

Geotextiles—A Versatile Tool for Environmental Sensitive Applications in Geotechnical Engineering

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Abstract: Geotextiles, a group of high-performance materials, have grown during the last decades into needful auxiliaries when it comes to infrastructure, soil, construction, agriculture and environmental applications. Although geotextiles made of synthetic fibers (geosynthetics) are considered a modern achievement, the basic concept dates back to ancient times when textiles consisting of locally available natural fibers were employed to increase the stability of roads and soils. In recent decades, considering the growing interest in environmental protection and sustainable development based on using renewable resources and the recovery and recycling of waste of various origins, the use of natural fibers-based geotextiles is a viable alternative, despite their limited-life service owing to their biodegradability. In addition to this feature, their low cost, good mechanical properties and large-scale accessibility recommend them for geo-engineering applications, environmental sensitive applications in geotechnical engineering, such as land improvements and soil erosion control. This paper focuses on geotextiles as a versatile tool in environmental applications given their high theoretic and practical relevance as substantiated by recent literature reports. Natural and synthetic geotextiles are presented herein, as well as their features that recommend them for geo-engineering. Insights on the main types of applications of geotextiles are also included, along with a wide variety of materials employed to perform specific functions.

Keywords: geotextiles; natural fibers; synthetic fibers; geo-engineering; environmental applications

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1. Introduction

1.1. General Considerations

Geotextiles, a group of high-performance materials, have grown during the last decades into needful auxiliaries when it comes to infrastructure, soil, construction, agriculture and environmental applications. Although geotextiles made of synthetic fibers (geosynthetics) are considered a modern achievement, the basic concept dates back to ancient times when textiles consisting of locally available natural fibers were employed to increase the stability of roads and soils [1–3]. Nowadays, whether it is the stabilization of soil in arid regions [4] or the river banks and seafronts (in tidal areas or harbor infrastructure) [5,6], ground reinforcement for civil infrastructure [7–9] or filtration of water excess in farmlands and flood protection [10–12], hill slopes stabilization and drainage [13] or even the reinforcement of airstrips under the tarmac layer [14,15], geotextiles are successfully performing in civil engineering and agriculture and becoming an increasingly viable alternative in many other applications.

Geosynthetics [16], the geotextiles made of synthetic polymers (such as PP, PE, PET and PVC) manufactured as fibers, are used in notably large amounts as the polymer production is cost-effective and the corresponding fibers are easily obtained by melt

spinning using already existing technology. Their remarkable mechanical properties (mainly tensile strength), durability and hydrophobicity make them fit for geotechnical engineering applications, such as the improvement of the bearing capacity of the ground in preparation of construction sites [17]. On the other hand, some polymers require a supplemental employ of additives, prior to their spinning, in order to improve or customize some of their properties with respect to their further applications. Thus, the UV resistance of PE fibers is significantly increased by adding carbon black as a stabilizer to the pristine polymer [18], while composites based on epoxy resins or unsaturated polyesters have achieved improved thermal and mechanical characteristics upon incorporation of glass fibers or carbon fibers in their formulations [19]. The main drawback of the long-term use of geosynthetics is their degradation under environmental conditions (humidity, acid/base or salty atmosphere, pollutants, UV-vis irradiation, wind and particle abrasion, microorganisms attack, temperature variation and seasonal freeze–thaw cycles, etc.) [20–22]. Nevertheless, the lifetime of geosynthetics and their operating performance depend directly on the chemical and structural stability of the synthetic polymers in their composition [23]. The advanced geosynthetics are, thus, designed so as to have better stability during their service time. Even more, with the considerable help of intelligent geotextiles which have sensors and/or sensing-and-actuating devices incorporated in their structure, it was possible to first discern chemical and/or physical changes of materials and to identify precociously the imminent material failure, whether a brittle or ductile failure.

In recent decades, considering the growing interest in environmental protection and sustainable development based on using renewable resources and the recovery and recycling of waste of various origins, the use of natural fibers-based geotextiles is a viable alternative, despite their limited-life service owing to their biodegradability. In addition to this feature, their low cost, good mechanical properties and large-scale accessibility recommend them for geo-engineering applications, such as soil stabilization and reinforcement, and erosion control [13,24–26]. Moreover, natural fibers (such as sisal, kenaf, hemp, jute, ramie and coir, etc.) employed for geotextiles are locally available which counterbalances their properties' variation (sometimes within large limits). Therefore, complex approaches have been developed in order to improve their properties and include (but are not limited to) fiber surface modification by various treatments [27], use of special additives or degradable thermoplastic biopolymers [28], employment of hybrid yarns made of natural and synthetic fibers [29,30], etc. Recently, it was assessed that natural geotextiles are able to replace geosynthetics in almost 50% of their applications [26].

1.2. Types of Geotextiles

Considering the structures obtained by manufacturing, geotextiles can be produced as various fabrics, as follows [1]:

1. **Woven**—these materials are obtained by classic weaving; their mesh opening (pore size and distribution) varies depending on the tightness of the weave; they provide high tensile strength and modulus but poor dimensional stability and resistance to abrasion;
2. **Nonwoven**—they are often referred to as mats, can be manufactured in a large variety of formulations and spatial layouts and provide high strain and permeability; their most relevant feature is their ability to resist damage by local lengthening, despite their low tensile strength;
3. **Knitted**—whether warp-knitted [31] or weft-knitted [32], these fabrics have tridimensional architectures with multiaxial, in-plane and out-of-plane reinforcements; they represent only 5% of the geotextiles currently used, but the demand for knitted geotextiles is rapidly increasing due to their particular mechanical properties [31].

Aside from these types of geotextiles, in practice there are other materials considered as geotextile-related products, such as geomesh, geonets, geocells, geogrids and geo-composites [3], which are used individually or in combination with others in order to enhance their action by working in synergy or to obtain a multitask layer.

General requirements that operative geotextiles need to meet in terms of properties are as follows [16]:

1. **Mechanical**—materials having specific mechanical properties, such as tensile strength and ultimate tensile strength, bursting strength, elasticity, abrasion resistance, bending strength and creep, are needed not only for infrastructure but for agriculture as well;
2. **Hydraulics**—properties such as water permeability and transverse water permeability are considered when geotextiles are used for drainage or to maintain soil humidity;
3. **Weathering**—this category of characteristics refers to the capability of geotextiles to withstand degradation under environmental conditions (humidity, UV-vis irradiation, biologic attack, temperature variation and seasonal freeze–thaw cycles, etc.). Due to the environmental impact of the degradation of geosynthetics, a wise selection of materials and scheduled maintenance (initial assessment of performance and service life, periodic inspections on site, replacement) are of high importance.

1.3. Geotextiles Main Functions

Filtration is one of the most important functions of geotextiles. Materials used for geo-filtration must respond to two opposite demands: they must possess a satisfactory level of cross-plane permeability to allow fluids to pass through and provide suitable pore size and distribution fit to stop (or, at least, limit) the migration of the smallest soil particles through their pores. In the dynamic of these processes, a natural filter is formed by coarse particles blocked, and subsequently compacted, on the geotextile [33].

Closely related to filtration, drainage refers to the ability of geotextiles to allow fluids to flow through their structure and along it, as well. Properties such as soil retention, clogging and flow capacity must be considered when selecting a geotextile for drainage [34]. Furthermore, these functions can be successfully employed when it comes to soil decontamination of heavy metals such as lead [35] or even aluminium [36].

Separation—this function is mostly relevant when geotextiles are employed in reinforcing and the stabilization of aggregate layers (roads, buildings foundation) in order to prevent them sinking into more fluid (fine particles soil, labile layers of clay) base soils. Bursting strength refers to the property of a geotextile to withstand a force applied perpendicular to the plane, with a certain deformation, up to the bursting point when the applied force exceeds the material strength. In correlation with the grab strength and puncture resistance, it indicates if a selected geotextile is suitable for such an application [37].

Geotextiles are also used widely for soil reinforcement in different situations: slopes and river banks, roads and infrastructure [38], etc. For such applications, properties such as tensile strength, surface friction, compression strength, pull-out strength and creep are most relevant as they grant the selected materials a long-term service life.

Geotextiles with low permeability are often used as barriers, especially geosynthetics, because they prevent water (fluid) infiltration into the protected structure (waterproofing) [16,39]. At the same time, the performance of the state-of-the-art containment barrier technical designs depends on the geosynthetics stability, especially when it comes to modern landfills where the geosynthetics are employed to prevent the leachate contamination of the surrounding soil [40]. For such environmental sensitive applications, geotextiles with complex formulation have been employed (such as geosynthetic-clay liners), and the main requirements are the low hydraulic conductivity and high mechanical characteristics [41].

Geotextiles present a series of limitations due to service stress, weathering and degradation under environmental conditions, which limit their level of performance. Nevertheless, their lifespan and cost-effectiveness, associated with increasing environmental awareness, are the main driving forces to expand the range of applications and demand for geotextiles, as well as the impact on market growth. In this regard, the global geotextiles market size was estimated at USD 4.6 billion in 2019 (when the largest market share was in road construction) and the projection for the interval 2020–2027 indicates a compound annual growth rate (CAGR) of 11.9% [42]. As for the regional aspects, it is noteworthy that Asia Pacific will dominate the market in the period 2021–2028 due to fast urbanization, while the EU strongly encourages “green” infrastructures in order to limit pollution and enhance environment protection [43].

This paper focuses on geotextiles as a versatile tool for environmental sensitive applications in geotechnical engineering given their high theoretic and practical relevance as substantiated by the most recent literature reports. Natural and synthetic geotextiles are presented herein, as well as their features that recommend them for geotechnical engineering. Insights on the main types of applications of geotextiles are also reviewed, along with a wide variety of materials employed to perform specific functions. Furthermore, some of the most recent advances in geotextiles, such as high-performance “green” (wholly or partially) geotextiles, intelligent geotextiles incorporating sensors and/or sensing-and-actuating devices, as well as other highly specialized geotextiles with complex formulations and multilevel architectures, such as composites containing high-performance fibers (carbon, glass or basalt fibers) or particulate fillers (clays, graphene oxide particles, carbon black), are included as well.

2. Fibers Selected for Geotextiles

2.1. Synthetic Fibers

Geosynthetics are products made of synthetic or natural polymeric materials, or combinations of both, which are used in contact with soil or rock and/or other geotechnical materials. A general classification of geosynthetic materials based on their physical form mainly includes geomesh, geonets, geocells, geogrids, geopipes, geofoams that can be grouped as geotextiles, geosynthetic clay liners and plastic sheets that can be grouped as geomembranes and geocomposites which are a combination of the above-mentioned products as a single material. Technically, the term geosynthetics refers to synthetic polymer-based materials. Natural fibers, as well as synthetic fibers, are also important due to their cost-effectiveness, environmentally friendliness and improved strength, and therefore the natural geotextiles are incorporated in the general classification of geotextiles. Synthetic geotextiles are the most widely used geosynthetics due to the unique property and strength they exhibit. However, geotextiles made of synthetic polymer are less susceptible to biodegradation in comparison with the natural ones [44].

About 98% of geotextiles consist of non-degradable polymers belonging to four classes of polymers: polyolefins (low-density polyethylene LDPE, linear low-density polyethylene LLDPE, high-density polyethylene HDPE and polypropylene PP), polyester (polyethylene terephthalate PET), polyvinyl chloride (PVC) or polyamide (PA, nylon). Antioxidants, hindered amine light stabilizers, UV absorbers and stabilizers, long-term thermal stabilizers, processing modifiers, flame retardants, lubricants and antibacterial agents are usually added as additives to enhance the performance of geotextiles. Synthetic fibers are used in geotextiles manufacturing primarily because they are water resistant, or have low water absorption, and good resistance to biological and chemical degradation [44].

Geotextiles made of synthetic fibers need to have longevity and keep their characteristics when subjected to severe environmental conditions. Properties such as high thermal stability, resistance to UV radiation, oxidation and chemical degradation are of utmost importance and limited only by the chemical structure of the polymer. The rate of

degradation is reduced by the addition of carbon black but not eliminated. Polypropylene is the most widely used fiber for geotextiles because of its low density, low cost, acceptable tensile properties and chemical inertness. However, polypropylene has a poor sensitivity to UV and a low thermal stability that results in poor creep characteristics. PET is inherently stable to ultraviolet light but susceptible to high pH environments. On the contrary, PP has excellent chemical and pH resistance but requires additives for UV stability [45].

The mechanical properties of the synthetic fibers depend on the molecular weight of the polymer but also on the conditions used in their production. These materials are produced in the form of continuous monofilament or multifilament yarns by the melt-spinning process. Generally, fiber fineness ranges from 2.2 to 60 dtex and the length ranges between 20 and 100 mm. Synthetic polymer yarns may also be produced by slitting extruded plastic sheets or films into thin flat tapes or twisting fibrillated plastic ribbons into yarns.

The tensile characteristics of these fibers can be designed for the final application, but generally PET fibers have much higher strengths than PP fibers and much lower creep. In general, PET is more suitable for geotextiles for the reinforcement function and PP for less strength-critical applications. The deformation of amorphous regions in polymers also has a significant effect on the stress–strain behavior of geotextiles and in the prolonged loading. It is one of the reasons that polyolefins, such as polyethylene and polypropylene (70–80% crystallinity), have higher creep characteristics [46]. PET has excellent tensile properties, high thermal stability and high creep resistance. The main drawback of polyester fiber is the easy hydrolysis and degradation in the soil with a pH > 10. Chemicals in the groundwater can react with polymers. All polymers gain water with time if water is present. High pH water can be harsh on polyesters, while low pH water can be harsh on polyamides [47].

Although most geotextiles are polyolefin- and polyester-based, polyurethane, glass and carbon-based polymers could be used for special purposes and functions. Because the manufacture of geosynthetic products requires large quantities of polymer materials, their cost should be low. PP and PET are therefore the most used synthetic fibers.

The type of application demands geotextiles have certain qualities and properties. Thus, geosynthetics exposed for long intervals to harsh and complex environmental conditions (wind, temperature, moisture, friction, UV radiation and pH) must be made of high-performance polymers in order to avoid precocious material failure as a result of polymer degradation (chemical, biochemical and photochemical reactions cause the weight and structural integrity loss of polymers) [48]. Still, as soon as the geosynthetic fails to perform its function, replacement procedures are initiated in order to prevent any hazardous side effects.

Their enhanced properties, such as aperture size, moisture sorption depth, mesh thickness, tensile strength, corrosion resistance, water permeability, hydraulic roughness and ease of processing, allow geotextiles to be used in soil protection applications where they accomplish functions: as filters, separator soils and other fine materials, drainers to remove or gather rainwater in the soil, reinforcement to stabilize and strengthen and, lastly, for protection in landfills or waste dumping sites and vegetation (afforestation, greening). Due to their applications in environmental protection, earthwork constructions, roadway and railway construction, marine and coastal structures constructions, riverbank and channels construction, the mining industry and landscaping, geotextiles have become the fourth largest new building material following steel, wood and cement [3].

According to the manufacturing processes, geotextiles can be divided into three major forms, namely woven, nonwoven and knitted, and they have multiple applications in various technical fields, such as construction, hydraulic, structural, transportation and agricultural engineering. Woven synthetic geotextiles usually have higher strengths and a lower breaking extension than nonwoven geotextiles of the same areal weight and

polymer type. In the domestic market, nonwoven geotextiles are primarily made with spunbonded, staple fiber needling and thermal bonding approaches. Spun-bonded geotextiles have good mechanical properties and filtration efficiency and a high production cost. Thermal bonded geotextiles have a higher tensile strength, tear strength, breaking elongation and vertical and horizontal ratio in comparison with needle-punched geotextiles that have the same specifications. Staple-fiber needle-punched geotextiles have a great thickness, a high density, a good permeability, a high pore fraction, a fluffy structure, a high deformation resistance and a low production cost, but their mechanical properties are not as good as those of common geotextiles [49,50].

2.2. Natural Fibers

Natural fibers are largely available in the surrounding environment and present some advantageous properties (proper strength and thermal attributes, reduced density, high level of mechanical resistance), making them suitable for ensuring an effective strategy which mainly envisages sustainable land management.

From natural fibers, those belonging to the plants' structural complex architecture are commonly used for natural geotextiles (known as limited life geotextiles—LLGs), given their abundance, easy processing for separation, reduced costs and excellent properties, mentioning only biodegradability which is essential for most short-term geotechnical applications from environmental considerations [51].

In Figure 1, a schematic presentation is given of some plant fibers investigated for employment in applications including geotextiles [52–55].

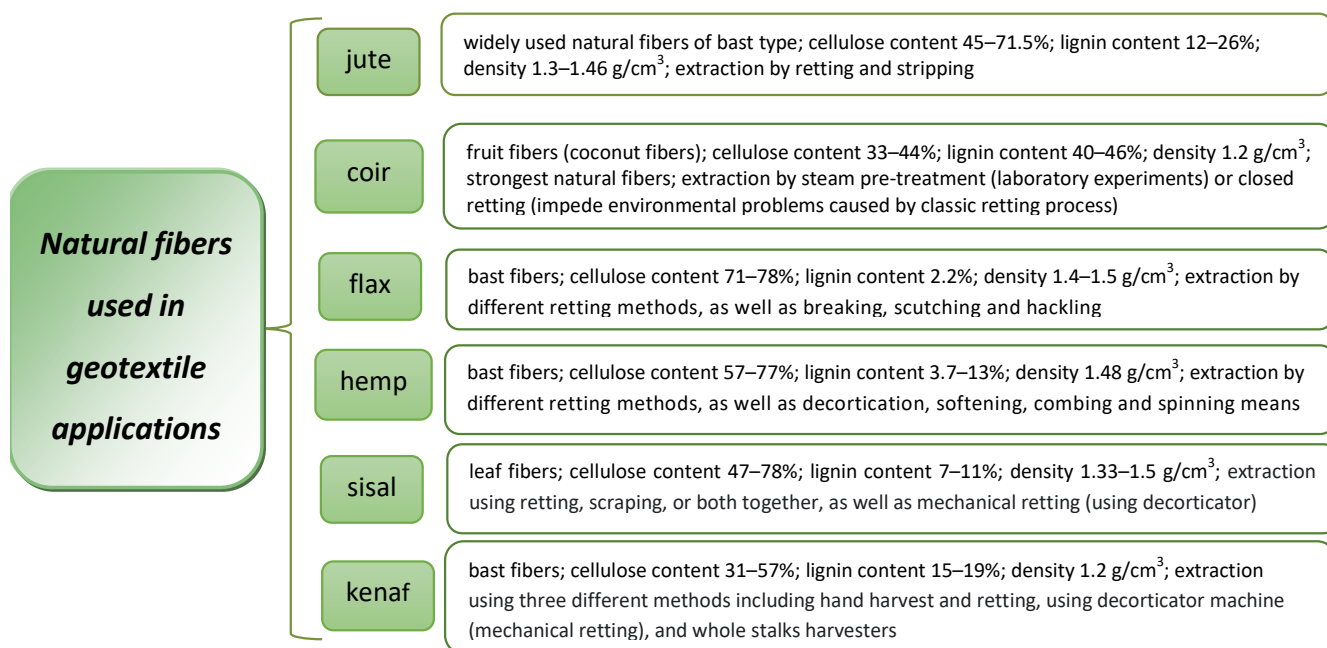


Figure 1. Most applicable natural fibers from plants for geotextile purposes.

The employment of the most suitable natural fibers in relation to their appropriate characteristics making them applicable for production of limited-life geotextiles has been comprehensively reviewed [26,51,52]. Most of the natural plant fibers present different strength and durability characteristics, for example, a high level of stiffness and outstanding thermal and soundproof properties [56].

Generally, natural fibers are suitable for the production of geotextiles when they have good mechanical performance and sometimes better hydraulic behavior depending on application and, as a pre-requisite, a better resistance to biodegradation processes. The

final characteristics of the natural fibers are strongly related to their variable chemical structure, dimensions, the varying physical characteristics in close relation to their kind/species, place of growth, harvesting time, location in the originating plant, processing methodologies and so on [57].

The largely employed natural fibers for geotextiles are jute and coir in relation with their abundance, reduced density, excellent mechanical properties, recyclability and outstanding quality as reinforcement for specific applications. Jute contains a significant amount of lignin. Coir is suitable for ensuring the fixation of vegetation at a certain level as well as maintaining it through proper conservation tillage, usually being spun and weaved into dense fabrics. These cover the soil in zones defenseless against the process of eroding and present good strength retention, a diminished degradation rate and good water absorption, meaning durability in field applications.

Coir-based geotextiles are fully biodegradable and present better resistance under sunlight exposure conditions. It was evidenced that the coir fibers can be effectively chemically modified by hydrophobization or acetylation [58] on a laboratory scale, with benefits through prolonging two or three times the functional service period of the resulted coir products.

When comparing with the classical fibers employed for geotextiles production which are prepared from recycled synthetic polymers, namely polypropylene and polyester ones, jute has better mechanical properties (which make it suitable for reinforcement application) and it is more hygroscopic (which makes it suitable for drainage application) [59,60]. When biodegradable geotextiles are required, natural fibers such as coir and jute are used. As the vegetation is fixed and developed to a certain degree, the degradation process of the fibers generates by-products which are useful for plants' growth. When jute and coir fibers are employed in geotextile applications, these absorb water to a large extent. Thus, the water run-off process alleviates the soil motion which maintains a certain adequate level of humidity.

2.3. Other Fibers

Along with the development of new technologies applied in geotechnical engineering, other high-performance synthetic fibers have been considered for geotextiles.

Carbon fibers are well represented in this category of applications due to their high strength, hydrophobic character and chemical and thermal stability [61]. In most geotechnical engineering applications, they are used in order to impart increased mechanical strength to materials. As felt [62], graphene oxide microparticles (0.5–5 μm) [63] and fibers [64], they can be found in various composites with geopolymers and are employed for filtration and building construction. Carbon fibers can be used as fabrics as well: sandwich structures made of electrospun polyimide nanofibers between two layers of carbon fabrics have been designed, produced and successfully used as filtration media able to retain PM 2.5 fine particles [65]. For reinforcing road structures, carbon fibers have been used in asphalt formulations, and the resulting geocomposites have improved resistance against crack growth, especially at low temperatures [66].

Glass fibers are also used in geotextiles as a nonwoven reinforcing material for soil stabilization, because the spatial orientation is random and the resulting structures are flexible, while imparting stability and strength to the engineered soils [67,68]. Another application of glass fibers refers to reinforced concrete formulations used in civil engineering [69,70], when materials with extended service life, fire resistance and improved thermal and mechanical characteristics were obtained.

Aramid fibers dominate the market of high-performance polymer materials. They have outstanding mechanical properties (e.g., high strength to weight ratio), impact resistance and chemical resistance and thermostability, along with low elongation. So, by consequence, the corresponding geotextiles showed excellent bursting strength and satisfactory elastic properties. One major drawback of aramid fibers is their high production cost, and it limited the use of these fibers in geotextiles. In their stead, recycled Kevlar®

fibers were employed for soil reinforcements in various geotextiles: as fiber in hybrid fibers [71,72], as a component in complex structures such as needle-punched nonwoven geotextiles, in combination with PET and PP fibers [73] or PET and nylon fibers [74], in epoxy- or PET-based composites as a reinforcing component [72,75] and in hybrid woven–nonwoven sandwich structures where nylon fabric was employed as an interlayer [76].

Other aramid fibers, such as Twaron® and Technora®, were also considered for geotextiles, as tridimensional nonwoven composites with epoxy resin as the polymer matrix [77]. A serious limitation of the service time of these geotextiles is the degradation of aramid fibers under alkaline and neutral conditions [78].

Basalt fibers, another group of high-performance fibers, are of natural origin (volcanic rock), and after industrial processing, they have properties close to glass fibers. They are used for soil reinforcement, not as typical geotextiles but as reinforcing fibers in mixtures with soil [79], or in other combinations intended for the reinforcement of roads and airstrips [80].

3. Applications of Geotextiles

3.1. Synthetic Geotextiles in Soil Erosion Control

Erosion can cause severe deterioration in coastal areas, on slopes and riverbanks, especially where vegetation is weak or lacking. Preventing or limiting soil movement under the influence of erosive forces, such as moving water and wind, is the basic principle for controlling soil erosion. Tidal situations (i.e., coastal and river) occurring naturally or by the movement of water induced by maritime transport can be controlled by techniques that provide armored protection with geotextile support. Sludge retention and ground cover retention and revegetation on steep slopes involve techniques that use geotextiles. Erosion control uses synthetic materials for silt containment and soil retention as long-term solutions and synthetic and natural materials for revegetation on steep slopes [44].

The introduction of geotextiles in erosion and sediment control systems has offered significant advantages when used alone or combined with traditional natural materials (such as straw, rock, brush and soil) and unique and quantifiable functions in erosion and sediment control applications. Stabilization of the surface by restricting movement and preventing the dispersal of soil particles subject to erosion (rain or wind) takes place by placing geotextiles on the soil surface where they can also allow or promote vegetative growth. The control of soil erosion under the action of geotextiles involves the active control of soil dislocation, while the control or retention of sediments consists of retention and filtration of dislocated soil (called sediment), transported by runoff.

As a consequence, new geotextile materials have been developed, aiming at the revegetation of bare soil or as a support of vegetation in erodible soil, long-term non-biodegradable support and temporary biodegradable support for new seedlings.

Synthetic polymers such as PP, PET and PA are modified with additives to improve their resistance under UV irradiation and are used for a long-term permanency (keeping 75% of its original strength after 10 years of life) [3]. Geotextile erosion control products, such as erosion control nets (ECN), open-weave erosion control meshes (ECM), blankets (ECB) and turf reinforced mats (TRM), provide greater strength, enhanced performance and greater longevity than that of conventional natural mulches such as loose straw, brush, soil or compost [81]. These geotextile-enhanced systems reduce seed and soil loss owing to erosive forces and facilitate site revegetation. Erosion control nets (ECN) typically consist of polyolefin biaxially-oriented process mesh and are used to bring together loose fiber mulch. Having been flattened out over the seeded and mulched area, ECN are stapled or staked in place. Open-weave erosion control meshes (ECM) are woven of organic twine of jute or coir or polyolefin yarns. Usually, organic meshes have 0.6–1.2 cm thick and 2.5 cm or larger square uniform openings. Polyolefin meshes are considerably

thinner with smaller openings. All meshes provide incomplete ground coverage, even though they are flexible and promote appropriate ground cover. At the same time, organic meshes absorb water and are beneficial for keeping soil moisture. Erosion control blankets (ECB) are organic fiber-filled blankets composed of straw, wood shavings or coconut fibers sewn to or between synthetic (or organic) nettings. The nets provide resistance to these materials to withstand the action of erosive forces. The durability of organic fibers decides the lifespan of these materials.

Fused or stitched polymer nettings (often filled with polymeric fibers), randomly settled monofilaments or yarns woven or tufted into an open and dimensionally stable mat, are the main components of turf-reinforced mats (TRM). An increased stiffness and strength are the result of the dimensional stability. Strong, durable and continuous soil-root-mat matrices are generated by these flexible, synthetic mats in combination with topsoil and seed or turf which can result in higher long-term erosion protection than grass alone.

Fabric-formed revetments (FFR) are low-cost, durable, synthetic fabrics used to produce three-dimensional mats for casting concrete slabs. They provide the durability of rigid linings such as cast-in-place concrete or asphaltic concrete and the flexibility and/or water permeability of protective rock systems such as riprap or gabions. Geocellular confinement systems, often called geocells (GCS), consist of strips of polymer sheets connected at staggered points. When the strips are pulled apart, a large honey-comb mat is formed that can be filled with soil, rock or concrete.

Usually, geocell thickness varies between 5 and 30 cm. This erosion control product is efficient when the surface soil is retained on a slope. Geotextile filter systems are placed on the soil surface beneath a hard armor system when they perform the function of dynamic filtration. The geotextile provides support for the armor layer over the seepage-induced softened subgrade as the water surface rises, and when the water surface recedes, seepage from the subgrade cannot carry soil particles with it which could cause undermining of the armor layer [82].

3.2. Synthetic Geotextiles in Railway Infrastructure

There are several factors such as the traffic, track structure, subgrade conditions, drainage conditions and maintenance requirements that impose the characteristics of geotextiles in a railroad track structure. In railway construction, geotextiles are used to increase track support for the laying of new lines and rail track rehabilitation and also to accomplish the separation, filtration and lateral drainage. Geotextiles have proved useful in the existing right-of-way where a large amount of track maintenance has been necessary due to poor drainage conditions, soft conditions and/or high-impact loadings. Usually, geotextiles are introduced between the subgrade and ballast layer or between the subgrade and subballast layer if one is present. Geotextiles are used in the “pumping track” and “ballast pocket areas” that are associated with fine-grained subgrade soil and difficult drainage conditions. The main foundation of a rail track is formed by subgrade soils, and layers of granular materials and subsequently the sleepers and rail lines are placed on them. The load-supporting intermediary between the railway lines and the subgrade is provided by the aggregate layers. When the wheels on each axle of a rolling stock traverse the line above a sleeper, the aggregate layers undergo a repeated cyclical stress. In time, a pocket of fouled and ineffective ballast is generated, and loss of track grade control takes place as ballast is forced deeper and deeper into the subgrade. Permanent track maintenance problems are attributed to these ballast pockets that collect water and decrease the strength of the roadbed around them. During the rehabilitation process, the geotextiles provide separation, filtration and drainage functions and can prevent the reoccurrence of a pumping track. Poor subgrade/drainage conditions, highway-railroad grade crossing, railroad crossings, turnouts and bridge approaches are locations of excessive track maintenance that require the installation of a geotextile in the railroad track. The installation of a geotextile in the track requires adequate drainage,

otherwise water will be kept in the track structure and the insecurity of the track will be more damaged. Geotextiles are not used to decrease the ballast or subballast design thickness because they have no reinforcement effect on soft subgrades under the railroad track [83].

Woven geotextiles tend to clog with time and act almost as a plastic sheet preventing water from draining out of the subgrade. Consequently, they are not recommended for use in the track structure of railroads, and nonwoven geotextiles and needle-punched materials are used instead.

Geotextiles are used in embankments and to separate the ballast or subballast from the subgrade (or the ballast from the subballast) in a railroad track. A stable railroad track structure is based on adequate drainage and provisions for improving both internal and external track drainage. Drainage provisions involve deep side ditches to manage surface runoff and an adequate crown in both the subgrade and subballast layers to prevent water from ponding on the top of the subballast or subgrade. Water accumulation in the track can be avoided by the installation of perpendicular drains, and the removal of water from the track structure is supported by French drains. The creation of bath-tub or canal effects should be avoided during track rehabilitation by having the shoulders of the track below the level of the ballast/geotextile/subgrade interface. Before geotextiles should be placed in a railroad track structure, the existing drainage problems must be corrected [84].

3.3. Geosynthetics as Reinforcements

The reinforcing function of geotextiles is one of the most used in geotechnical engineering. Tensile modulus, tensile strength and surface friction are the most important mechanical properties of a geotextile used for reinforcement.

The resistance of soils to tensile forces is much lower than to compressive forces. Soil stability through reinforcement can be achieved by inserting an appropriate geotextile into the soil and aligned with the direction of the tensile forces. The soil allows the transfer of these forces to the geotextile, using its axial strength.

Efficient reinforcement requires a high tensile strength and a high tensile modulus of the geotextile. The resistance of the geotextile to tensile loads generated in the soil occurs at sufficiently small strains to prevent excessive movement of the reinforced soil structure. The polymers used in these applications should have resistance to degradation by the soil and altering in these properties with time (i.e., creep behavior) must be insignificant [85,86].

Reinforcement exerted through a geotextile takes place when the stability of the weak subgrade or soil is complemented by the higher tensile strength of the fabric. The geotextiles embedded within the soil improve the cohesion between the grains and the resulting composite can sustain higher loads and tensile or shear forces. The forces applied on the soil structure through different loads are transferred into tensile stresses, which further influence other mechanical properties, such as puncture resistance [87].

An efficient reinforcement is provided by a geotextile with sufficient strength and embedment length to resist the tensile forces created. To prevent excessive movement of the reinforced structure, the strength must be developed at sufficiently small strains (i.e., high modulus). Woven geotextiles are used to reinforce embankments and retaining structures, because they provide high strength at small strains.

A compacted layer of aggregate has good compressive strength but very poor tensile resistance. As a consequence, a geotextile is necessary to reinforce the soil and confer resistance to a compacted soil from breaking up under tensile stresses [88]. Most reinforcements use fabrics obtained from PP or PET filaments. Very high strength applications, requiring strength of 400 kN/m, use *para*-aramid (e.g., Kevlar), glass or basalt filament. Applications where strength/cost ratio is a required factor use PET filaments. PP cannot always be used because it is susceptible to chemical attack in high pH environments. PP is more resistant to chemical degradation, but its long-term creep characteris-

tics are much poorer than PET. Generally, PET is more suitable for geotextiles having a reinforcement function and PP for less strength-critical applications. The monofilament woven fabrics made of PET provide better permeability, because multifilament is used for higher strength reinforcement.

Slit film, flat-tape fabrics are usually PP materials, which are quite strong but have relatively poor permeability. On the other hand, fabrics from fibrillated tape yarns have better permeability and more uniform interstice openings than flat-tape products [85,89].

3.4. Geosynthetics for Filtration

For a very long time, geotextiles have been widely applied for filtration purposes. One can mention here the drainage of pavements, dewatering of trenches, reinforcement of shorelines and slopes, inclusion in panels for drainage in their stage of prefabrication, as well as in systems for leachates' accumulation and caps for landfill function [90].

There are some filtration prerequisites to be fulfilled by geotextiles in order to function as an efficient filter [91]. Liquid is passing through the filter while the soil particles remain if they have a larger dimension than the pores of the geotextile filter from which those larger are in fact smaller, comparative with the size of soil particles.

The clogging of the geotextile filter may be prevented if a major part of the pores in the filter are large enough to allow the passing of the smaller soil particles. A proper flow through a geotextile filter is ensured by the presence of a significant number of large pores in its structure, the inter-relation between the flow dimension as volume passes through the filter and its effectiveness for filtration applications being well recognized. [92].

In the filtration application, the geotextile filter may function in three different manners, and these include close contact with soil particles, interaction with suspension of soil particles and cyclic loading when the migration of soil particles occurs. A geotextile filter should act as an effective barrier and/or as part of a self-filtration or vault network formation mechanism when combined with a natural filter. Thus, the migration of soil particles is ceased through the formation of a rough layer at the interface of the geotextile filter (self-filtration). The second mentioned mechanism (vault network formation) involves electrical and adsorption interactions usually present between soil particles as well as between lubricant and an antistatic agent at the interface of geotextile fibers/soil particles, when these particles appear as ordered vaults. A geotextile filter may present an impervious layer of particles formed through an interaction with a suspension of soil particles, impeding the flow in a given time period and consequently requiring its replacement. Easy soil particle migration at the geotextile filter interface is observed in the cyclic loading filtration mechanism when the hydraulic force pushes the smaller soil particles to migrate toward the filter [93].

Geotextile filters applied for filtration purposes should fulfill some important criteria, as follows:

(1) Blockage or retention criteria: The free flow of water through the pores of a geotextile filter is impeded to a certain extent or completely stopped when fine particles are present [91,94]. The retention ability of the filter is strongly related to its structure, as well as to both soil characteristics (type, uniformity, curvature, density) and flow regime [95,96]. For various fabrics, a simple relationship can be established considering the yarn diameter of the spun geotextile and soil particle size [89].

(2) Blinding or permeability criteria: On the geotextile filter surface, overlays of fine particles are sometimes formed, usually when phenomena such as water flow ceasing and drying of the geotextile surface take place [97]. Generally, a certain relation between geotextiles' permeability and corresponding flow at the interface between soil particles and the filter can be established, meaning that based on this assumption, the geotextile filters have to be more pervious than the retained soil particles. An important issue related to these second above-mentioned criteria is the comparison between the permeability ability for both the geotextile filter and soil particles. Thus, a geotextile can be used

as an effective filter through an appropriate design in order to allow an easy flow of liquids from one side of the material to the other side, impeding the soil particles passing from the upstream side.

A geosynthetic filter must fulfill a satisfactory level of permeability to allow the liquid flow and also have an average pore size and pore-size distribution sufficiently small to obstruct all particles migrating through its thickness, except the finest ones. These contradictory requirements are accomplished by textile structures, which are the only material form that can be readily manufactured.

Geo-filtration uses the basic mechanism of wet filtration, and a geotextile filter enables the finer particles to be either carried through the filter thickness by the fluid flow or lodged within it. Whether the fine particles leave the soil/filter interface, the coarse ones are blocked at the interface and form a compact porous layer that allows the appearance of small pores. An additional filter layer is formed by blocked coarser particles at the interface which becomes a new filtration zone for smaller particles. As the process goes on, the geotextile filter acts as a graduated soil filter and a catalyst to produce a natural filter within the soil. The dynamic equilibrium stage involves a gradation of permeability, when the geotextile filter is the most permeable, and the soil furthest from the filter has the lowest permeability. Thus, the fluid flow into the filter will ultimately be controlled by the parent soil. Therefore, the material cross-plane permeability and pore-size characteristics are the two properties that define the performance of geotextiles as filter media [98].

(3) Clogging criteria: This is a gradual clustering of soil particles within the geotextile pore openings as they are trying to pass through the pores [92]. It was suggested that the geotextile having more openings should be beneficial in comparison to the geotextile with fewer openings. As the liquid flows through the openings, some of them will be blocked by soil particles, but the remaining openings are still available for keeping the satisfactory permeability characteristics [93]. The concept of positive wash through, as a lower limit for a filter criterion, is based on beneficial loose soil particles that provide a satisfactory permeability and resistance to clogging [94,99]. Preventing the clogging of a geotextile can be evaluated using a relationship between particle size to both the diametric and volumetric pore size distributions. When geotextiles are used for filtration, long-term clogging emerges as a serious issue [100].

A geotextile material designed to work as a filter must have an appropriate pore size and distribution and a corresponding degree of permeability in order to ensure the easy flow of liquid as required. Slit film geotextiles are not preferred because opening sizes are unpredictable [98,101].

A particular range of applications for synthetic-based geotextiles are summarized in Table 1.

Table 1. Applications of synthetic polymers in geotextiles.

Polymer	Application	Ref.
PP	soil erosion control, prevent waterlogging and holding higher stable grounds	[102,103]
PP	carpet backing for unpaved road and inland reclamation drives at coastal lands	[104]
PP	as core material in geocomposite drains	[105]
PP	geotextile filters	[103]
PP	as a breakwater in marine engineering applications	[105]
PP	road construction and re-pavement	[106]
PP, PE	manufacturing artificial grass and geogrids, embankment support and soil reinforcement	[107]
PET	separation and filtration	[104]

PET	geogrids, embankment support and soil reinforcement	[105]
PET	as a puncture-resistant layer over geomembranes in civil applications	[108]
PET	for tidal barrage protective devices	[107]

3.5. Applications of Geotextiles Made from Natural Fibers

The main characteristics needed to decide if a given natural fiber could be appropriate for working in a specific geotextile application consist of its mechanical response, hydraulic properties and durability. These properties are intrinsic outcomes from specific fiber composition, structure, spatial architecture and size, but not all are translated without alterations into the end geotextile product. The variable extent of changes may be induced by choosing a particular fiber extraction technique, yarn and/or fabric structure.

Increased requests for biomass-derived fibers are largely driven by the strong environmental concerns regarding the extensive use and subsequent disposal of synthetic polymers [28]. The benefits of being non-toxic and biodegradable are furthermore accompanied by improvements in soil texture and fertility as a result of better blending and coalescence with soil particles, as well as increased organic content and humidity. It must be mentioned that moisture retention is possible due to the hydrophilic feature of natural fibers, the usually good water absorption further contributing to a lower surface runoff during strong rainfalls which is a significant benefit. Unfortunately, these advantages come together with a limited durability and difficulties in the attempts to increase at will the available raw material volumes or to finely adjust the working properties. Fiber properties may also exhibit subtle variations between different batches of natural fibers, even for the same vegetal variety, due to the plants' growing environments such as soil type and treatment, inconstant climate, harvesting and conditioning circumstances.

The complex interplay between components and their structural arrangement is a determinant for the properties shown by natural fibers. Cotton, for instance, is lignin-free and may contain up to 96% cellulose [109]. It is highly hydrophilic, soft, but exhibits poor mechanical properties and rapidly degrades in soil, even in terms of weeks, strongly limiting its potential use as a geotextile. On the other hand, coir fibers, which have the highest lignin content (up to 46%), are less hydrophilic, rough and resist much better to microbial attacks and even to salty water [109]. Although, increased lignin content reduces the resistance to UV degradation [110]. Mechanical properties are mixed, a high elasticity being accompanied by low tensile strength and modulus. On the contrary, bast fibers have a low elongation at break comparable with leaf fibers. Foliage fibers are in turn weaker than most bast fibers, except jute [111]. Jute shows a rough texture that improves both the friction soil interface and water absorption. It was found that wet jute swells and could attain contents in moisture higher than 300% [2], which translates into an excellent flexibility over uneven surfaces and recommendations for use in applications such as hill slope protection, erosion control and road construction. In fact, both jute and coir are already used in such interventions, for example, under the form of open-weave woven fabrics, with the mention that coir exhibits a higher durability.

The process of fiber extraction could interfere with the specific mechanical properties. For example, a device-driven extraction of fibers from flax straw has almost halved the tensile strength as compared with classical manual extraction, together with a smaller decline in modulus [112].

After extraction, plant fibers are commonly processed by heavy duty mechanical equipment in nonwoven, woven and mixed fabrics [52]. Both techniques start with fiber opening and carding which homogenize, clean and segregate the raw material. In the case of nonwoven fabrics, the resulting web of longitudinally aligned fibers is made isotropic by cross-lapper and is finally needle punched to increase the cohesion, strength and density by inducing binding points on the randomly oriented fibers stuck by fric-

tional forces. In the woven technique, carding results in a sliver (non-twisted rope strand). Furthermore, sliver fibers are parallelized by sequential drawing and spun into twisted yarns. An increased twist improves the yarn strength and water absorption but is detrimental to yarn tensile modulus. Two sets of threads, longitudinal and transverse, are finally interlaced in a weaving process to obtain the end structure of a woven fabric. Some relevant geotechnical applications of natural fibers are presented in Table 2.

Table 2. Examples of employment of natural fibers in geotechnical applications.

Natural Fibers	Source/Types	Properties	Processing	Application	Ref.
Water hyacinth	<i>Eichhornia crassipes</i> /stem fibers	high water absorption, low strength, low cost, high availability	woven limited life geotextiles (LLGs)	soil erosion control	[113]
Reed	<i>Arundo donax</i> /stem fibers	high water absorption, low strength	woven limited life geotextiles	soil erosion control, improve soil quality	[114]
Roselle or Thai kenaf	<i>Hibiscus sabdariffa</i> /long bast fibers	low moisture absorption, high strength	woven limited life geotextiles	soil reinforcement	[51]
Sisal	<i>Agave sisalana</i> Perr/long leaves fibers	low moisture absorption, high strength	woven limited life geotextiles	soil reinforcement	[115]
Coir	<i>Cocos nucifera</i> /coconut shells	good hygroscopicity, with high moisture content per volume unit	coir matting	slope stabilization in highland regions, soil moisture retention	[13]
	<i>Cocos nucifera</i> /coconut husk	high compressibility, low shear strength, high swelling/shrinkage	coir netting	road construction and embankment, eco-friendly drainage/stabilization	[116]
Palm	<i>Borassus aethiopum</i> /leaves fibers	proper permeability for cohesive soils, highly effective in rainfall handling, increase saturation/infiltration and decrease runoff, high durability	Borassus palm mats	soil erosion control in temperate climates, soil stabilization and conservation in conditions of non-uniform torrential rains	[117]
	<i>Mauritia flexuosa</i> /leaves fibers	similar to <i>Borassus</i> , but slightly less durable and effective in rainfall handling	Buriti palm mats	soil erosion control, stabilization and conservation	[118]
Jute	<i>Corchorus capsularis</i> /bast fibers	size increase in pores under pressure allows fast dewatering rates, low tensile strengths limit their use to smaller tube diameter	woven/non woven jute geotextiles tubes	soil erosion control, filtration, drainage	[119]
Cotton	<i>Gossypium</i>	high water repellency	various	soil erosion control	[120]

	<i>sp./seed fibers</i>	associated with dry patch formation underneath, increased water losses, low mechanical properties and durability	limited-life cotton geotextiles	
Bamboo	<i>Bambuasa blumeana</i> /grass fibers	good tensile/breaking strengths, effective in rainfall handling of topsoil mass runoff	fiber ropes	surface erosion, slope stabilization [121]
Kenaf	<i>Hibiscus sabdariffa var altissima</i> /bast fibers	high tensile strengths, high resistance at direct shear and pullout	hexagonal, plain and knot-plain woven yarns	soil reinforcement [122]
Flax	<i>Linum usitatissimum</i> /bast fibers	high porosity, high hydraulic conductivity and sorption capacity of cationic metals	nonwoven geotextiles	design of wastewater, retention and runoff treatment systems [123]

4. Concluding Remarks and Future Trends

Geotextiles have proven to be classic, as well as high-performance, modern materials. They are successfully applied in geotechnical and civil engineering, in both developed and emerging countries, and the global demand is growing. On a historical scale, there is a certain cyclicity regarding the nature of the fibers used as geotextiles. In antiquity, natural fibers have been used for soil and road stabilization. Modern times have promoted synthetic fibers for geotextiles. Nowadays, the need to reduce the environmental impact of polymer waste has brought back to attention the natural fibers-based geotextiles.

Natural geotextiles respond to societal concerns about the environment by reducing the pollution. Used in short- and medium-term applications, natural geotextiles can replace geosynthetics up to a certain point and are recommended for controlling the soil erosion and in agriculture, for slopes and riverbank stabilization, and in other applications where revegetation is highly desirable. Aside from their properties and low production cost, the local availability of natural fibers is another advantage. Still, their limitation resides in their main feature—biodegradability—but their service life can be prolonged by different strategies, such as modification of natural fibers through various methods or the use of hybrid fibers.

Geosynthetics have superior properties, owing to the synthetic fibers they are made of, and a wider range of applications. Their performance can be further improved using additives during polymer processing or in post-processing stages, or by including the raw polymers in composite formulations along with other reinforcing components (clay micro- and nanoparticles, carbon nanotubes, graphene and graphene oxide particles, carbon fibers, basalt fibers).

The knowledge-based development of technical textiles opens new perspectives for geotextiles. For example, intelligent geotextiles used to stabilize railway infrastructure, dams, embankments or slopes incorporate sensors and are able to sense and monitor mechanical deformations, variation of temperature, humidity and pressure. Thus, they can be used for the early detection of structural failure and its location, which is a major advantage as it allows damage control and timely repairs. However, advances are constantly reported, which proves geotextiles remain an active field of research.

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