The role of geotextile fabric in enhancing the properties of stabilized expansive soils

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Abstract

Geotextile fabrics are integral to modern soil stabilization practices, offering benefits such as cost-effectiveness, ease of installation, and environmental sustainability. This paper explores the mechanisms of geotextile reinforcement, including separation, filtration, drainage, and reinforcement, which contribute to their effectiveness in stabilizing expansive soils. Geotextiles reduce swelling pressure, improve load-bearing capacity, and mitigate shrinkage cracks, making them essential in various geotechnical applications. Despite their advantages, challenges such as durability, compatibility with different soil types, and potential clogging issues need to be addressed. Recent technological advancements, including smart and nano-modified geotextiles, and improved manufacturing techniques have significantly enhanced their performance. Hybrid approaches integrating geotextiles with other stabilization methods demonstrate synergistic effects, providing comprehensive solutions to complex geotechnical challenges. This review highlights the critical role of geotextiles in soil stabilization, emphasizing the need for ongoing innovation and careful material selection to maximize their benefits and address existing limitations.

Keywords: Geotextile fabrics, soil stabilization, expansive soils, separation, filtration, drainage, reinforcement.

Kulcsszavak: geotextíliák, talajstabilizálás, duzzadó talajok, elválasztás, szűrés, vízelvezetés, megerősítés.

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1. Introduction

Expansive soils, commonly known as swelling soils, are clay-rich soils that exhibit significant volumetric changes in response to moisture variations [1]. These soils primarily contain clay minerals such as montmorillonite, smectite, and bentonite, which have a high affinity for water. The ability of these clay minerals to absorb water leads to an increase in their volume, causing the soil to swell [2]. Conversely, when moisture is lost, these soils contract, leading to shrinkage. This dual nature of expansive soils results in considerable cyclic changes in volume, which can cause severe engineering problems [3]. The mineralogical composition of expansive soils is critical to their behavior. Montmorillonite, for example, is characterized by a large surface area and a high capacity for ion exchange, both of which contribute to its significant water absorption capabilities [4]. These minerals expand as water molecules enter the interlayer spaces, leading to swelling. Upon drying, the water is expelled, and the soil contracts. This swell-shrink behavior is influenced by several factors, including the soil's clay content, the type of clay minerals present, the soil's initial moisture content, and environmental conditions such as precipitation and temperature fluctuations [5].

Geopolymers play a vital role in addressing the challenges associated with expansive soils, particularly through their filtration function. Acting as a stabilizing medium, geopolymers enhance soil stability by filtering fine particles, thereby preventing their migration and maintaining the integrity of the soil structure. This filtration mechanism, coupled with the mechanical strength and durability of geopolymers, contributes to the reduction of swelling pressure and supports the improvement of expansive soil performance in geotechnical applications.

Fig. 1 by Wu *et al.* [52] illustrates the filtration function of geotextiles in soil stabilization. In the absence of a geotextile layer, water flow through the soil carries fine particles (fines) into the underlying coarse aggregate layer, leading to clogging and destabilization of the soil structure. This migration of fines can compromise the load-bearing capacity and drainage efficiency of the soil. In contrast, when a geotextile is placed between the fine soil and coarse aggregates, it acts as a filtration barrier. The geotextile allows water to pass through while effectively retaining the fines in the upper soil layer. This separation prevents particle migration, preserves the structural integrity of the soil, and enhances its drainage capabilities. Such functionality makes geotextiles indispensable in geotechnical engineering, particularly in applications requiring soil stabilization, erosion control, and improved drainage performance.

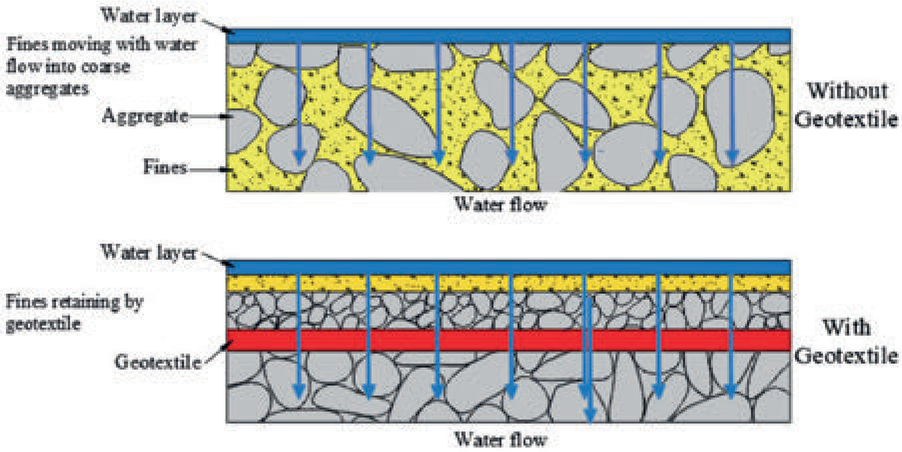

Fig. 1. Filtration Function of Geotextiles in Soil Stabilization [52]
1. ábra A geotextíliák szűrési funkciója a talajstabilizálás során [52]

2. Problems associated with expansive soils

Expansive soils pose numerous challenges for civil engineering and construction due to their unpredictable volume changes. The primary problems associated with expansive soils are:

- **Swelling and Shrinkage**: The alternating swelling and shrinkage of expansive soils exert pressure on structures built on or within these soils [6]. During periods of high moisture, the soil expands, generating uplift forces that can heave foundations, pavements, and other structures. Conversely, during dry periods, the soil contracts, leading to settlement and the formation of cracks [7]. This cyclical movement can cause considerable damage to buildings, roads, pipelines, and other infrastructure.
- **Impact on Infrastructure**: The volumetric instability of expansive soils significantly impacts infrastructure integrity and longevity [8]. The heaving and settling of soils beneath foundations can lead to differential settlement, causing structural distress manifested in cracks in walls, floors, and ceilings. Roads and pavements constructed over expansive soils are prone to surface irregularities such as bumps and cracks, which degrade the riding quality and increase maintenance costs. Underground utilities like water and sewer lines are also susceptible to damage due to soil movement, resulting in leaks and service disruptions [9].

Expansive soils are particularly problematic in regions where seasonal moisture variations are pronounced. In such climates, infrastructure must be designed to accommodate or mitigate the effects of soil movement to ensure stability and durability [10]. Traditional mitigation strategies include soil replacement, moisture control, and chemical stabilization, but these methods can be costly and labor-intensive. Therefore, innovative solutions such as the use of geotextile fabrics are being explored to enhance the properties of stabilized expansive soils, offering potential improvements in both

Problem	Description	Effects on Structures	Infrastructure Impact	Mitigation Strategies	References
Swelling and Shrinkage	Alternating swelling and shrinkage due to moisture change	Exerts pressure on structures, leading to uplift and settlement	Causes cracks in buildings, roads, pipelines	Soil replacement, moisture control, chemical stabilization	[6], [7]
Heaving	Expansion of soil during high moisture periods	Uplift forces heave foundations and pavements	Differential settlement, structural distress	Geotextile fabrics, soil replacement	[6], [7], [8]
Shrinkage	Contraction of soil during dry periods	Leads to settlement and formation of cracks	Surface irregularities in roads, increased maintenance costs	Moisture control, chemical stabilization	[7], [9]
Impact on Foundations	Volumetric instability under foundations	Causes differential settlement	Cracks in walls, floors, ceilings	Innovative solutions like geotextile fabrics	[8], [9], [10]
Impact on Pavements	Heaving and settling beneath pavements	Surface irregularities like bumps and cracks	Degraded riding quality, increased maintenance costs	Soil replacement, geotextile fabrics	[9], [10], [11]
Impact on Underground Utilities	Soil movement affecting utilities	Damages water and sewer lines, causing leaks	Service disruptions	Chemical stabilization, innovative solutions	[9], [10], [11]
Regional Challenges	Pronounced seasonal moisture variations	Greater infrastructure damage in affected regions	Need for designing to accommodate soil movement	Geotextile fabrics, other innovative stabilization techniques	[10], [11]
Cost and Labor	Traditional methods can be costly and labor-intensive	High costs and extensive labor for mitigation	Need for cost-efficient and effective solutions	Geotextile fabrics, innovative approaches	[11]

Table 1 Problems Associated with Expansive Soils
1. táblázat Az duzzadó talajokkal kapcsolatos problémák

performance and cost-efficiency [11]. *Table 1* highlights the engineering challenges posed by expansive soils, including swelling and shrinkage, infrastructure damage, and various mitigation strategies such as soil replacement and the use of geotextile fabrics.

3. Soil stabilization

Soil stabilization is a crucial process in geotechnical engineering aimed at improving the physical properties of soil to enhance its performance for construction and infrastructure projects. The primary objectives of soil stabilization include increasing the soil's strength, reducing its compressibility, and controlling its swell-shrink behavior, particularly in expansive soils. There are several techniques employed to achieve soil stabilization, each with its specific applications and benefits. They include; [12].

- **Mechanical stabilization**: This method involves physically altering the soil's properties through compaction and the addition of aggregates [13]. Compaction increases the soil's density, thereby enhancing its load-bearing capacity and reducing its susceptibility to moisture-induced volume changes. The incorporation of aggregates such as gravel, sand, or crushed stone improves the soil's gradation and mechanical interlocking, leading to enhanced stability and reduced deformation [14].

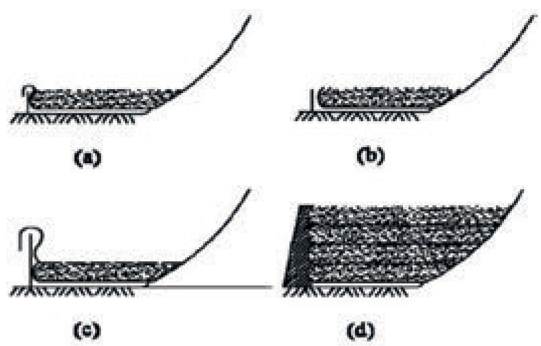

Fig. 2 Construction of a reinforced retaining wall using geotextile sheets
2. ábra Geotextília lapokkal megerősített támfal építése

Fig. 2 above illustrates the construction of a reinforced retaining wall using geotextile sheets and granular backfill, with each layer typically 0.3 to 0.5 meters thick. First, the surface is leveled, and a geotextile sheet is laid with 1.5 to 2 meters draped over a temporary wooden form at the wall face (*Fig. 2a*). Granular soil is placed in layers of 0.3 to 0.5 meters and compacted using a suitable roller, and the geotextile is folded upwards (*Fig. 2b*). This process is repeated, adding successive geotextile sheets and compacted backfill layers, until the desired height and stability are achieved (*Fig. 2c*). The completed structure consists of alternating soil and geotextile layers, ensuring reinforcement and stability (*Fig. 2d*).

- **Chemical stabilization**: Chemical stabilization techniques involve the addition of chemical agents to soil to alter its properties. Common chemical stabilizers include lime, cement, fly ash, and other industrial by-products. Lime stabilization is particularly effective for expansive soils, as it induces pozzolanic reactions that transform clay minerals into more stable compounds, thereby reducing plasticity and swelling potential. Cement stabilization binds soil particles together through hydration reactions, significantly increasing strength and durability. Other additives, such as fly ash, can enhance soil properties by providing additional binding agents and improving workability [15].
- **Biological stabilization**: Emerging as an innovative approach, biological stabilization involves using microorganisms or plant roots to stabilize soil [16]. Microbial-induced calcite precipitation (MICP) is one such method, where bacteria induce the formation of calcium carbonate, which binds soil particles together and enhances stability. Although still in the experimental stages, biological stabilization offers a sustainable and environmentally friendly alternative to traditional methods [17].
- **Geosynthetic stabilization**: Geosynthetics, including geotextiles, geogrids, and geomembranes, are synthetic materials used to reinforce, separate, filter, or drain soils. Geotextiles, in particular, play a significant role in soil stabilization by providing tensile strength and enhancing soil-structure interaction. These materials are widely used due to their versatility, cost-effectiveness, and ease of installation [18].

4. Role of geotextile fabric in soil stabilization

Geotextile fabrics have emerged as a vital component in soil stabilization strategies, particularly for managing expansive soils [19]. These permeable fabrics are made from synthetic polymers such as polypropylene or polyester, and they come in woven and non-woven forms, each suited for different stabilization applications.

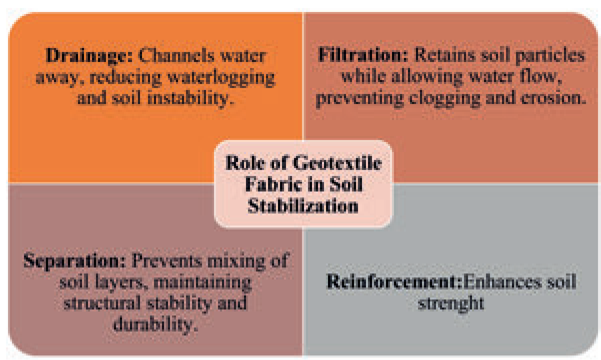

Fig. 3 Role of Geotextile Fabric in Soil Stabilization
3. ábra A geotextília szerepe a talajstabilizálásban

Fig. 3 illustrates the key functions of geotextile fabrics in soil stabilization: drainage to channel water and prevent waterlogging, filtration to retain soil particles while allowing water flow, separation to prevent soil layer intermixing and maintain structural integrity, and reinforcement to enhance soil strength and stability. These roles ensure improved durability and performance of geotechnical structures.

- **Separation**: Geotextile fabrics serve as a separation layer between different soil layers to prevent intermixing. This is particularly important in road construction, where a geotextile placed between the subgrade (native soil) and the aggregate base layer maintains the integrity and function of both layers [20]. By preventing the intrusion of fine subgrade particles into the aggregate layer, geotextiles help maintain the structural stability and load distribution capacity of the pavement system. This separation function ensures that the subbase remains clean and free-draining, thereby enhancing the overall durability and performance of the structure [21].
- **Filtration**: Geotextiles function as filters, allowing water to pass through while retaining soil particles. This filtration capability is critical in applications like retaining walls, drainage systems, and erosion control [22]. In retaining walls, for example, geotextiles are placed behind the wall to prevent soil migration while allowing water to drain away, reducing hydrostatic pressure. Similarly, in drainage applications, geotextiles prevent clogging of drainage pipes or channels by keeping soil particles out while facilitating the movement of water. This helps in maintaining the efficiency of drainage systems and preventing soil erosion [23].
- **Drainage:** The drainage function of geotextiles involves their ability to channel water away from soil or structures. When used in conjunction with other drainage materials, geotextiles help create an efficient drainage pathway that prevents water accumulation [24]. In roadways and embankments, for example, geotextiles placed under or alongside the structure ensure that water is quickly drained away from the soil, reducing the risk of waterlogging and associated problems like soil weakening and structural instability. Proper drainage is essential in managing expansive soils, as it minimizes the moisture fluctuations that cause swelling and shrinkage [24].
- **Reinforcement:** Geotextiles provide reinforcement by adding tensile strength to the soil, which improves its load-bearing capacity and resistance to deformation [25]. This reinforcement mechanism is crucial in applications like embankments, slopes, and retaining structures where enhanced soil stability is required. Geotextiles work by distributing applied loads more evenly across the soil, reducing stress concentrations and preventing localized failures. They also help confine soil particles, improving the overall shear strength of the soil and reducing the risk of settlement and deformation under load [26].

The application of geotextile fabrics in soil stabilization offers several advantages, including cost-effectiveness, ease of installation, and versatility. Their ability to address multiple stabilization functions include separation, filtration, drainage, and reinforcement, which makes them an indispensable tool in geotechnical engineering. Moreover, geotextiles are compatible with various soil types and can be combined with other stabilization methods to achieve optimal results [27].

In conclusion, soil stabilization is essential for enhancing the performance and durability of expansive soils in construction projects [28]. Geotextile fabrics play a pivotal role in this process by providing multifunctional solutions that address the unique challenges posed by expansive soils. As research and technology advance, the integration of geotextiles with other innovative stabilization techniques will continue to improve infrastructure resilience and sustainability.

4.1 Types of geotextile fabric

Geotextile fabrics are categorized into woven and non-woven types, each with distinct properties and applications:

- **Woven geotextiles**: These fabrics are made by weaving threads or yarns in a systematic pattern. Woven geotextiles are characterized by high tensile strength and load-bearing capacity, making them suitable for reinforcement applications. They are commonly used in road construction, embankments, and retaining walls where high strength and durability are required [52].

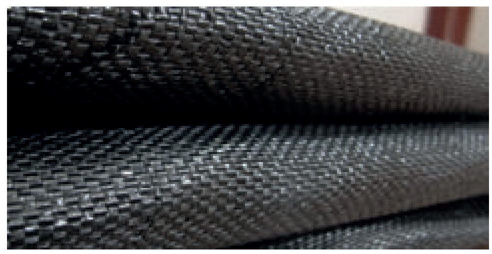

Fig. 4 Example of Woven Geotextiles
4. ábra Példa szövött geotextíliákra

Fig. 4 compares the effect of using geotextile fabric in a soil stabilization application. On the left side, labeled "Without geotextile," the aggregate layer intermixes with the underlying soil, leading to uneven settlement and reduced structural stability. On the right side, labeled "With geotextile," the fabric acts as a separation barrier, preventing the mixing of soil and aggregate layers, ensuring a more stable and durable foundation. This demonstrates the geotextile's role in enhancing load distribution and maintaining the integrity of the structure.

Fig. 5 Example of a Non-Woven Geotextiles
5. ábra Példa nem szövött geotextíliákra

- **Non-woven geotextiles**: These fabrics are produced by bonding fibers together using chemical, thermal, or mechanical processes. Non-woven geotextiles are known for their excellent filtration and drainage properties. They are used in applications such as drainage systems, erosion control, and soil separation where permeability and filtration are critical [29].

4.2 Properties and selection criteria

The selection of geotextile fabrics depends on the specific requirements of the project, including:

- **Tensile strength**: The ability of the geotextile to withstand tension without breaking is crucial for reinforcement applications. Woven geotextiles typically offer higher tensile strength [30].
- **Permeability**: The ability of the geotextile to allow water to pass through while retaining soil particles is essential for drainage and filtration applications. Non-woven geotextiles generally provide better permeability [30].
- **Durability**: The geotextile must withstand environmental conditions, including UV exposure, chemical degradation, and mechanical damage. The material composition and manufacturing process influence durability [30].
- **Puncture and tear resistance**: For applications involving sharp or angular materials, the geotextile's resistance to puncture and tear is important to maintain its integrity [31].
- **Compatibility with soil**: The geotextile must be compatible with the soil type and the specific conditions of the project site. This includes considering factors such as soil grain size, moisture content, and chemical properties [32].

In conclusion, geotextile fabrics play a critical role in soil stabilization by providing reinforcement, filtration, drainage, and separation functions. Their versatility and effectiveness make them indispensable in modern geotechnical engineering, particularly for managing the challenges associated with expansive soils.

4.3 Interaction of geotextile fabric with expansive soils

4.3.1 Reduction of swelling pressure

Geotextiles help reduce the swelling pressure exerted by expansive soils by providing a barrier that controls moisture movement [33]. By facilitating proper drainage and preventing water accumulation within the soil, geotextiles reduce the extent of moisture-induced swelling. Additionally, the separation function of geotextiles can isolate expansive soil layers from non-expansive materials, further mitigating the effects of swelling. This reduction in swelling pressure is critical for maintaining the structural integrity of foundations, pavements, and other infrastructure built on expansive soils [33].

4.3.2 Improvement in load-bearing capacity

The reinforcement provided by geotextiles enhances the load-bearing capacity of expansive soils. By adding tensile strength and improving soil confinement, geotextiles increase the soil's resistance to deformation under load. This improvement is particularly beneficial for foundations and pavements constructed on expansive soils, where enhanced load-bearing capacity translates to reduced settlement and increased durability. Geotextiles also help distribute loads more evenly, preventing localized failures and ensuring a more stable and reliable foundation for structures [34].

4.3.3 Mitigation of shrinkage cracks

Geotextiles mitigate shrinkage cracks in expansive soils by maintaining consistent moisture levels and providing structural reinforcement. During dry periods, expansive soils tend to shrink and develop cracks, which can compromise the stability of overlying structures. Geotextiles, by promoting uniform moisture distribution and reducing moisture fluctuations, help minimize the occurrence of shrinkage cracks. Additionally, the reinforcement effect of geotextiles enhances the soil's tensile strength, making it less prone to cracking under drying conditions. This mitigation of shrinkage cracks is essential for preserving the integrity of pavements, foundations, and other infrastructure elements [34].

In summary, geotextile fabrics play a crucial role in stabilizing expansive soils through mechanisms such as separation, filtration, drainage, and reinforcement. Their ability to reduce swelling pressure, improve load-bearing capacity, and mitigate shrinkage cracks makes them an effective solution for managing the challenges posed by expansive soils in various engineering applications.

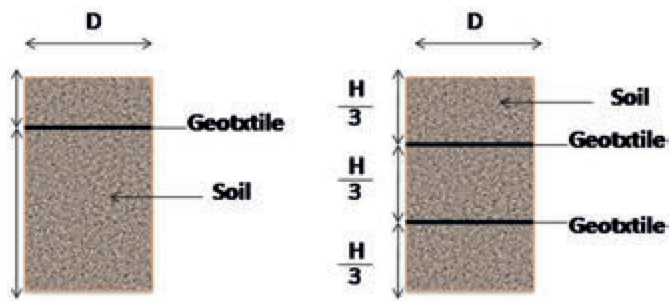

Fig. 6 Single and Multi-Layer Geotextile Reinforcement Configurations in Soil Blocks
6. ábra Egy- és többrétegű geotextil megerősítési konfigurációk talajtömbökben

The *Fig. 6* shows two geotextile reinforcement configurations in a soil block. The first (left) has a single geotextile layer placed horizontally at mid-height, while the second (right) features multiple layers spaced evenly, dividing the height (H) into thirds (H/3). Both setups, with width denoted as D, are used to enhance soil stability and load-bearing capacity in geotechnical applications.

4.4 Advantages of geotextile fabric

4.4.1 Cost-effectiveness

Geotextile fabrics offer a cost-effective solution for soil stabilization and reinforcement. They often reduce the need for more expensive construction materials and techniques. For example, geotextiles can minimize the amount of aggregate required in road construction by improving load distribution and enhancing the performance of the base layers [35]. Additionally, geotextiles can extend the lifespan of infrastructure, thereby reducing maintenance and repair costs over time. Their relatively low initial cost and long-term economic benefits make them an attractive option for a wide range of civil engineering projects [36].

4.4.2 Ease of installation

One of the significant advantages of geotextile fabrics is their ease of installation. They are lightweight, flexible, and can be easily handled and placed on site [37]. This reduces labor costs and time required for installation compared to traditional methods.

Geotextiles can be rolled out and cut to fit various project dimensions and shapes, making them suitable for diverse applications such as road construction, erosion control, and drainage systems. The simplicity of installation also allows for quick deployment in emergency situations where immediate stabilization is required [38].

4.4.3 Environmental considerations

Geotextile fabrics contribute to environmentally sustainable construction practices. They can reduce the need for extensive earthworks and the use of natural resources like gravel and sand [39]. By enhancing soil stabilization and reducing erosion, geotextiles help protect natural landscapes and water bodies from sedimentation and pollution. Additionally, many geotextiles are made from recyclable materials, which can be reclaimed and reused, further reducing their environmental footprint. Their role in promoting sustainable construction practices makes geotextiles an eco-friendly choice in geotechnical engineering [40]. Recycled materials commonly used in geotextiles include recycled polyester (PET) from plastic bottles, polypropylene (PP) from packaging waste, and nylon from carpets and fishing nets, all valued for their strength and durability**.** Recycled rubber from tires enhances water permeability, while cotton or textile waste provides biodegradable options for temporary applications. Additionally, recycled glass fibers offer high tensile strength for reinforcement, and cellulose fibers from paper are used in silt fences. These materials promote sustainability while meeting the performance needs of geotechnical projects.

Recycled materials play a key role in the production of geotextiles, promoting sustainability while maintaining performance. Recycled polyester (PET), sourced from plastic bottles and textile waste, is durable, UV-resistant, and widely used in erosion control, filtration, and reinforcement applications. Recycled polypropylene, derived from packaging materials, offers excellent chemical resistance and is ideal for soil separation, drainage, and stabilization. Recycled nylon, from products like carpets and fishing nets, is strong, resilient, and commonly used in road reinforcement and high-stress environments.

Recycled rubber, such as that from used tires, enhances water permeability and shock absorption, making it useful in soil stabilization and erosion control projects. Recycled cotton or textile waste, being biodegradable, is used for temporary geotextiles in erosion control and landscaping. Recycled glass fiber, known for its tensile strength and corrosion resistance, is employed in soil reinforcement, while recycled paper and cellulose fibers are used in temporary applications like silt fences and erosion barriers.

These recycled materials help reduce waste and offer eco-friendly alternatives in geotechnical applications, ensuring both sustainability and high performance.

4.5 Challenges of geotextile fabric

4.5.1 Durability and longevity

While geotextile fabrics are designed to be durable, their longevity can be a concern, particularly in harsh environmental conditions. Factors such as ultraviolet (UV) exposure, chemical degradation, and mechanical wear and tear can affect the lifespan of geotextiles. UV exposure can degrade the polymer fibbers in geotextiles, reducing their strength and effectiveness over time [41]. Chemical interactions with soil and groundwater contaminants can also lead to material degradation. Additionally, geotextiles used in high-traffic areas or subjected to heavy loads may experience physical damage. Ensuring the durability and longevity of geotextiles requires selecting appropriate materials and considering protective measures such as UV-resistant coatings or burial below ground [42].

4.5.2 Compatibility with different soil types

The performance of geotextile fabrics can vary depending on the soil type they are used with. Some soils, particularly those with high clay content, can pose challenges for geotextile effectiveness [43]. In clayey soils, fine particles can clog the geotextile, reducing its filtration and drainage capabilities. On the other hand, sandy soils may not provide sufficient support for geotextile reinforcement. Therefore, it is essential to select the appropriate type of geotextile based on the specific soil conditions of the project site. This involves conducting thorough soil assessments and choosing geotextiles with properties that match the soil characteristics [44].

4.5.3 Potential for clogging and maintenance issues

Geotextile fabrics used in filtration and drainage applications are susceptible to clogging by fine soil particles, organic matter, and other debris. Clogging can significantly reduce the effectiveness of the geotextile in allowing water to pass through while retaining soil particles [45]. This issue is particularly prevalent in soils with a high percentage of fines or in environments with heavy organic content. Regular maintenance is required to ensure the geotextile continues to function as intended. This may involve cleaning or replacing clogged geotextiles, which can be labour-intensive and costly. Implementing proper design and installation practices, such as using multiple layers or selecting geotextiles with appropriate pore sizes, can help mitigate clogging issues [46].

In conclusion, while geotextile fabrics offer numerous advantages in terms of cost-effectiveness, ease of installation, and environmental benefits, there are also challenges related to durability, soil compatibility, and maintenance [47]. Addressing these challenges through careful material selection, design considerations, and regular maintenance can maximize the benefits of geotextiles in soil stabilization and reinforcement applications.

4.6 Technical recommendations for geotextile selection and use

Selecting the appropriate geotextile requires careful consideration of soil type, application needs, and site conditions to ensure optimal performance and durability.

For cohesive soils like clay, non-woven geotextiles are preferred due to their permeability and ability to prevent clogging from fine particles. In sandy or gravelly soils, woven geotextiles are better suited because of their superior tensile strength and resistance to abrasion, making them effective for separation and reinforcement. Silty soils demand geotextiles with moderate pore sizes to balance filtration, drainage, and structural support. Organic soils with high moisture content benefit from chemically resistant and UV-stabilized geotextiles to withstand decomposition and environmental degradation.

Grain size plays a critical role in determining geotextile density. Fine-grained soils require geotextiles with larger pore sizes to maintain permeability and prevent clogging, while coarse-grained soils demand denser fabrics to handle mechanical stresses and ensure durability. For applications involving heavy loads or high traffic, woven geotextiles with higher density are recommended for reinforcement, while non-woven geotextiles are ideal for drainage and filtration.

Proper installation is key to achieving effective performance. The geotextile should be rolled out on a prepared surface, ensuring overlap between layers to avoid gaps. Anchoring at edges and joints is essential to prevent displacement during backfilling. Uniform backfilling with compatible materials must follow to maintain the geotextile's position and function. In environments with UV exposure or chemical contaminants, protective measures such as burial or using UV-resistant coatings can extend the geotextile's lifespan. Regular inspections and maintenance, including cleaning or replacement of clogged sections, are vital to sustain long-term effectiveness in soil stabilization and drainage applications.

5. Recent advances and innovations

5.1 Technological improvements

5.1.1 Advanced materials

Smart Geotextiles

- To protect soil sensors embedded in smart geotextiles and ensure their longevity, several solutions can be implemented. First, encapsulating sensors within durable, waterproof, and corrosion-resistant materials, such as epoxy resin or specialized polymer coatings, can shield them from environmental factors like moisture, chemical interactions, and mechanical wear. Second, designing the geotextile with reinforced layers or compartments can provide a buffer against physical damage from soil pressure or construction activities.
- Additionally, careful placement of sensors in low-stress zones or integrating flexible, impact-resistant sensor designs can reduce the risk of breakage. The use of wireless data transmission systems can eliminate the need for vulnerable wiring, further enhancing durability. Lastly, regular inspection and maintenance of the smart geotextile system, coupled with robust installation practices, such as ensuring the sensors are positioned away from heavy machinery pathways or compacted soil zones, can significantly minimize damage and extend operational life.

Nano-modified geotextiles

Nano-modified geotextiles incorporate nanomaterials to enhance their physical and chemical properties. The addition of nanoparticles, such as carbon nanotubes, nanoclays, or nanosilica, can improve the tensile strength, durability, and resistance to environmental degradation of geotextiles [49]. These modifications also enhance the fabric's barrier properties, making it more effective at filtration and separation. Nano-modified geotextiles can provide superior performance in challenging conditions, extending the range of applications and increasing the reliability of geotextile solutions in soil stabilization projects.

5.1.2 Improved manufacturing techniques

Advancements in manufacturing techniques have led to the development of geotextiles with enhanced performance characteristics. Improved weaving and non-woven production processes allow for better control over the fabric's properties, such as pore size distribution, thickness, and mechanical strength. Techniques like meltblown, spunbond, and needle-punched processes have been optimized to produce geotextiles with specific attributes tailored to different applications. Additionally, new methods for coating and treating geotextiles with protective substances improve their resistance to UV radiation, chemical exposure, and mechanical wear, thereby extending their service life and functionality [50].

5.2 Integration with other stabilization methods

5.2.1 Hybrid approaches

Hybrid stabilization approaches combine geotextiles with other soil stabilization techniques to enhance overall performance. For instance, the integration of geotextiles with chemical stabilization methods, such as lime or cement treatment, can produce synergistic effects that improve soil properties more effectively than either method alone. These hybrid approaches leverage the strengths of each technique, providing a comprehensive solution to soil stabilization challenges. For example, geotextiles can be used to reinforce chemically treated soils, enhancing load-bearing capacity and reducing settlement [51].

Hybrid approaches also include the combination of geotextiles with mechanical stabilization methods, such as soil compaction or the use of aggregates. Geotextiles can be placed within compacted soil layers to provide additional reinforcement and separation, preventing intermixing of materials and enhancing the overall stability of the structure. These integrated methods offer greater flexibility and adaptability, making them suitable for a wide range of geotechnical applications [52].

5.2.2 Synergistic effects

The synergistic effects of integrating geotextiles with other stabilization methods result in improved soil performance and increased infrastructure durability. For example, combining geotextiles with geogrids can create a multi-layer reinforcement system that significantly enhances the tensile strength and load distribution capacity of soils. This combined approach is particularly effective in applications such as embankments, slopes, and retaining walls, where additional reinforcement is required to prevent failure [53]. Furthermore, the use of geotextiles in conjunction with drainage systems can enhance the effectiveness of soil moisture management. Geotextiles can act as both a filter and a reinforcement layer, ensuring efficient drainage while maintaining soil stability. This dual functionality helps mitigate issues related to expansive soils, such as swelling and shrinkage, by controlling moisture levels and providing structural support [54].

In summary, recent advances and innovations in geotextile technology, including the development of smart and nano-modified materials and improved manufacturing techniques, have significantly enhanced their performance and application range. The integration of geotextiles with other soil stabilization methods through hybrid approaches and the realization of synergistic effects provide comprehensive and effective solutions to complex geotechnical challenges. These advancements ensure that geotextiles continue to play a crucial role in modern soil stabilization practices [55].

6. Conclusions

The implementation of geotextiles should be tailored to soil mechanics, soil composition, and topographic conditions to ensure optimal performance. For expansive soils, non-woven geotextiles with high permeability are recommended to manage drainage and reduce swell-shrink behavior. Soft or loose soils benefit from woven geotextiles with high tensile strength to improve load distribution and minimize settlement, while sandy soils require geotextiles with moderate permeability for erosion control. In clayey soils, non-woven geotextiles with larger pore sizes prevent clogging, whereas silty soils demand intermediate pore sizes to balance filtration and drainage. Gravelly soils are best suited for woven geotextiles with abrasion resistance. For steep slopes, high-strength geotextiles with excellent frictional properties enhance stability, while wetlands or areas with high water tables require permeable and chemically resistant materials. Additionally, flood-prone regions need geotextiles with superior filtration and clogging resistance. Selecting geotextiles with appropriate properties such as permeability, tensile strength, UV and chemical resistance, and durability ensures long-term effectiveness in diverse environmental and soil conditions.

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