined to simulate the materials adjacent to the GCD layer. For instance:

- Hard/Hard plates with geomembrane (GMB) over and under the GCD plane
- Soft/Soft plates with natural soil over and under the GCD plane
- Hard/Soft plates with GMB under the GCD plane and natural soil over the GCD plane

It is important to remark that technical datasheets must provide the transmissivity test constraints, typically located on the footer. Under ASTM standards, transmissivity is often expressed for a normal stress of 10,000 psf (480 kPa) and a hydraulic gradient of 0.1 between Hard/Hard plates, with a water temperature set to 20 ºC and for 15 minutes (Figure 3).

Although the short-term transmissivity value provides a solid estimate of the hydraulic performance of the GCD, the real on-site behavior will be much lower by the end of the project's life cycle. Koerner and Koerner (2007) investigate this issue and provide a set of reduction factors involved in the decrease of transmissivity, which are expressed as follows:

- RF_{IN}: Reduction factor due to GTX intrusion inside the GNT
- RF_{CR}: Reduction factor due to creep of the GNT
- RF_{CC}: Reduction factor due to chemical clogging of the GCD
- RF_{BC}: Reduction factor due to biological clogging of the GCD

Koerner and Koerner (2007) also provide a range of values for these reduction factors depending on the application area (Table *3*).

Table 3. Range of reduction factor values (Koerner and Koerner, 2007)

Application Area	RF_{IN}	RF_{CR}	RF_{CC}	RF_{BC}
Sport fields	1.0 to 1.2	1.0 to 1.5	1.0 to 1.2	1.1 to 1.3
Capillary breaks	1.1 to 1.3	1.0 to 1.2	1.1 to 1.5	1.1 to 1.3
Roof and plaza decks	1.2 to 1.4	1.0 to 1.2	1.0 to 1.2	1.1 to 1.3
Retaining walls, seeping rock, and soil slopes	1.3 to 1.5	1.2 to 1.4	1.1 to 1.5	1.0 to 1.5
Drainage blankets	1.3 to 1.5	1.2 to 1.4	1.0 to 1.2	1.0 to 1.2
Infiltrating water drainage for landfill covers	1.3 to 1.5	1.1 to 1.4	1.0 to 1.2	1.5 to 2.0
Secondary leachate collection (landfills)	1.5 to 2.0	1.4 to 2.0	1.5 to 2.0	1.5 to 2.0
Primary leachate collection (landfills)	1.5 to 2.0	1.4 to 2.0	1.5 to 2.0	1.5 to 2.0
Wick Drains (PVDs)	1.5 to 2.5	1.0 to 2.5	1.0 to 1.2	1.0 to 1.2
Highway edge drains	1.2 to 1.8	1.5 to 3.0	1.1 to 5.0	1.0 to 1.2

This is, the transmissivity value shown in the technical datasheet must be divided by a global safety factor that accounts for all the reduction values selected by the final application:

$$q_{GCD,long\text{-}term} = q_{GCD,short\text{-}term} / \Pi RF = q_{GCD,short\text{-}term} / (RF_{IN}\ RF_{CR}\ RF_{CC}\ RF_{BC}) \quad [3]$$

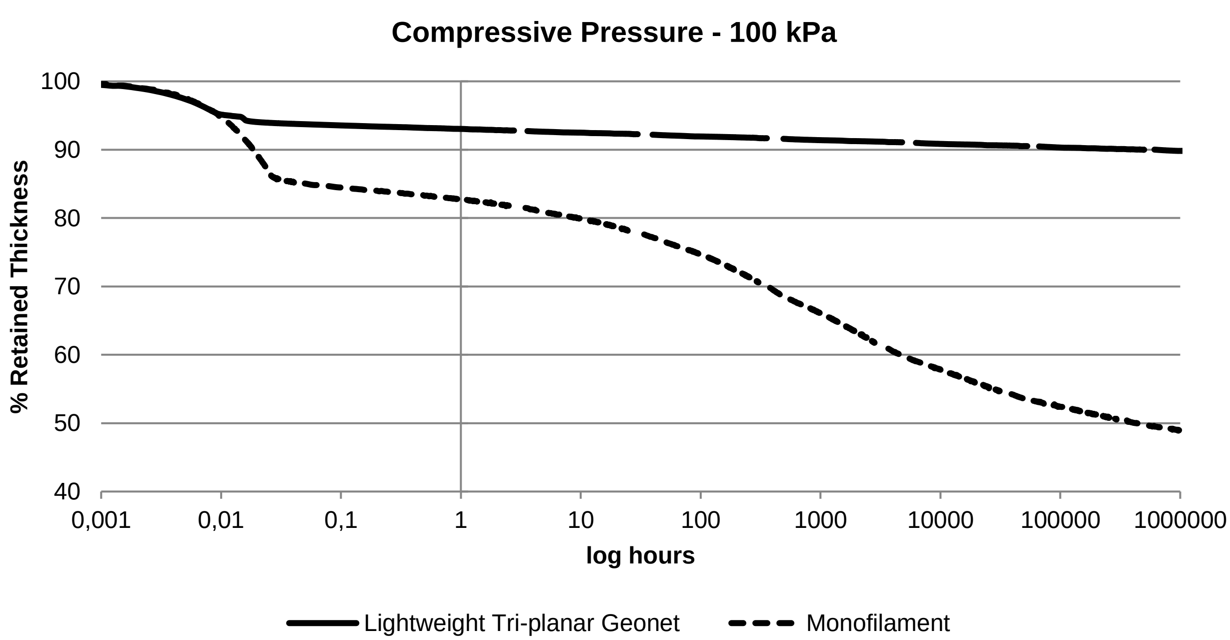


Figure 5. Retained thickness comparison between a lightweight tri-planar GNT and a monofilament after 1,000,000 hours and under 100 kPa normal pressure. Source: TRI Environmental External Laboratory (Austin, TX, USA).

Designers must be aware that the RF_{CR} is mainly dependent on the performance of the GNT itself, rather than the final application. Moreover, this is the most demanding reduction factor, as the value ranges from 1.05 up to 10.

Giroud et al. (2000) provides the recommendations to obtain the RF_{CR} considering the GNT thickness before and after the loading and the initial porosity, which depends on the GNT resin. For instance, based on a 1,000-hour test from the independent laboratory TRI (Austin, TX, USA), a lightweight tri-planar GNT shows a reduction factor of 1.08 after 1,000,000 hours and under 100 kPa, while a monofilament reaches the value of 4.13 under the same conditions, i.e. 3.8 times higher. This represents that the GNT will only experience a reduction of 8% of the initial transmissivity at the end of its life cycle due to the creep factor, while the monofilament will experience a reduction of 313% of the value provided in the datasheet.

Based on the project constraints, the GCD proposal either presented in bi-planar GNT (Table *1*) or tri-planar GNT (Table *2*).

2.3 Safety Factor

The safety factor is defined as the ratio between the long-term drainage capacity of the GCD and the flow capacity of the layer of granular material:

$$FS = q_{GCD,long\text{-}term} / q_{granular} \quad [4]$$

This representative value will be determinant to observe the feasibility under certain hydraulic conditions and applications, for instance under and/or over landfill waste (Figure 6).

a) New cells b) Capping systems

Figure 6. Cross-sectional view comparison between the conventional solution based on a layer of granular material (left) and the geosynthetic design (right). Source: Intermas Nets.

3. CASE STUDY

Given a primary leaching collection system (new cell, Figure 6a) with a slope of 10% and a 100-meter thick material placed over the GCD, the analysis over the conventional granular layer and the geosynthetic translation is hereby presented.

The conventional design will involve an 80-cm thick granular layer with permeability of 10^{-4} m/s, which has the following drainage capacity based on Equation [1]:

$$q_{granular} = (10^{-4})\ (0.1)\ (0.8) = 8e\text{-}6\ m^2/s = 0.008\ l/s/m \quad [5]$$

For an average unit weight of 18 kN/m^3 of the top material, the normal pressure over the GCD is estimated to be 1,800 kPa. Note that only a GCD formed by a tri-planar GNT thicker than 7 mm is able to sustain such loads (Figure 4). No other static or dynamic load is considered to surpass this value throughout the project's life cycle.

Considering that the leaching system is composed by a GMB/GCD/sand distribution (Hard/Soft boundaries), under all the stated conditions the short-term drainage capacity of the T-27.6 GCD tested under the ASTM D4716 standard is:

$$q_{GCD,short\text{-}term} = 0.21 \text{ l/s/m} \quad [6]$$

For the primary leachate collection application, the reduction factors chosen are shown in Table 4.

Table 4. Chosen reduction factor values

Application Area	RF_{IN}	RF_{CR}	RF_{CC}	RF_{BC}
Primary leachate collection (landfills)	1.8	1.1	1.8	1.5

The global reduction factor is then obtained:

$$\Pi RF = RF_{IN}\, RF_{CR}\, RF_{CC}\, RF_{BC} = (1.8)\ (1.1)\ (1.8)\ (1.5) = 5.4 \quad [7]$$

Therefore, employing the expression in Equation [3]:

$$q_{GCD,long\text{-}term} = q_{GCD,short\text{-}term} / \Pi RF = 0.21 / 5.4 = 0.039 \text{ l/s/m} \quad [8]$$

Finally, comparing with the conventional solution based on the aggregate as in Equation [4]:

$$FS = q_{GCD,long\text{-}term} / q_{granular} = 0.039 / 0.008 = 4.9 \quad [9]$$

This value represents that the T-27.6 GCD can drain 4.9 times more than a granular layer of 80 cm thickness accounting for the entire project's life cycle.

4. LOGISTIC FOOTPRINT

The case study presented in Section 3 is further extended in this section to account for the greenhouse gases (GHGs) emissions due to transportation from source/factory to jobsite.

The Global-warming potential (GWP) is an index that defines the amount of heat a greenhouse gas traps in the atmosphere. It's a value relative to the carbon dioxide effect (Table 5) and the total emissions are given in CO_2 equivalents (CO_2e), which result from the weighted sum of all the GHGs considered.

Table 5. GWP at 100 years for selected greenhouse gases (IPCC (2007), modified by CLECAT (2012))

Greenhouse gas	Chemical formula	GWP
Carbon dioxide	CO_2	1
Methane	CH_4	25
Nitrous oxide	N_2O	298

Given that the scope of this study is limited to the logistic footprint, the analysis won't consider the following processes:

- Manufacturing and transportation of laminated GTXs. Calculations will be based on a tri-planar 7-mm GNT, onwards T-27. This approximation is valid in terms of drainage and compression, as these properties are mainly derived from the geospacer.
  For further reference, Raja et al. (2015) investigate the carbon emissions embodied to GTXs and geogrids considering the entire cradle-to-grave life cycle.
- Manufacturing and transportation of HDPE pellets.
  For further reference, Hammond and Jones (2011) provide a list of the embodied carbon of most common thermoplastics.

Regarding the material transportation, the following hypotheses will be considered:

- Granular material:
  - Road freight from the natural source placed 20 km away from the jobsite. Transported one-way by a diesel dump truck with a payload up to 32 metric tons.
- Geosynthetic:

- Manufacturing plant placed 13,250 km away from the jobsite, divided into three itineraries:
  - S1: Road freight from the factory to the port of loading. 50 km transported by a trailer diesel fueled.
  - S2: Sea freight from the port of loading to the port of discharge. 13,000 km transported by a Transatlantic Panama ship class (2,000 - 4,700 TEU, volume goods) fueled by Heavy Fuel Oil (HFO) (CLECAT, 2012).
  - S3: Road freight from port of discharge to the jobsite. 200 km transported by a trailer diesel fueled.

Note that these conditions are site-specific and therefore results may vary significantly depending on the locations and the means of transport.

The consumption will be modelled similarly for each mean of transport:

- Road freight: An average consumption of 30 L of diesel per 100 km and emissions of 2,67 kg CO_2e/L (EN 16258:2012) yields an equivalent of 0,80 kg CO_2e/km.
- Sea freight: An average consumption of 0,0089 kg of HFO per ton-km and emissions of 3,15 kg CO_2e/kg (EN 16258:2012) yields an equivalent of 0,028 kg CO_2e/ton-km.

The project will require to drain over an area of approximately 6,000 m^2. This quantity is adjusted to one 40HC full container load of T-27 GNT, accounting for overlaps and scraps. This is the most common operative for long haul transportation due to the limited amount of material that can fit inside a container (volume limited).

4.1 Conventional Design

The volume of aggregate required in the conventional design can be easily obtained by multiplying the surface area to drain times the thickness of the granular layer. For an 80-cm thick granular layer, the volume of material needed is expressed as follows:

$$V = A\ b = (6{,}000)\ (0.8) = 4{,}800\ m^3 \qquad [10]$$

where

V is the volume of material needed
A is the area of coverage
b is the thickness of the drainage layer

Estimating an approximate amount of 12 m^3 for each truck load, a total of 400 trucks are required to reach the volume needed. This solution may represent a major problem for many construction sites due to the lack of access to natural deposits and/or develop logistic issues regarding supply needs.

Finally, the derived emissions after the completion of the material delivery will be:

$$E = N\ T\ d = (400)\ (0.80)\ (20) = 6{,}400\ kg\ CO_2e \qquad [11]$$

where

E is the total emissions (kg CO_2e)
N is the number of transportation units
T is the emissions per unit of distance (kg CO_2e/km)
d is the itinerary distance run by one mean of transport (km)

4.2 Geosynthetic Design

The geosynthetic approach with the T-27 GNT has an approximate mass per unit area of 1.25 kg/m^2. For a 3.6-meter breadth and optimized in length to fill a 40HC container, in this case 38 meters for a 48-roll distribution, the weight of each container is obtained as the sum of the total payload plus the tare weight:

$$Q = G + C = N\ R\ M\ w\ L + C = (1)\ (48)\ (1.25)\ (3.6)\ (38) + 4.00 = 12.21\ ton \qquad [12]$$

where

Q is the total gross weight per container (ton)
G is the tare of the container (ton)
N is the number of transportation units
R is the number of GCD rolls per transportation unit
M is the mass per unit area of the GCD (ton/m^2)
w is the roll width of the GCD (m)
L is the roll length of the GCD (m)

Therefore, the emissions due to transportation along the itinerary will be:

- S1 and S3: Both road transfers will yield the same amount of kg CO_2 per km. Therefore:

$$E = N\ T\ d = (1)\ (0.80)\ (50 + 200) = 200 \text{ kg } CO_2e \tag{13}$$

- S2: For a total weight per container of 12.21 ton, the equivalent emissions are 0.34 kg CO_2e/km. Then, the total emissions for sea freight transfer is obtained:

$$E = N\ T\ d = (1)\ (0.34)\ (13{,}000) = 4{,}420 \text{ kg } CO_2e \tag{14}$$

Overall, the itinerary for the geosynthetic approach result in a total of 4,620 kg CO_2e. This result represents a reduction of approximately 30% compared to the traditional solution based on a natural layer.

5. CONCLUSIONS

This study has presented the main benefits of high-quality GCDs against conventional solutions based on mineral resources from both the performance and the environmental viewpoints.

While the drainage of a layer of granular material can be simply verified using Darcy's Law, the analysis for the geosynthetic approach under the ASTM D4716 standard is dependent of three main variables experimentally reproduced in the laboratory: the hydraulic gradient, the normal pressure over the GCD and the boundary conditions over and under the latter. Moreover, the crush resistance is checked under the ASTM D6364 standard to ensure that the breaking point of the GCD is never reached throughout the design's life cycle, not by static nor by dynamic forces.

A customizable configuration of the GCD is important to adapt to the hydraulic and mechanical requirements of each project. In other words, different GTXs weights and different GNTs structures and thicknesses are combined to provide a cost-effective solution able to offer the expected performance. Having that said, high-quality GNT cores are essential in terms of in-plane drainage and crush resistance and their analysis is basic to understand the GCDs overall behavior.

Over the long-term, reduction factors are applied to the tested drainage capacity to account for the progressive GTX intrusion inside the GNT (RF_{IN}), the creeping factor of the GNT (RF_{CR}) and the chemical and biological clogging of the GCD (RF_{CC} and RF_{BC}). The safety factor at the end of the project's life cycle is obtained as a factor of the drainage capacity of the natural layer and the long-term drainage capacity of the GCD.

The case study presented a situation that can be typically found in heap leaching designs. The drainage of an 80-cm thick layer of natural soil with permeability 10^{-4} m/s is compared to the GCD type T-27.6 considering both the hydraulic and the compressive resistance demands of the project. Results show that high-quality GCDs can provide a reliable factor of safety over the long-term even under very demanding conditions.

Finally, the case study was extended to account for the analysis over the greenhouse gas emissions due to transportation to a jobsite required to drain approximately 6,000 m^2. Considering that the source material of the conventional approach is placed 20 km away from the jobsite, 400 trucks filled with the aggregate were accounted to generate a total of 6,400 kg CO_2e. On the other hand, the geosynthetic solution based on the GNT type T-27 resulted to produce a total of 4,620 kg CO_2e (i.e. 30% reduction), even though being supplied a total of 13,250 km away from the factory.

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