The role of geosynthetics in sustainable development and the circular economy

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1. Introduction

Geosynthetics have been the most important innovation in the field of geotechnical engineering in the second half of the 20th century (Giroud 2006). Although some may think that the International Geosynthetics Society (IGS) is similar to any other engineering professional society, in reality, the IGS was tailored to meet the specific needs of the geosynthetics discipline, as discussed in the brief history by Giroud (2006). However, the IGS can achieve more than this: it can make a real contribution to a number of issues currently of concern all around the world. The United Nations program "Transforming our world: The 2030 Agenda for Sustainable Development" (United Nations, 2015), which came into effect in January 2016, establishes 17 sustainable-development goals (SDGs) to guide decisions taken by nations and organizations over the next 15 years (United Nations, 2015). Dixon et al. (2017) were the first IGS authors to mention this document and the role geosynthetics could play in SDG 6, clean water and sanitation; SDG 9, industry, innovation, and infrastructure; SDG 12, responsible consumption and production; SDG 13, climate action; and SDG 17, partnerships for the goals. The IGS has published on the support of geosynthetics to this effort (IGS 2021a): The IGS website contains a dedicated page to this topic. The webpage also includes a series of "Did You Know" pamphlets, each highlighting a contribution of geosynthetics toward the UN's 17 Sustainable Development Goals (Ramsey, 2022).

The appropriate application of geosynthetics can make significant contributions to reduce energy consumption and emissions, preserve surface and groundwater and safeguard it from contamination, replace and reduce the use of construction materials, assist flood prevention and mitigate natural disasters, ensure environmental protection, allow economic growth and social welfare (IGS, 2021b).

In recent years, the circular economy has gained increasing prominence as a tool which presents solution to some of the world's most pressing cross-cutting sustainable development challenges. A circular economy is an economy in which waste and pollution do not exist by design, products and materials are kept in use, and natural systems are regenerated. The circular economy shifts wealth and prosperity from an unsustainable linear (take-make-waste) means of consumption to a system that is continuous and long-lasting. It is a system that is regenerative by design, where the needs of all citizens are provided within the natural means of the Earth. By addressing root causes, the concept of a circular economy provides much promise to accelerate implementation of the 2030 Agenda (The Netherlands Entreprise Agency, 2020).

The objective of this paper is to address the way geosynthetics contribute to the sustainable development goals, included through the spectrum of their contribution to the circular economy. Section 2 briefly overviews geosynthetics, describing what they are and presenting the main families of materials and their functions. Section 3 introduces various applications of geosynthetics and their contribution to the 17 SDGs. Section 4 evidences how unequalled solutions are possible when one is to use geosynthetics. Section 5 describes the joint environmental and economic benefits of the use of geosynthetics. Section 6 gives a brief insight in some of the many societal benefits of the use of geosynthetics, namely the contribution to resilience and economic growth and its impacts. Finally, Section 7 addresses the concept of the circular economy and the contributions of geosynthetics to this concept.

2. Geosynthetics

A geosynthetic is defined by the international standard EN ISO 10318-1 (CEN, 2015) as a product, at least one of whose components is made from a synthetic or natural polymer, in the form of a sheet, a strip, or a three-dimensional structure, used in contact with soil and/or other materials in geotechnical and civil engineering applications. Geosynthetics have pervaded geotechnical engineering to the point where it is no longer possible to practice geotechnical engineering without geosynthetics. Geosynthetics are not only convenient products; they constitute the basis of a recognized discipline because they perform a variety of functions and because, in many cases, their characteristics are essentially inherent to the geosynthetic, as opposed to being governed primarily by the interaction with a structure (Giroud, 2005). Various families of geosynthetics can be defined depending on the functions they fulfill: barrier on the one hand, drainage, filtration, protection, reinforcement, separation, and surface-erosion control, on the other hand.

The barrier function consists of preventing or limiting the migration of fluids. Geosynthetic barriers (GBRs) are geosynthetic materials that fulfill this function. A geosynthetic barrier is defined in the EN ISO 10318-1 standard (CEN, 2015) as a low-permeability geosynthetic material used in geotechnical and civil engineering applications with the purpose of reducing or preventing the flow of fluid through the construction. GBRs fall into three categories according to the material that fulfills the barrier function: (i) clay geosynthetic barriers (GBR-C) whereby the barrier function is implemented by clays, (ii) bituminous geosynthetic barriers (GBR-B) whereby the barrier function is implemented by bitumen, and (iii) polymeric geosynthetic barriers (GBR-P) whereby the barrier function is implemented by a polymer.

Other terminologies exist. The word "geomembrane" is often used to refer to GBR-Bs and GBR-Ps. The terminology "geosynthetic clay liner" (GCL) is also used to designate a GBR-C. A geomembrane is a planar, relatively impermeable, polymeric sheet used in civil engineering applications. GCLs are assembled structure of geosynthetic materials and low hydraulic conductivity earth material (clay) in the form of manufactured sheets used in civil engineering applications. Multicomponent GCLs are also available on the market. A multicomponent GCL is a GCL onto which is attached a film, coating, or membrane that decreases the hydraulic conductivity, protects the clay core, or both (von Maubeuge et al., 2011). Herein, the term "geomembrane" and the designation "GCL" are used together with the generic term "barrier".

A geosynthetic barrier must maintain its barrier function under the strains of installation, in service, and in operation. Because its sole function is to present a barrier to fluids, and given the various aforementioned strains, a geosynthetic barrier is integrated into a multistructure system, with each structure performing other specific functions. The principal other functions that other families of geosynthetics can fulfill are drainage, filtration, protection, reinforcement, separation, and surface-erosion control (CEN, 2015). According to EN ISO 10318-1 (CEN, 2015):

- Drainage is the collection and transportation of precipitation, ground water and/or other fluids in the plane of a geosynthetic material,
- Filtration is the restraining of uncontrolled passage of soil or other particles subjected to hydrodynamic forces, while allowing the passage of fluids into or across a geosynthetic material,
- Protection is the prevention or limitation of local damage to a given element or material by the use of a geosynthetic material,
- Reinforcement is the use of the stress-strain behavior of a geosynthetic material to improve the mechanical properties of soil or other construction materials,
- Separation is the prevention from intermixing of adjacent dissimilar soils and/or fill materials by the use of a geosynthetic material,
- Surface erosion control is the use of a geosynthetic material to prevent or limit soil or other particle movements at the surface of, for example, a slope.

Various materials within the family of geotextiles and related products can fulfill the six functions just described. A geotextile is defined as a planar, permeable, polymeric (synthetic or natural) textile material, which may be nonwoven, knitted, or woven and that is used in contact with the soil and/or other materials in geotechnical and civil engineering applications (CEN, 2015).

Geotextile-related products are planar, permeable, polymeric (synthetic or natural) material used in contact with the soil and or other materials in geotechnical and civil engineering applications, and that do not comply with the definition of a geotextile (CEN, 2015).

Various polymers are used to manufacture geosynthetics: high-density polyethylene (HDPE), flexible polypropylene (PP), linear low density polyethylene (LLDPE), plasticized polyvinyl chloride (PVC-P), ethylene propylene diene terpolymer (EPDM), and even bitumen (Touze-Foltz, 2010). In addition, a number of additives (i.e., chemical compounds) are used in the manufacturing process to ensure the durability of the polymeric materials. The chemical and mechanical characteristics of geosynthetics depend strongly on the type of polymer used, the additive formulation, the morphology, and the application of the geosynthetic (Hsuan et al., 2008).

3. The multiple applications of geosynthetics and their contribution to the SDGs

In the first "Did you know … Geosynthetics make significant contributions to the UN Sustainable Development Goals" of the International Geosynthetics Society (IGS, 2021a) some of the sustainable applications made possible by geosynthetics are listed. Geosynthetics contribute to the preservation of surface and groundwater and to safeguarding water from contamination, for example via landfill lining and construction of hazardous waste. More generally, environmental protection and resilience is achievable though the use of geosynthetics: other construction materials can be replaced or reduced, ensuring the reduction in energy consumption and emissions. Finally, economic growth and social welfare is enabled through the use of those unequalled solutions. Those various aspects are going to be presented in the following of this paper. Fig. 1 illustrates some of the many application in which geosynthetics are involved to feed the world, ensure quality water for all, protect the environment, mitigate natural disasters, ease economic development and the living together. The 17 goals from the United Nations' program are distributed around the various compartments mentioned above and are presented in Fig. 2.

4. Unequalled solutions are possible

Most of the applications in which geosynthetics are used are designed to perform at least equally to traditional design solutions. Part of the reason geosynthetic solutions have improved performance over traditional designs

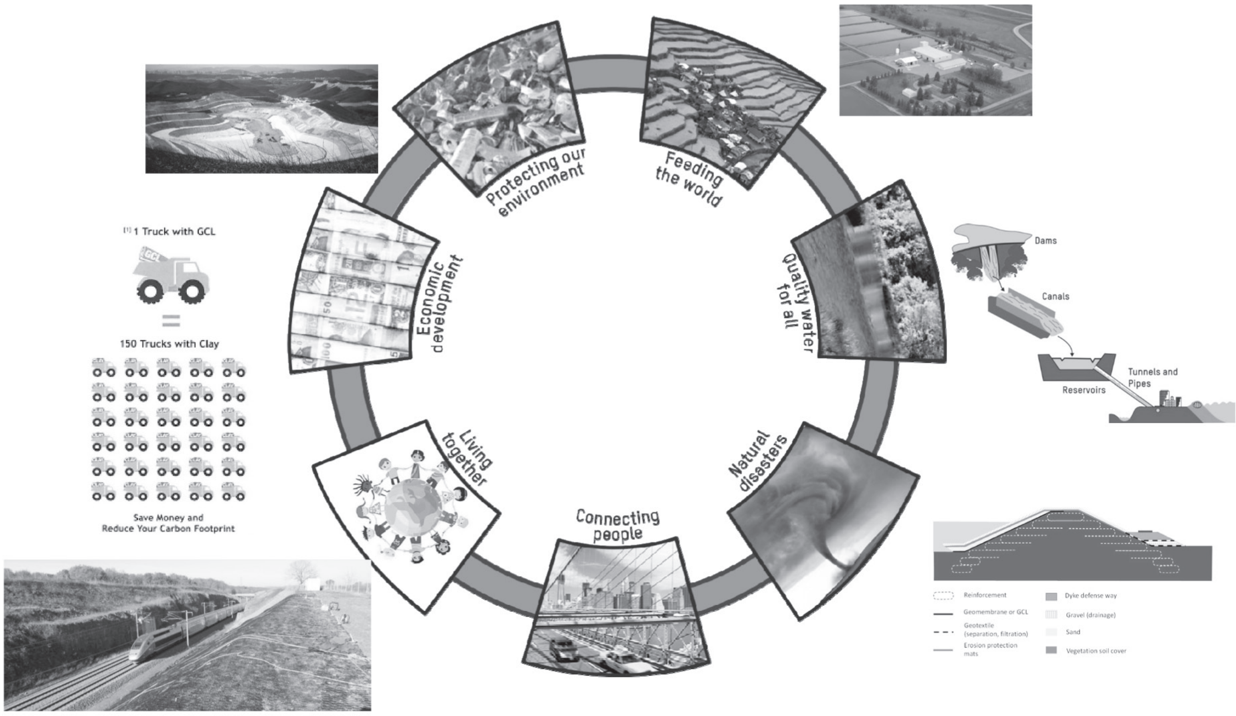

Fig. 1 - Some of the many applications and advantages of the use of geosynthetics to feed the world, ensure quality water for all, protect the environment, mitigate natural disasters, ease economic development and the living together (adapted from Touze, 2021).

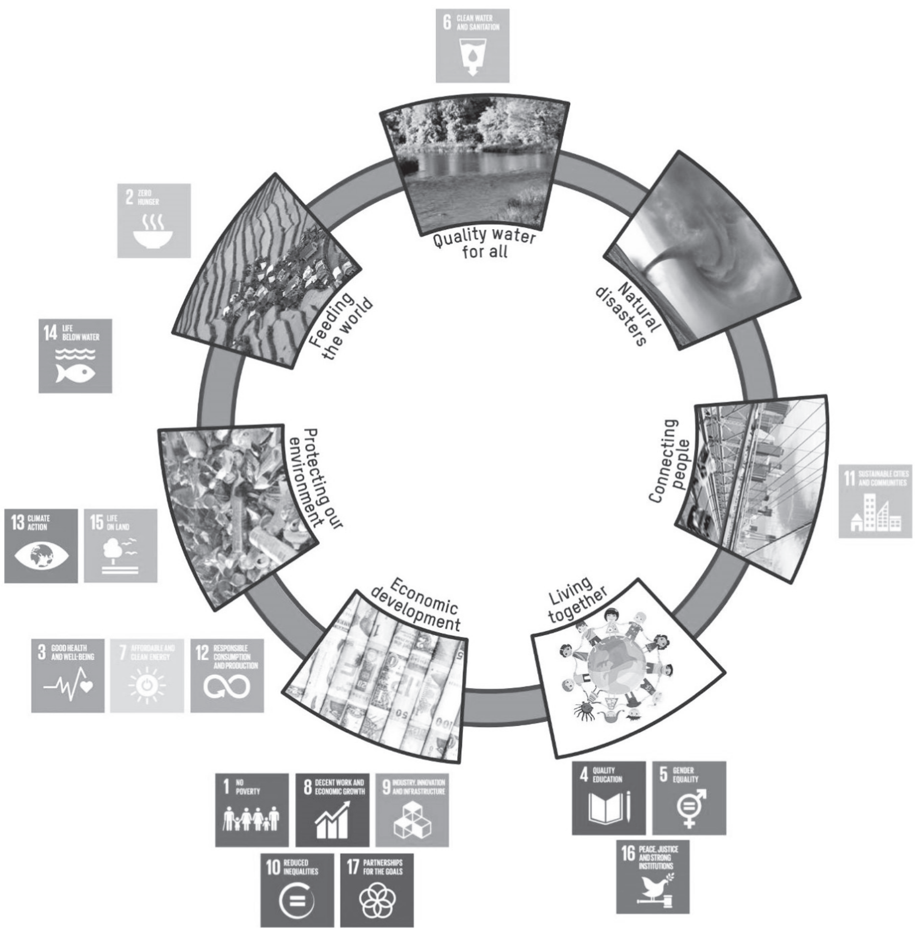

Fig. 2 - The sustainable development goals and the axes for action of geosynthetics (from Touze, 2021).

Material	Testing conditions	Hydraulic conductivity (ms^{-1})	Thickness (m)	Flow rate (m^3 m^{-2} d^{-1})
Cement concrete	In the field	10^{-10}	0.1	9.5×10^{-5}
Roller compacted concrete		10^{-8}	0.5	2.6×10^{-3}
Asphaltic concrete	In the field with excellent construction and quality control	10^{-9}	0.1	9.5×10^{-4}
Asphaltic concrete	In the field with ordinary construction and quality control	10^{-8}	0.1	9.5×10^{-3}
Compacted clay liner	With excellent construction and quality control	10^{-9}	1	1.7×10^{-4}
Compacted clay liner	With ordinary construction and quality control	10^{-8}	1	1.7×10^{-3}
Geosynthetic clay liners	As manufactured, confined and hydrated with low cation concentration solutions	10^{-11}	0.01	8.7×10^{-5}
Multicomponent GCLs	As manufactured	Meaningless	0.01	$<2\times10^{-5}$
Geomembranes	As manufactured	Meaningless	≥0.001	$<10^{-6}$

Tab. 1 Properties and flow rates through various lining materials including geosynthetic clay liners and geomembranes for an applied hydraulic head of 1 m for porous materials. The difference in pressure applied between both faces of the geomembranes and multicomponent GCLs is 100 kPa (from Touze, 2021).

is that they work better than the geotechnical material they replace. The performance improvement is gained by using manufactured materials with known properties as compared to the relative high variability of soils and requirements for monitoring of the installation/compaction of soils to allow for their desired properties to be achieved in the field. In some applications geosynthetics also improve the performance of geotechnical materials (Christopher, 2014).

In order to quantify the unequalled performance of geosynthetics the example of geosynthetic barriers is significant. Tab. 1 gives the level of performance in terms of flow rates of various mineral and geosynthetic materials. In fact, geomembranes are nonporous media so Darcy's law does not apply to them. The same rationale applies to multicomponent GCLs. Assigning a hydraulic conductivity to geomembranes or multicomponent GCLs is thus nonsense.

The data presented in Tab. 1 show that geomembranes are significantly more impervious than other barrier materials. Multicomponent GCLs and GCLs also offer greater hydraulic performance than mineral materials.

5. Environmental and economic benefits

There is a common misconception that sustainable solutions for infrastructure will cost more. This is not so in the case of geosynthetics. In reality, many geosynthetics solutions were developed to provide financial benefits and only later did the huge energy savings and environmental benefits become obvious (IGS, 2021c). In the following of this section financial benefits arising from the use of geosynthetics will be presented.

5.1. Financial benefits associated with the use of geosynthetics

The use of geosynthetics in civil engineering applications often provides financial benefits by reducing the cost of imported materials, reducing the amount of waste, and generally provides more efficient use of resources compared with traditional solutions that use soil, concrete, and steel (Jones 2015). Information allowing the evaluation of cost savings thanks to the use of geosynthetics is scarce. Christopher (2014) thus focused on the construction of civil engineering projects such as roads, embankments, retaining structures, erosion-control features, drainage systems, reservoirs, and waste-containment systems. The use of geosynthetics in roadways is the best documented regarding long-term performance, which is one of the following four types of cost savings that were identified:

- Reduction of the quantity or need for select soil material,
- Easier and/or accelerated construction,
- Improved long-term performance, and
- Improved sustainability.

Those aspects are presented in more details in the following.

5.2. Reduction of the quantity or need for select soil material

To reduce the use of certain soil materials, geosynthetics often replace the given soil and rock materials at a material and installation cost that is less than that of the natural-material alternative. Furthermore, geosynthetics are often used in geotechnical systems and, due to improved performance efficiency, may decrease the volume of other geotechnical materials used in that system. These reductions are combined with economic savings on both the purchase and transport of aggregate, soils and sand. Typically, this alone covers the cost of the geosynthetic (IGS, 2021c). In many cases the cost benefit is such that the use of geosynthetics is now the standard practice (Christopher, 2014).

Results obtained in recent studies show that geosynthetics reinforcement is promising for use as low-grade and low-cost sub-ballast material in railway construction. The use of materials such as mixtures of nonstandard material and mining waste instead of ballast can further reduce construction costs, particularly in regions where good-quality fill materials are scarce or expensive. More generally, a better use of residues and waste in engineering works is important to reduce the exploitation of natural material and to preserve the environment. The combination of geosynthetics with such residues may provide less expensive and more environmentally friendly solutions (Palmeira, 2016; Palmeira et al., 2021).

5.3. Reduction in energy consumption

In relation with the reduction of material amount to transport when geosynthetics replace aggregates, the reduction of onsite activity associated with the excavation of in-situ material and the placement and compaction of the soils and aggregates, energy consumption is logically reduced. These benefits apply in particular to the replacement of clay by impermeable geosynthetics in landfills, ponds, dams and reservoirs, but also when they are used to replace aggregates fulfilling the drainage function in various applications (IGS, 2021c).

5.4. Less long-term maintenance associated with significant contribution to the life span

Because geosynthetics last, they increase the lifespan of the infrastructure they are included in, saving resources, costs and time (IGS, 2021d).

Indeed, geosynthetic materials can provide long, useful lifespans for the projects that use them, maintaining performance for decades, and sometimes with the potential to last more than 100 years. A focus will be given in the following subsection to the durability of geomembranes, in the context of hydraulic applications. Knowledge of the service life of a geomembrane is of great interest because it is linked to the safety of the structure and can facilitate avoiding economic and human damages (Blanco et al., 2017a). Experience gained from samplings on site provides the benefit of feedback regarding reasonable minimum lifetimes that may be expected especially for geomembranes that are properly designed, constructed, and maintained in hydraulic works.

The hydraulic applications are those for which the most feedback exists on durability of exposed geomembranes evaluated by in situ sampling. The following subsections discuss the durability of exposed oxidized bituminous geomembranes, polymeric bituminous geomembranes, PVC-P geomembranes, PP geomembranes, HDPE geomembranes, and EPDM geomembranes in hydraulic applications based on recent findings reported in the literature following on-site samplings of exposed geomembranes and subsequent testing.

5.4.1. Durability of oxidized bituminous geomembranes

Microcracks can be observed at the surface of oxidized bituminous geomembranes when they are left exposed, leading in some cases to an increase in the flow rate through the geomembrane as compared with a virgin material. In some cases, the performance of the geomembrane is equivalent, but not better, than that of a one-meter-thick clay layer with a hydraulic conductivity in the range 10^{-9} to 10^{-8} m/s. When an oxidized bituminous geomembrane with no mechanical protection remains under water, the loss of performance is less pronounced than for one exposed to air and UV radiation. For covered oxidized bituminous geomembranes, on the one case tested, no microcracks appear and the performance remains stable for 30 years after installation. Thus, oxidized bituminous geomembranes should not remain exposed if long-term hydraulic performance is the goal (Touze-Foltz et al., 2010).

5.4.2. Durability of elastomeric bituminous geomembranes

The results for oxidized bituminous geomembranes cannot and must not be extended to elastomeric bituminous geomembranes (Touze-Foltz et al., 2010). The analysis of samples from various ponds (Fig. 3) indicates that the polymer is completely consumed within the first few microns of the surface of geomembranes exposed for over 15 years. In parallel, within the same surface layer of geomembranes exposed for over 15 years, the bitumen is oxidized. However, the disappearance of the polymer and the oxidation of the bitumen do not extend through the entire layer of bitumen binder. For geomembranes exposed for 30 years, the polymer, although still present at the core, is altered. Nevertheless, these geomembranes still deliver the same level of watertightness as do virgin geomembranes. Thus, the hydraulic properties of geomembranes are not significantly affected by these chemical modifications at the geomembrane surface (Touze-Foltz and Farcas, 2017).

5.4.3. Durability of PVC-P geomembranes

Cazzuffi et al. (2010) report on the use of PVC-P geomembranes in dams constructed in the mid-1970s (see Fig. 4). They conclude that, in this type of environment, the service life of PVC-P composite geomembranes exceeds 50 years. Considering that the quality of PVC-P geomembranes is better today than it was in the 1970s, longer lifetimes can be expected.

According to Blanco et al. (2017a), the service life of

PVC-P geomembranes can thus be determined by considering the plasticizer content. Depending on its composition, the geomembrane may last between one to two years for poorly formulated geomembranes to over 20 years (Girard et al., 2002; Carreira and Tanghe, 2008) and even 26 years as reported by Blanco et al. (2012a). A solution to reduce shrinkage induced by the manufacturing process and by ageing is the use of reinforced geomembranes or composite geomembranes (i.e., with an associated geotextile), which can reinforce durability on major structures such as the Barlovento dam (Fayoux and Potié, 2006; Blanco et al., 2012b), for which the geomembrane remains in good condition 23 years after installation, particularly on the nonexposed side (Blanco et al., 2016). Similarly, good results were obtained for the geomembranes at the Barranco de Benijos reservoir 19 years after installation (Blanco et al., 2012c). Blanco et al. (2017b) also report on the durability of six reinforced PVC-P geomembranes 18 to 31 years after installation in reservoirs in eastern Spain.

Fig. 3 - Pond lined with bituminous geomembranes at the Bazancourt sugar refinery at the time of geomembrane sampling for durability study (Touze-Foltz et al., 2015).

Fig. 4 - Camposecco dam samplings in Italy, courtesy D. Cazzuffi.

5.4.4. Durability of polypropylene geomembranes

Peggs (2008) summarized the use of PP geomembranes for a number of hydraulic applications: potable-water reservoirs, ponds for various applications, and floating covers on potable-water reservoirs. A number of failures occurred in the case of potable-water reservoirs and covers, typically after 3 to 10 years of service. However, PP geomembranes performed extremely well in other weather-exposed applications even in the case of potable-water-reservoir covers. For example, Wallace (2008) reports satisfactory performance over 5 years of floating covers on potable-water reservoirs. Furthermore, different PP resins have become available, opening the door to potentially more efficient geomembranes than was previously possible.

5.4.5. Durability of high-density polyethylene geomembranes

According to Blanco et al. (2017a), stress-crack resistance should be considered to determine the service life of HDPE geomembranes although HDPE is the most chemically stable polymer available (Touze et al., 2021). For a geomembrane installed in the Canary Islands under a subtropical climate and year-long sun exposure, Blanco et al. (2012a) and Noval et al. (2014a) report good performance of a HDPE geomembrane 20 years after installation. Baldauf et al. (2012) also studied the durability of a HDPE geomembrane after 17 years of service in a water reservoir in Spain under high levels of UV radiation. They reported that the geomembrane continued functioning as an impermeable barrier despite a significant decrease in resistance to stress cracking (Fig. 5).

5.4.6. Durability of ethylene propylene diene terpolymer geomembranes

Blanco et al. (2017a) suggest that elongation at break should be considered to determine the service life of EPDM geomembranes. Over a period of 21 years, No-

Fig. 5 - HDPE geomembrane installed in La Mericana reservoir (Jarandilla de la Vera-Cáceres-Spain) Courtesy M. Blanco.

val et al. (2014b) analyzed the evolution of an EPDM geomembrane installed in the El Boqueron reservoir on Tenerife Island in Spain. They noticed that the orientation of the geomembrane influences its ageing. Despite the evolution of the geomembrane (loss and oxidation of paraffinic oils), the flow rate through the geomembrane after 21 years measured according to the EN 14150 standard (CEN 2019) was less than 10^{-6} m^3 m^{-2} d^{-1}, which is consistent with values obtained for virgin geomembranes (see Tab. 1). References given by Blanco et al. (2012a, d) to studies of four additional reservoirs discuss situations where geomembrane properties remained stable for 13 to 15 years after installation.

Thus, although geomembrane properties evolve over time, most results show that the hydraulic performance of exposed geomembranes remains stable, except for oxidized bituminous geomembranes, which must be covered to maintain long-term performance.

5.5. Reduction in emissions

Two categories of actions are required to tackle climate change and its effects: (i) mitigation to reduce greenhouse gases (GHG) emissions, and (ii) adaptation. Geosynthetics can make a contribution to mitigation by reducing GHG emissions from construction and operating infrastructure as mentioned in Section 5.3.

The carbon footprint is a measure of total GHG emissions caused directly or indirectly by a person, organization, event, or product. The carbon footprint can include emissions over the entire life of a product or construction. Embodied carbon (EC) is an indicator of cumulative carbon emissions used in the solution adopted. Life-cycle assessment (LCA) is a tool for measuring the environmental impact of products or systems over their lifetime. It considers the extraction of raw materials, production, use, recycling, and disposal of waste (Dixon et al., 2017). It offers not only a basis for better economic decision-making but shows the ecological impact of choosing a particular method of construction (IGS, 2022).

The sustainability of materials and processes is commonly assessed by calculating the carbon emissions (CO_2) generated that can be used as “short LCA” for the ecological evaluation (Dixon et al., 2016). Taking into account the extraction and production of the used construction materials, loading, transport and installation, the cumulated energy demand (CED) and CO_2 emissions are determined for each of the construction alternatives.

Although this is a simplification, the ease of calculation encourages comparisons between solutions and makes such assessments accessible, transparent, and repeatable so that the CO_2 emitted can more easily be counted towards industry, national, and international targets (Dixon et al., 2016). Some studies have incorporated other indicators such as cumulative energy demand, climate change, photochemical ozone formation, particulate formation, acidification, eutrophication, land competition, and water use. Such calculations were made for various applications including filtration (Ehrenberg et al., 2012; Laidié et al., 2012), stabilization of foundations (Ehrenberg et al., 2012: Elsing et al., 2012), construction of a landfill drainage layer (Ehrenberg et al., 2012; Werth et al., 2012), building soil-retaining walls (WRAP, 2010; Ehrenberg et al., 2012; Fraser et al., 2012; Bouazza and Heerten, 2012; Damians et al., 2016a,b), implementing slope protection (Heerten, 2012; Bouzza and Heerten, 2012), road construction (Heerten, 2012; Bouzza and Heerten, 2012), implementing a capping system for landfills (Bouazza and Heerten, 2012), engineering slopes by using an electrokinetic geosynthetics treatment (Jones et al., 2014), and using geosynthetics to reinforce bridge abutments (Beauregard et al., 2016). The results of these studies show that structures that incorporate geosynthetic layers tend to have a lower EC compared with conventional granular solutions. The use of geosyntheics results in massive improvements to CO_2 savings as opposed to nearly all alternative civil engineering materials used. An additional study, however, analyzed the EC of a landfill-capping project (Raja et al., 2014). In this case, if clay is available on site or has to be transported only a short distance, the clay solution may be both more economical and more sustainable.

Raja et al. (2014) and Dixon et al. (2017) point out a limitation of these studies, which is that the databases used to do the LCA do not include values specific to geosynthetic products but only values for generic plastic materials. This point is pertinent because a key component of LCAs is the EC value of the materials used (Dixon et al., 2016). In fact, Raja et al. (2015) showed that the use of generic-material values from commonly used databases can significantly degrade the accuracy of carbon-footprint calculations. They improved the situation by offering EC values for geotextiles and geogrids. However, this dataset needs to be developed and extended to cover a range of other categories of geosynthetics. The availability of such comprehensive data would allow the production of a geosynthetics-EC inventory and an extension of existing databases to include geosynthetics.

Beauregard et al. (2016) also underlined the regional validity of data. Because most studies mentioned herein were done in Europe, they may not be applicable, for example, in the USA because of differences in transportation and energy production and use.

Dixon et al. (2016) further argue that a need exists for an industry-standard carbon calculator that is backed and endorsed by a number of geosynthetic manufacturers and suppliers and recognized and trusted by construction organizations and clients.

Example calculations presented by Dixon et al. (2016) demonstrate the importance of defining the LCA boundaries, the selection of EC values, and the critical role of transport-related carbon emissions. Furthermore, calculations should be site specific.

The approach proposed by Damians et al. (2016a,b) allows a more in-depth environmental assessment of soil-retaining wall structures. The full LCA method uses midpoint and endpoint indicators. There are 18 midpoint indicators, some of which appear in previous studies, such as cumulative energy demand, climate change, photochemical ozone formation, particulate formation, acidification, eutrophication, land competition, and water use (Ehrenberg et al., 2012; Elsing et al., 2012; Fraser et al., 2012; Heerten, 2012; Laidié et al., 2012; Werth et al., 2012). The endpoint indicators are human health, ecosystem diversity, and resource availability. According to the authors, midpoints give more reliable results whereas endpoints are more useful for making decisions because they are expressed as a single numerical score. Rather than comparing indicators one by one, Damians et al. (2016b, 2022) offer an elegant weighing and aggregating method to combine indicators. The resulting sustainability assessment method accounts for environmental impact, cost, societal and functional considerations, and stakeholder preferences.

In conclusion, the past few years have seen an improved mastery of techniques of LCA in the field of geosynthetics. The latest calculations done by Dixon et al. (2016) and Damians et al. (2016a,b) are indicative of the progress made in this field, in which an ever-more constructed standard approach is evolving by using EC values representative of geosynthetics and by comparing the EC values for entire construction solutions. Thus, results are recognized and trusted when the conclusion indicates that solutions using geosynthetics significantly reduce environmental impact.

The IGS is currently working on the development of a calculator focused on identifying, demonstrating and measuring generic environmental and sustainability benefits of using geosynthetics.

6. Societal benefits

6.1. Resilience is achievable

Water is the origin of life but also threatens life when it breaks out of its normal boundaries: all modes of human life require a balance between water and ground. Unfortunately, such a balance is not a persistent condition in many parts of the world inhabited by humans (Heibaum, 2014). The question of protection against water gains importance as population density increases in areas of the world exposed to the threat of climate change. Geosynthetics can make a significant contribution to adaptation, specifically by improving the resilience of communities and infrastructure against extreme climate disasters, such as flooding and landslides (Dixon et al., 2017).

In the context of climate change and the resulting expected increased frequency and magnitude of natural disasters, longitudinal dykes, constitute one of the most often used active structural methods to control the course of a river. Dykes are commonly made of different natural materials. They can also incorporate geosynthetics. A synthesis on the appropriate use of geosynthetics in dykes and their advantages in this context has recently been prepared by Rimoldi et al. (2021). The objective of this review paper was to compile a synthesis of the existing literature on this topic to address the many ways in which geosynthetics contribute to sustainable construction of dykes and thus contribute to water systems management. Emphasis was put in this paper on the fact that the use of geosynthetics not only allow more economic construction methods to be implemented, but also bring solutions with increased resilience to face the extreme stresses related to climate change, while at the same time bringing about a positive contribution to the reduction of greenhouse gas emissions during the construction process itself. The appropriate use of geosynthetics in dykes in relation to filtration and separation, to the management of the drainage of water within the structure over time, strengthening or steepening the structure with reinforcement and stabilization, minimizing impacts of erosion on the structure and enhancing barriers to water flow contributes to the improvement of dykes cross-section and to the reduction of their vulnerabilty towards floods (Rimoldi et al., 2021).

Damians et al. (2022) have adressed the question of the sustainable use of geosynthetics in the prevention of landslides. Landslides have occurred since time immemorial, even without any land transformation generated by human actions. Historically, different construction solutions have been considered with the aim of avoiding ground displacements, especially where there is risk to life, or where infrastructure, buildings or service installations are vulnerable to damage. Among the natural causes, the most frequent are rainwater infiltration, rising groundwater levels, loss of vegetated surface, erosion, and weathering. Damians et al. (2022) have identified the sustainability factors to be considered when applying geosynthetics for these purposes and present an overview based on existing literature to illustrate how geosynthetics typically outperform traditional methods across a range of sustainability criteria across the entire life cycle. The use of geosynthetics is evidenced to not only save time and money in installation but also to save lives. Sustainability assessment methods that account for environmental impact, cost and societal/functional considerations are becoming an important civil engineering tool for selecting the best option among multiple solutions performing the same function as evidenced by those authors who offer a model to analyse landslide mitigation application cases under a global sustainability approach.

6.2. Economic growth and welfare is enabled

The use of geosynthetics brings financial benefits, in relation with a number of avoided costs. There is thus more money available. For example, If the construction and maintenance of infrastructure is more efficient, then more investment capital is available for additional projects to help drive economic growth. The simple addition of a rail line extension or construction of a resilient and durable road could help improve the lives and prospects for entire communities, now and in the future (IGS, 2021c). Furthermore, the collection of plastic bot-

tles from which some geosynthetics are manufactured creates a significant number of income-generating opportunities for the people involved, with the example of South Africa (Ramsey, 2022). The lives of a number of often unskilled people with few or no other employment alternative is thus improved (IGS, 2021e).
A very simplistic virtuous circle can then be drawn, in which the available money in relation with the previously mentioned savings can be invested, depending on political decisions in more and better infrastructure, healthcare, education for example (Fig. 6). It is important to notice at this stage that the IGS also contributes to education through the resources made available like the Digital Library and the Educate the Educators (EtE) program. A synthesis of the first sessions of the EtE, an initiative aimed at providing Geotechnical Engineering university professors with the content and pedagogical tools needed to offer undergraduate civil engineering students ample exposure to geosynthetics, initiated in 2012 was given by Zornberg et al. (2020). The IGS' chosen approach of teaching educators who will in turn teach students was deemed the most rapid way to spread basics on the appropriate use of geosynthetic technologies. To ensure that environmental justice is achieved and consequently make the knowledge available to all, the IGS provides equal support, including financial support, to all chapters organizing an EtE event. Furthermore, supplemental IGS educational material is made available, for example in the form of a sustainability video, technical leaflets and a glossary of geosynthetics terminology. A series of videos and webinars is also made available through the Digital Library on the IGS website. This investment results in healthier better educated and efficient people. In a virtous circle, this finally results in avoided costs and financial benefits.
Finally, when people are confident that their children will live in good conditions, be educated to prepare their future, and live longer, the birth rate decreases. People also become more concerned by the quality of their environment. The decrease of the population (expected from 2064) and the awareness of environmental issues should result in a positive impact on climate change and use of resources (Norberg, 2016).

7. The geosynthetics contribution to the circular economy

7.1. What is the circular economy and what are its principles?

In recent years, circular economy has gained increasing prominence as a tool which presents solution to some of the world's most pressing cross-cutting sustainable development challenges. By addressing root causes, a circular economy is an economy in which (i) waste and pollution do not exist by design, (ii) products and materials are kept in use, and (iii) natural systems are regenerated. Resources are not consumed but recovered in a system that is continuous and long-lasting, with the goal of keeping them functioning at their highest potential. Instead of destroying value after the use phase, value is

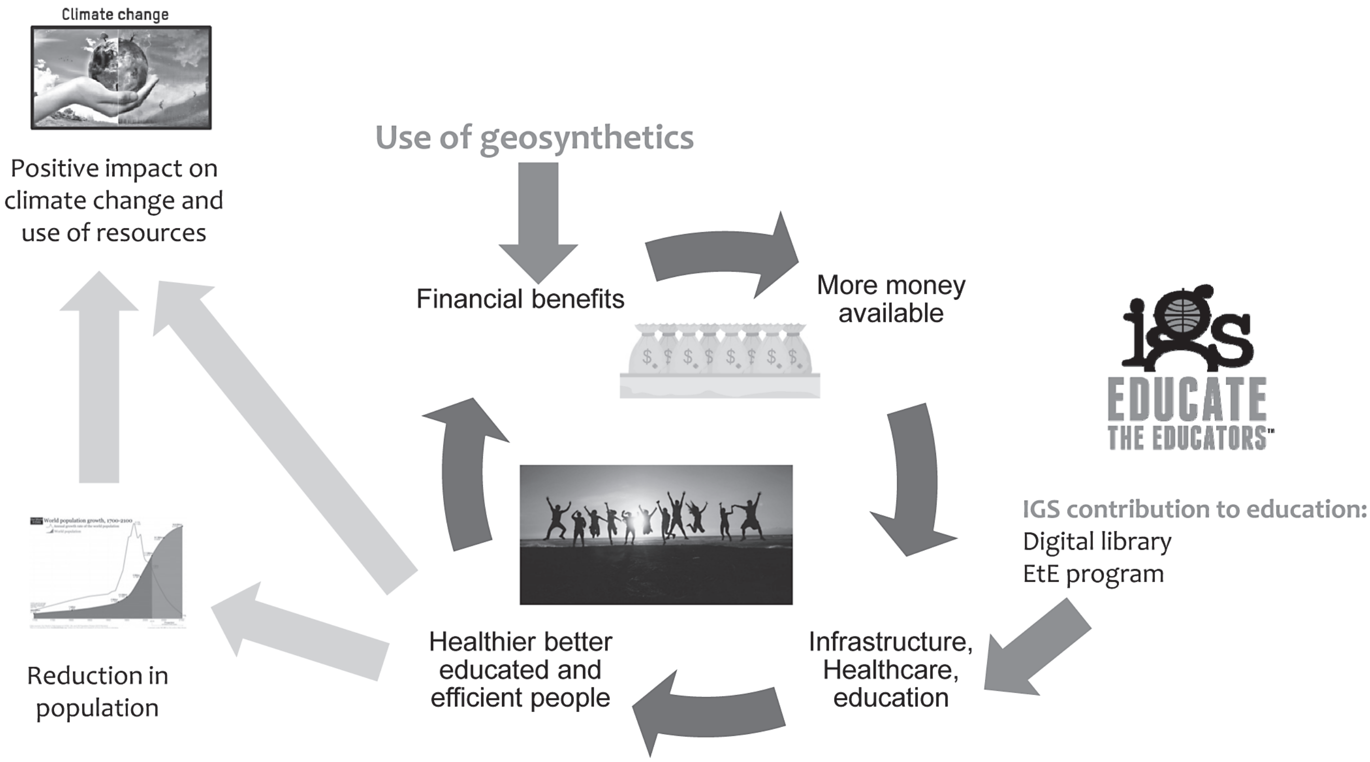

Fig. 6 - Virtuous cycle connected with the use of geosynthetics.

retained through cycles of reusing, repairing, remanufacturing or recycling.
the ReSOLVE framework takes the core principles of circularity and applies them to six actions: Regenerate, Share, Optimise, Loop, Virtualise, and Exchange that represent a major circular business opportunity (McKinsey, 2015):

- Regenerate. Shift to renewable energy and materials; reclaim, retain, and regenerate health of ecosystems; return recovered biological resources to the biosphere,
- Share. Keep product loop speed low and maximise utilisation of products by sharing them among users (peer-to-peer sharing of privately owned products or public sharing of a pool of products), reusing them throughout their technical lifetime (second-hand), and prolonging their life through maintenance, repair, and design for durability,
- Optimise. Increase performance/efficiency of a product; remove waste in production and the supply chain (from sourcing and logistics to production, use, and end-of-use collection); leverage big data, automation, remote sensing, and steering,
- Loop. Keep components and materials in closed loops and prioritise inner loops. For finite materials, this means remanufacturing products or components and as a last resort recycling materials,
- Virtualise. Deliver utility virtually, and
- Exchange. Replace old materials with advanced non-renewable materials; apply new technologies.

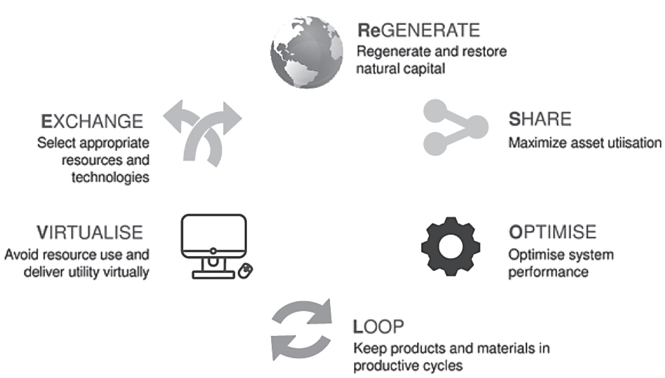

Fig. 7 - The ReSOLVE Framework.

7.2. How do geosynthetics support the circular economy?

What are, classifying following the ReSOLVE Framework, the ways in which geosynthetics support the circular economy? As regards a shift to reneawable energy, geosynthetics contribute by facilitating the recovery of biogas in agricultural and environmental applications but also through photovoltaic covers that can be encountered to cover ponds in hydraulic applications or on the covers of waste landfills for example, on top of geomembranes (Touze, 2021).
Section 5.5, has evidenced how the use of geosynthetics can contribute to reduce carbon emissions but also the impact to ecosystems, thus indirectly contributing to *Regenerate* by reducing the impact on ecosystems compared to other techniques like the use of concrete. In addition, geosynthetics have been used in environmental applications, where they protect soil from contamination from liquid or solid waste, including nuclear waste (Touze, 2021). More generally, geosynthetics have been used in remediation of polluted sites (Gisbert, 2009). Electrokinetic geosynthetics have in particular been proved to facilitate dewatering of waste like fluid fine tailings generated by the oil-sands industry (Gastaud et al., 2015; 2017) or soil decontamination (Jones et al., 2008). Finally, the use of geosynthetics for geotechnical purposes is a good example of a particular circularity, as the oil taken from the underground is processed and used to jointly reach development goals and returning the resource to the ground, without the liberation of the carbon included in the geosynthetic. It is one of the few application of oil based products, where the potential of CO_2 emission is returned to the soil (Fontana, 2022).
Section 5.4 has evidenced, discussing the durability of geomembranes, that less long-term maintenance is associated with significant contribution to the life span of works by the use of geosynthetics. Whether they are used as the one material in the original design or to rehabilitate works, by essence, they allow maintenance, repair, and as they are designed for durability, prolonging lifetime in their many applications thus contributing to the *Share* facet of the Resolve framework.
A recent piece from the IGS (2021f) puts emphasis on the optimisation process ensured in the production chain of geosynthetics with the examples of recovering the waste heat produced in manufacturing facilities to improve the energy efficiency of other spaces. Taking advantage of low outside temperatures wherever possible, reducing plants use refrigerants has also became a practice, as is recycling and reusing water wherever possible.
As previously noticed, geosynthetics are designed to last for decades. When the times comes to deconstruction the requirement of recyclability is always fulfilled by geosynthetics, with the theoretical exception of rare complicated composite materials impossible to separate back to the original components. The major obstacles to recycle a geosynthetic product at the end of its life are the distance of the specific project location from the possible recycling facility and the necessary cleaning, but this is the problem of any other product, and has to be evaluated every time in terms of economic and ecological costs (Fontana, 2022). The IGS (2021e) reports on the example of a company that salvages geomembranes used in containment before delivering them to recycling partners to process for re-use. This contributes to the market for recycled materials while also diverting materials from landfilling.
As regards the *Loop aspect*, a common approach is used by several companies related to packaging. Indeed a take-back program for packaging, overwraps, slings and other materials supplied with the geosynthetic materials for identification and transport exist. In these

cases, the manufacturing company has much more control over the packaging content of the materials. This is supported by mandates from engineering and general contractors for all waste materials associated with geosynthetics not to be left on construction sites for disposal (Ramsey, 2022). More use of recycled materials for the production of geosynthetics is possible, but, as for any other product, it has to be promoted if and when it is appropriate and useful to our environmental goals, thus taking into account (i) the geosynthetic in its application (Fontana, 2022), and (ii) difference between mechanically and chemically recycled polymers and the actual higher economic and environmental costs of chemically recycled polymers compared to mechanically recycled polymers. (Parenty, 2022). This is an important point, contrary to the objection to the use of recycled materials in the manufacturing process as detrimental to the performance of geosynthetics as compared to “prime/virgin” grades. Intelligent use, as less critical components, and in less critical applications, is a good first step (Fontana, 2022; Ramsey, 2022).

Geosynthetics products designed to strengthen road asphalt and extend road lifetimes can be manufactured from 100% recycled plastic originating from bottles and such geosynthetics products can themselves be recycled at the end of their useful life, typically through milling and re-manufacture (IGS 2021e). There are many places in the geosynthetic world where recycled feed streams can and are making contributions today in noncritical applications. As the quality of recycled feed streams improves, their use can be expanded (Ramsey, 2022). In its «Spotlight on Sustainable Initiatives in Geosynthetics», the IGS (2021e) reports on companies that use recycled contents in their products thus contributing to the diversion from million plastic bottles from being diposed of in landfill or waterways.

The geosynthetics industry is playing an ever-bigger role in making use of valuable materials that would otherwise be wasted and disposed of carelessly as stated in Section 5.2. Waste materials will degrade with time and may contain substances that can cause ground contamination. Responsible re-use and recycling therefore requires careful evaluation, design and thorough testing, to ensure all benefits of circular practices are captured, without incurring harm (IGS 2022b).

In terms of *Virtualization*, the IGS has made a tremendous effort to make more material available, in the past two years, on a revisited website, and especially in https://library.geosyntheticssociety.org/ where conference proceedings, educational materials, including educational lectures and webianrs videos are available, in order to share the knowledge on the appropriate use of geosynthetics at large. A tremendous effort has been made, by various chapters of the IGS and the IGS itself to develop webinars series and digital or hybrid conferences.

Geosynthetics have, by definition, and taking into account of the various advantages they offer compared to older technologies, the potential to be the *Exchange* resource to replace for example concrete in various applications like canal lining, aggregates in road construction, as two examples, allowing significant cost savings and environmental benefits, as previously emphasized.

8. Conclusions

The objectives of this paper were to evidence the many contributions of geosynthetics to the sustainable development goals of the United Nations. This question was first addressed, after a definition of what geosynthetics are, introducing some of their many applications in relation with the sustainable development goals. Particular emphasis was put on the fact that geosynthetics in their applications bring joint economic and environmental advantages compared to other geotechnical construction materials. They also contribute to reuse of materials of poor quality, included some waste, contributing to the mechanical or hydraulic perfomance of the resulting structure. This constitutes a first contribution to the circular economy.

Detailed data were given on the durability of geomembranes, that are geosynthetics used to ensure the barrier function. In addition to facts related with their better performance compared to compacted soil or concrete, the longevity of geomembranes is one of the elements resulting in reduced economic and environmental costs.

Various authors have worked in the past years on environemental analysis of bulding with geosynthetics. The various examples mentioned have shown how positively the geosynthetics industry has evolved in this matter in the past years, making progress in the evaluation of the environmental impact of geosynthetics. The experience gained results not only in positive communication as regards the use of geosynthetics, in line with the context of the sustainability web page on the IGS web site, but also in a continuous progress to keep on reducing their impact: reduction in water and energy consumption and in waste production during manufacturing and installation, rational incorporation of recycled polymer in the manufacturing process, virtualization.

Through the continuous effort made in improving practices, delivering materials of high performance, long lasting and environmentally sound, the geosynthetics industry as evidenced in this paper is, by its contribution to the sustainable development goals that expresses also through a contribution to the circular economy, an important actor of sustainable development.

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RIASSUNTO

Il ruolo dei geosintetici per lo sviluppo sostenibile nell'ambito dell'economia circolare

Gli obiettivi di questo contributo, attraverso la descrizione dei vari aspetti delle molteplici applicazioni dei geosintetici, sono principalmente quelli di dimostrare che questi materiali hanno costituito la più importante innovazione della seconda metà del XX secolo nell' ingegneria geotecnica, hanno inoltre contribuito in maniera decisiva alla realizzazione degli obiettivi di sviluppo sostenibile raccomandati dalle Nazioni Unite, hanno inevitabilmente comportato un impatto positivo sul nostro ambiente e sulle nostre vite ed hanno infine consentito un pieno rispetto delle tematiche sempre più attuali e fondamentali suggerite dall' economia circolare.

ABSTRACT

The role of geosynthetics in sustainable development and the circular economy

The objective of the paper, is to illustrate through various aspects of geosynthetics, that have been the most important innovation in the field of geotechnical engineering in the second half of the 20th century, how they do not only contribute to the Sustainable development goals of the United Nations, and thus to bring positive impact on our environment and lives, but are also able to get on board of the circular economy action along their manufacturing and their use.

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ECONOMIA CIRCOLARE
E APPLICAZIONI RESILIENTI

a cura di

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