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Review

Use of geosynthetic materials as soil reinforcement: an alternative eco-friendly construction material

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Abstract
Geosynthetics have emerged as innovative, efficient, and cost-effective solutions for a myriad of engineering challenges in construction. This paper explores the extensive applications of geosynthetics in construction, encompassing liner systems for landfills, containment zone barriers, embankments, filters, pavement drainage systems, slope stabilization, reinforcement for shallow foundations, and barriers in earthen dams. Various types of geosynthetic materials, such as geotextile, geomembrane, geogrid, geonet, geocomposite, geofiber, geobags, geopipes, geosynthetic clay liner, and geofoam, further broaden their utility. A significant focus is on soil stabilization, where geosynthetics play a crucial role in reinforcing weak soil, improving stability, erosion protection, enhanced drainage, and effective soil retention. Geosynthetics helps in improving soil strength which could be used in subgrade, embankment, slopes, foundations, and earthen dams, it could be an efficient alternate to traditional construction materials. The findings of this research have practical implications for engineers and construction professionals, offering innovative and cost-effective solutions to engineering challenges.

Keywords Geosynthetic · Soil reinforcement · Cost-effective solutions · Geoenvironmental · Construction material

1 Introduction

In the dynamic realm of modern construction and engineering, geosynthetics stand as versatile and innovative solutions, playing a pivotal role in addressing a myriad of challenges and revolutionizing traditional practices. Geosynthetics are adaptable and creative solutions that alter conventional techniques and tackle a wide range of issues in the fast-paced world of modern engineering and construction [1]. The development of geosynthetics may be traced back to significant turning points and discoveries that have influenced its past. Geosynthetics were first developed as an answer to the shortcomings of traditional building materials and techniques. Over time, they have advanced to become essential elements of many different types of construction projects [2].

The history of geosynthetics starts with its modest beginnings when the necessity for efficient solutions for soil stabilization, erosion management, and environmental protection drove the field's early uses. Several revolutionary developments have characterized the evolution of geotextiles, geomembranes, geogrids, and other geosynthetic materials over time [3–7]. Expanding the breadth and uses of geosynthetics has been made possible by seminal events like the invention of woven geotextiles in the 1950s. Geosynthetics have become popular in the building sector as affordable, effective, and ecological substitutes, moving from specialized uses to general use.

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The emergence of problems in conventional construction methods is closely linked to the historical story of geosynthetics. Problems including slope instability, poor drainage, and soil erosion led engineers and researchers to look into creative fixes. With their multifunctional qualities, geosynthetics provided a paradigm shift in how these problems were addressed. Their use in building methods was marked by a dedication to improving durability, reducing environmental effects, and boosting stability.

The relevance of geosynthetics now emphasizes its ongoing importance in meeting changing engineering needs. Liner systems for landfills [8–10], containment barriers, embankments, pavement drainage systems, slope stabilization, shallow foundations, and barriers in earthen dams [11–17] are only a few of the new uses for them. Geosynthetics have not only shown to be useful in a variety of applications, but they have also shown to be resilient and adaptable, making them an essential tool for today's building professionals.

It is essential to grasp important terminology to traverse this complex world. The terminology of geosynthetics includes geotextiles, geomembranes, geogrids, and other classifications, each of which has a distinct function in tackling particular engineering issues. With a focus on historical development, kinds, functions, applications, material qualities, manufacturing processes, performance assessments, and sustainability issues, this review paper aims to give a thorough analysis of geosynthetics. This study tries to contribute to a greater understanding of the revolutionary impact of geosynthetics on building methods and their key role in influencing the future of engineering by exploring the past, present, and future of this technology.

Due to the increasing demand for creative and sustainable solutions in the fields of environmental protection, building, and civil engineering, geosynthetics research has made tremendous strides in recent years. Geosynthetic materials are gaining popularity in various countries which is depicted in Fig. 1.

Researchers are increasingly working on producing sustainable geosynthetic materials with little environmental effect [18]. This involves looking at biodegradable geotextiles and other environmentally friendly options to help build a more sustainable construction sector. The incorporation of smart technologies into geosynthetics is a rapidly growing topic of

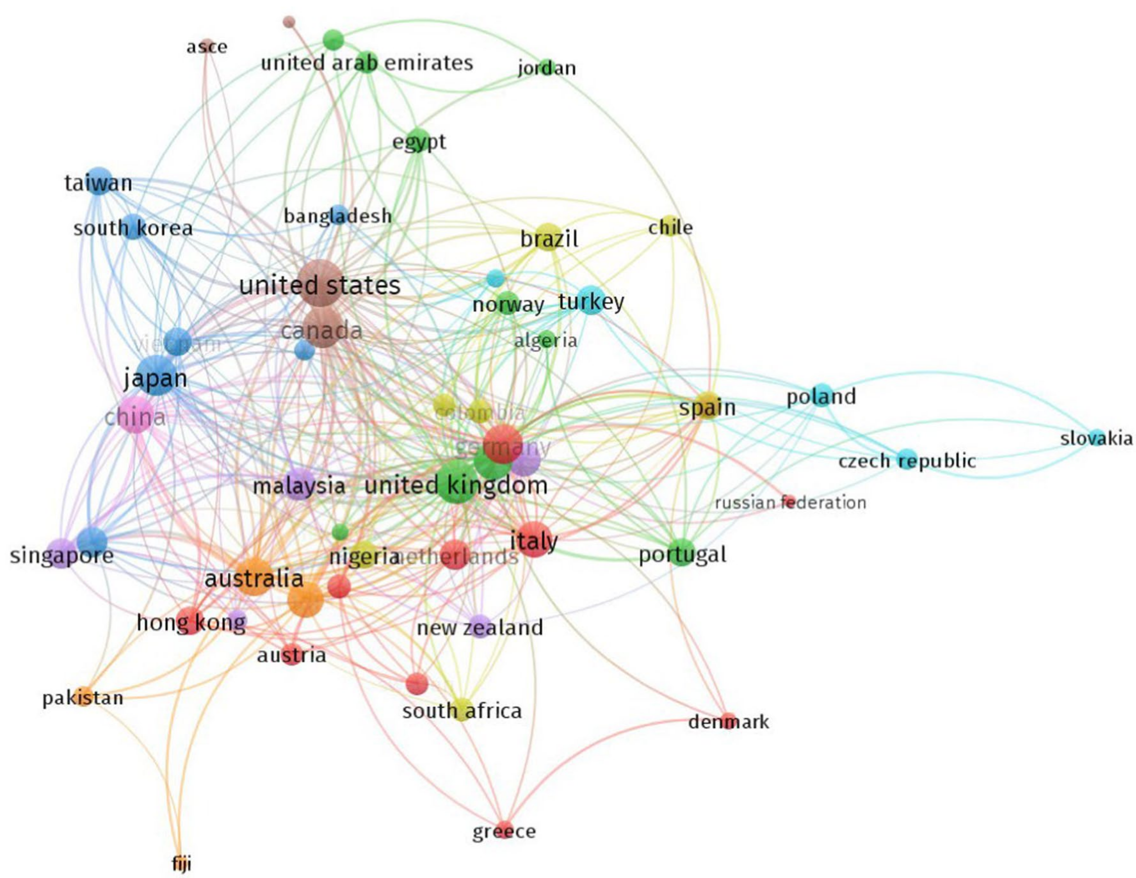


Fig. 1 Research on geosynthetics in different countries

research. Smart geosynthetics may include sensors or monitoring devices that offer real-time data on strain, temperature, and environmental variables [19]. This technology improves the capacity to evaluate the performance of geosynthetic systems and identify potential problems quickly. Advances in soil–geosynthetic interaction and reinforcing processes have resulted in better design techniques [20–22]. Researchers are looking at new reinforcement techniques, such as the usage of improved geogrids and geofibers, to improve the stability and load-bearing capability of different structures. Climate change resilience is an important research priority, and geosynthetics can help mitigate the effects. Studies are looking into how geosynthetics might help with adaptive measures including coastal protection, flood management, and infrastructure resilience in the face of changing climate patterns.

Ongoing research is enhancing the performance of Geosynthetic Clay Liners [23], which blend clay and geotextiles. These liners are essential for containment applications such as landfills, and researchers are looking for ways to improve their impermeability and long-term endurance. Ground improvement with geosynthetics is an important topic of research, particularly in areas with difficult soil conditions. Researchers are looking into novel approaches for stabilizing unstable soils, reducing settlement [24], and improving the overall engineering qualities of the ground. Advanced numerical modeling and simulation approaches are helping to accurately forecast the behaviour of geosynthetic-reinforced structures [25]. Researchers and engineers use finite element analysis and other modeling tools to optimize designs and evaluate the long-term performance of geosynthetic systems.

The development of multifunctional geosynthetics, which combine many capabilities into a single material, is gaining popularity which is represented in Fig. 2, the diameter of circle represent the proportion of work in the field. This comprises geocomposite materials that combine filtration, drainage, and reinforcing qualities, simplifying construction operations [26–29]. These improvements significantly contribute to the growth of geosynthetics as vital components in modern infrastructure projects, providing sustainable, resilient, and efficient solutions to today's construction and environmental management concerns [30–33].

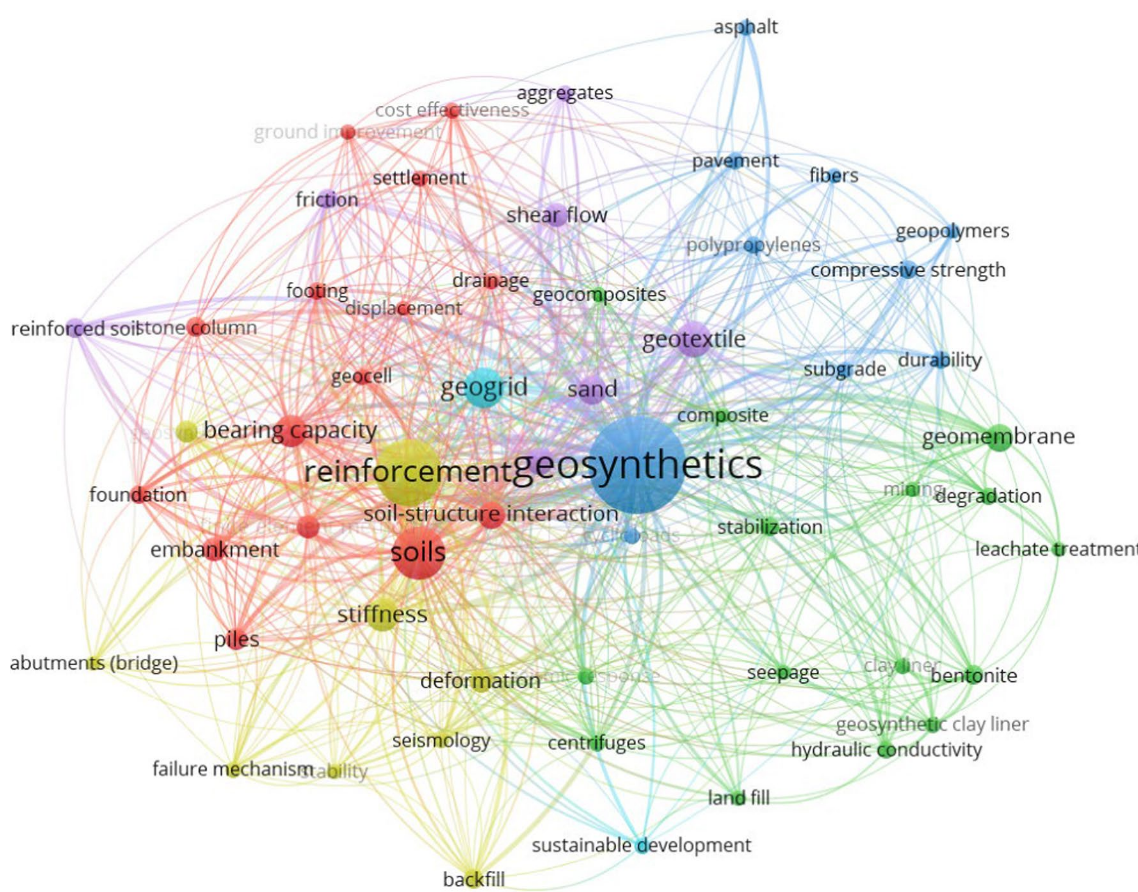


Fig. 2 Routine practice of geosynthetic

Geosynthetic materials durability and longevity are based on various factors such as design, construction standards, materials, environment, age, and loads. End-of-service life criteria typically include weathering resistance and capacity to handle specified loads [34, 35]. It deteriorate due to factors such as ultraviolet exposure, temperature stress, biological aggression, chemical aggression, and mechanical fatigue.

2 Why geosynthetics is a better alternative?

Geosynthetics can help with environmental sustainability in a variety of ways, and their environmental impact is an important factor in modern engineering methods. Here are some characteristics of geosynthetics' environmental and sustainability impacts:

Landfill management: Geosynthetics, especially in applications like landfill liners, help manage garbage and prevent pollution of soil and groundwater. This is critical for environmental preservation and sustainable landfill management [36].

Waste reduction: Geosynthetics often enable the use of locally available soils and materials, reducing the need for transporting and excavating large quantities of natural resources. This can lead to less environmental disruption and a reduction in waste generation [37].

Soil stabilization and erosion control: Geosynthetics help to stabilize soil and control erosion, which prevents soil degradation and loss. This is especially crucial in construction and infrastructure projects that aim to preserve natural habitats and ecosystems [38].

Sustainable construction: Using geosynthetics in construction projects can lead to more sustainable practices. For example, soil reinforcement with geosynthetics can eliminate the need for substantial excavation and the use of traditional materials, contributing to the sustainability of construction [39].

Recycling and reusability: Some geosynthetics are made from recyclable or reusable materials, which reduces the overall environmental impact. Recyclability enables the recovery of valuable resources while reducing the requirement for new raw materials.

Energy savings: In some applications, such as road construction, using geosynthetics can result in energy savings by lowering the thickness of construction layers. This can lead to a decreased environmental footprint from energy usage in material manufacturing and transportation.

Environmental performance certifications: Many geosynthetic materials go through testing and certification processes to determine their environmental performance. Certifications, such as ISO 14001, help ensure ecologically responsible manufacturing and use.

Geosynthetics help to build climate change resilience by providing solutions for coastal protection, flood management, and infrastructure stability. These applications assist communities in adapting to shifting climate patterns and reducing exposure to extreme weather occurrences.

Environmental monitoring and remediation: Geosynthetics are used in environmental monitoring and remediation operations like contaminated site containment or landscape regeneration. This helps to restore ecosystems and reduce environmental harm.

Carbon footprint reduction: By streamlining construction processes and minimizing the demand for traditional materials, geosynthetics can help to reduce construction projects' overall carbon footprint. This is consistent with attempts to minimize environmental effects.

While geosynthetics offer sustainable solutions, it's crucial to assess each application's specific environmental considerations and choose materials and practices that align with broader sustainability goals. Balancing the benefits of geosynthetics with their environmental impact ensures responsible and sustainable engineering practices.

3 Historical development

Geosynthetics have evolved from humble origins to become vital components in modern engineering and construction techniques, making their history fascinating. Here is a summary of the history section of geosynthetic materials.

The early twentieth century saw the rise of theories regarding the use of synthetic materials in civil engineering applications. Notable innovations include the use of textiles and membranes to reduce erosion and stabilize soil. During this time, there was a growing interest in using synthetic materials to improve soil quality. The emergence of woven geotextiles in the 1950s was a watershed moment in geosynthetic innovation. Pierre Lemoigne, a French engineer and inventor, developed the first nonwoven geotextile in 1958, which marked a significant achievement. Geotextiles, which are generally constructed of polymeric materials, were developed to address soil erosion, drainage difficulties, and layer separation.

Geosynthetics saw global commercialization and popularity in the 1970s–1980s, leading to an expansion of their applications. Geomembranes, impermeable polymeric sheets, have gained popularity in containment applications like landfills and reservoir liners. The introduction of geogrids, or flexible polymer grids, broadened the spectrum of uses to include soil reinforcement and stability.

In the 1990s, the field experienced improvements in production methods and material formulations. Geocomposite, which combine various forms of geosynthetics, were created to provide multifunctional solutions. Continued research and development improved geosynthetic materials' durability, strength, and environmental sustainability.

The twenty-first century has seen an increase in research and innovation, with a particular emphasis on sustainable geosynthetic materials. Biodegradable geotextiles, geomembranes with recycled content, and unique green infrastructure applications are among the innovations. The current study is driven by challenges such as understanding long-term performance and environmental impact.

Geosynthetics are now widely used in infrastructure development, affecting civil, environmental, and geotechnical engineering procedures worldwide. Standardization groups, such as the International Geosynthetics Society (IGS), have been instrumental in developing rules and standards for the production, testing, and deployment of geosynthetic materials.

4 Properties of geosynthetics

The material properties of geosynthetics play a crucial role in determining their performance and suitability for various applications in civil engineering and construction. Here are some key material properties of geosynthetics:

Physical properties: It means the composition of materials that are used to make geosynthetic material like specific gravity, type of structure, thickness, flexibility, mass per unit area and stiffness. Specific gravity is based on polymeric material which is used to originate geosynthetic, its range varies from 0.91–1.14. Thickness is the extent of layers of geosynthetic material generally it is between 0.25 to 7.5 mm. Flexibility means the ability to bend under its weight. Mass per unit area expresses the mass of a material per unit area.

Mechanical properties: To use geosynthetics in soil extensively it should have some mechanical properties which implies geosynthetic material should bear some load without deformation or failure. Mechanical properties are mainly categorised into two types i.e., with or without soil present in the surrounding. Index properties are the only properties of geosynthetic material without soil in the surroundings whereas performance properties involve those determined when geosynthetic is in contact with soil. Mechanical properties include the Compressibility of geosynthetic means the reduction of the thickness of the material when a normal load is applied. For a good material, compressibility should be as low as possible. The tensile strength of geosynthetics is the resistance to deformation when tension is applied to it. It is evident that the tensile strength of geosynthetics is unequal in all directions this is because in woven geotextiles, the tensile strength is produced due to the weaving structure, strength in the warp direction or parallel direction is known as warp strength, which may not be equal to the strength of perpendicular direction called as weft strength. Bursting strength is the ability of geosynthetics to resist bursting when the load is applied and material is covered from all directions. The tearing strength of geosynthetic material is the ability to withstand tears which happens due to installation on hard and coarse material. Pull-out resistance means analysing geosynthetic material to determine its anchorage and pull-out capacity for structures like slopes and retaining walls. Friction assessment is necessary to know the amount of friction between soil and geosynthetic.

Hydraulic properties: To effectively use geosynthetics as a material to transport or contain liquid, it is necessary to know about its hydraulic properties, like porosity, permittivity and transmissivity. To measure porosity, we must look into its physical properties like density, thickness, and mass per unit area and the main factor is the percentage of open area. It is a property that explains the ratio of the open area to the total area. The open area is measured by the amount of shining light passing through the material. The permittivity describes the ability of a liquid to pass through geosynthetic, it is a cross-sectional flow divided by the thickness of the medium. Transmissivity is the ability of the liquid to move within the plane of the material also known as in-plane permeability. Soil retention is a property of geosynthetics that allows the flow of water while holding soil particles in them.

Endurance properties: These are the short-term properties that are affected due to weather, installation, and the effect of load applied. At the time of installation, geosynthetic material experiences much damage. Creep is continuous and slow deformation over the period. Stress relaxation is the relaxation of stress when the load is applied to the geosynthetic and achieves a fixed level of strain. The abrasion of geosynthetics is an important property that defines wear and tear by rubbing with different surfaces. Excessive abrasion is harmful as it leads to the loss of strength. Clogging may happen with time as fluid moves suspended particles get carried away and block the pores of geosynthetic materials.

Durability properties: Durability properties of geosynthetics safeguard the long-term benefits of the material it includes, *Chemical resistance*—Resistance to deterioration or degradation when exposed to various chemicals present in the soil or environment. *UV stability*—The ability to withstand prolonged exposure to ultraviolet (UV) radiation without significant degradation. *Oxidation resistance*—Some materials are susceptible to oxidation over time, leading to reduced performance. Oxidation resistance is crucial for long-term durability. *Creep resistance*—The ability to resist deformation under long-term sustained loads, ensuring stability over time. *Fatigue resistance*—The material's ability to withstand repeated loading cycles without experiencing damage or failure. *Joining and seaming integrity*—Properly executed joining and seaming during installation contribute to the overall durability of the geosynthetic system. *Resistance to biological factors*—Some environments may have microorganisms that can lead to biological degradation. Resistance to biological factors enhances long-term durability.

5 Type of geosynthetics

Geosynthetics encompass a diverse array of materials designed to address various engineering and construction challenges. Each type of geosynthetic material serves specific functions and applications. Here's an overview of common types given in Table 1.

5.1 Geotextiles

They are the core of geosynthetic material, with properties like a strong, porous, thin, flexible, planner or sheet-like structures made from fibers. Fibers are made up of polyester, polyamide, polypropylene etc. which results in very strong as well as thin fibers, which are either weaved by machines known as woven geotextile or joined together by making mechanical, thermal or chemical bonds between fibers are known as non-woven geotextile [40–42]. Geotextiles provide properties like separation, drainage, reinforcement, and filtration when used in soil. Due to their properties, they are used in many civil constructions works like roadways, landfills, drainage structures, erosion control, railways and many more. The use of geotextile makes pavements strong, rigid and durable helping in the reduction of maintenance costs and improving the life of infrastructure. It is proven that as the depth of the geotextile increases the strength of the soil increases up to a certain limit after which it remains constant.

To examine the effect of geotextile for subgrade reinforcement and to evaluate woven and nonwoven geotextile different types of soil namely silty sand and clayey soil are chosen. CBR tests were conducted on two types of geotextiles it was observed bearing capacity of the subgrade of soil improves. Woven geotextile has better efficiency compared to nonwoven geotextile this is because it has higher tensile capacity. The strength of pavement is dependent on the number and position of geotextiles [43, 44].

5.2 Geomembrane

Geomembranes are synthetic sheets that provide an impermeable barrier in engineering projects. It is a thin, strong and impervious sheet which are used to deal with the liquid flow by using them as a liner in landfills, and liquid storage facility, to control soil expansion by reducing soil exposure to water, act as a barrier for dams and coffer dams [45–47]. These materials have very low permeability due to this they can easily control harmful contaminants, and diffusion and are helpful in liner and control systems for radioactive and hazardous liquid waste. With all these properties and applications geomembranes are expensive compared to other geosynthetics. It is used in many water conservation projects like the making of ponds, lakes, and canals. They have many advantages over traditional barriers, such as, durability, rapid to install, economical, have a high deformability, require low maintenance and improve hydraulic efficiency of the system, Because of these advantages, geomembrane systems are used worldwide.

Table 1 Types of geosynthetics

Geosynthetic	Function	Description	Applications
Geotextiles	Filtration, separation, reinforcement, drainage	Permeable fabrics are made from synthetic fibers, such as polypropylene or polyester. Can be woven or nonwoven	Road construction, erosion control, soil stabilization, drainage systems
Geomembranes	Impermeable barriers to fluid or gas migration	Thin sheets of synthetic polymers (e.g., HDPE, PVC, EPDM) with high impermeability	Landfill liners, reservoirs, waste containment, environmental protection
Geogrids	Reinforce soil, improving stability and load-bearing capacity	Polymeric grids with large openings, typically made from materials like polyethene or polyester	Retaining walls, embankments, and soil reinforcement in pavements
Geonets	Reinforce soil, improving stability and load-bearing capacity	Open mesh-like structures made from polymer materials	Drainage systems, landfill liners, erosion control
Geofibers	Improve soil reinforcement and stability	Synthetic fibers (e.g., polyester, and polypropylene) are used to reinforce soils	Reinforcement of slopes, embankments, and retaining walls
Geobags	Provide erosion control and containment	Bags are made from geotextiles filled with soil or other materials	Coastal protection, riverbank stabilization, sediment containment
Geopipes	Facilitate drainage and fluid transport	Perforated or slotted pipes surrounded by a geotextile or geogrid	Drainage systems, leachate collection in landfills
Geosynthetic clay liners (GCLs)	Combine clay and geosynthetics for impermeable barriers	Layers of compacted clay sandwiched between geotextiles	Landfill liners, and containment systems
Geofoam	Lightweight fill material for construction	Expanded polystyrene (EPS) blocks	Road embankments, slope stabilization, lightweight fill
Geocell	Reinforcement structure for soil stabilization and erosion control	Geocell is a three-dimensional cellular confinement system typically made from (HDPE) or other durable polymers. It consists of interconnected cells that can be expanded and filled with soil, aggregate, or concrete	Soil stabilization, erosion control, load support, green spaces
Geocomposite	Combine multiple geosynthetic types for multifunctional purposes	Combinations of geotextiles, geomembranes, geogrids, or geonets	Versatile applications depend on the constituent materials

5.3 Geogrids

It is a material that is in a net or grid-like structure. There is a wide opening in them known as aperture. Polyester, polyvinyl, and polyethene are the base materials for its manufacturing. They are made by processes like extrusion and weaving. The working principle is, that these materials are very strong in tension which can easily distribute and transfer the load into large areas over the soil surface. Which ultimately improves the stability of the soil. It is used in subbases on pavements for its reinforcement properties. Other than road pavements it is used in dams and retaining structures. The addition of other additives like lime and cement geogrid improves the mechanical properties of soil.

5.4 Geonets

They are very similar to Geogrid. They are constructed by overlapping or joining fibers at acute angles which reassemble as a net-like structure. Polymers used to make geonets are of thermoplastic type which can be cast into different shapes easily. They have a hardness which makes them useful to bear the load. They can be used for their hydraulic properties like the transfer of fluid with this it is used in various fields like foundations, landfills, pavements, and drainage areas.

5.5 Geofibers

Geofibers are small, thin, hair-like structures made up of artificial fiber as shown in Fig. 3. They are made by using raw materials namely polypropylene, polyethene, polyester, polyvinyl etc. These fibers are available in various sizes like 3 mm, 6 mm, 10 mm, 12 mm, 15 mm, 30 mm, 50 mm, 60 mm and various other sizes, with diameters ranging from 10–100 microns. These fibers mixed with soil act as a reinforcement, because the soil is weak in tension and fiber acts as a reinforcement and improves its strength. From much research, it is concluded that generally, fibers are hand mixed with soil and if too many fibers are mixed in the soil there is a possibility of the formation of lumps in soil and uneven distribution of fibers which results in a lack of fiber and soil interaction [48, 49].

Geofibers are very effective in the reduction of cracking in soil. From experimentation work, it was clear that with the induction of fibers crack network changes from a regular to a small and irregular structure. So, it could be used in the prevention of the propagation of tension cracks in the soil. There are many advantages of fiber reinforcement [50] economical, speed of construction, ease of labor and availability [51].

The above Fig. 4. shows, variations of fibers generally of 6 mm and diameter of 100 microns in soil mainly of clayey type with different CBR values [52–54]. It is generally noted that with the addition of geofibers CBR value of soil increases.

5.6 Geobags

They are bag-like structures made of geosynthetic material. Which are typically filled with sand resulting in geotextile sand containers. It comes under three different specifications small, medium, and large. Small ones are used for temporary structures, medium-sized ones are for milder conditions and emergency works, and large ones are used for permanent structures. The bigger the size, the better their durability and lifespan, even under harsh conditions. They are easy to install, have less impact on the environment, can be used for a temporary and permanent structure, used in river bank stabilization, and erosion control. It is very simple to make and install. First, a frame is developed in which first geobag

Fig. 3 Geofibers

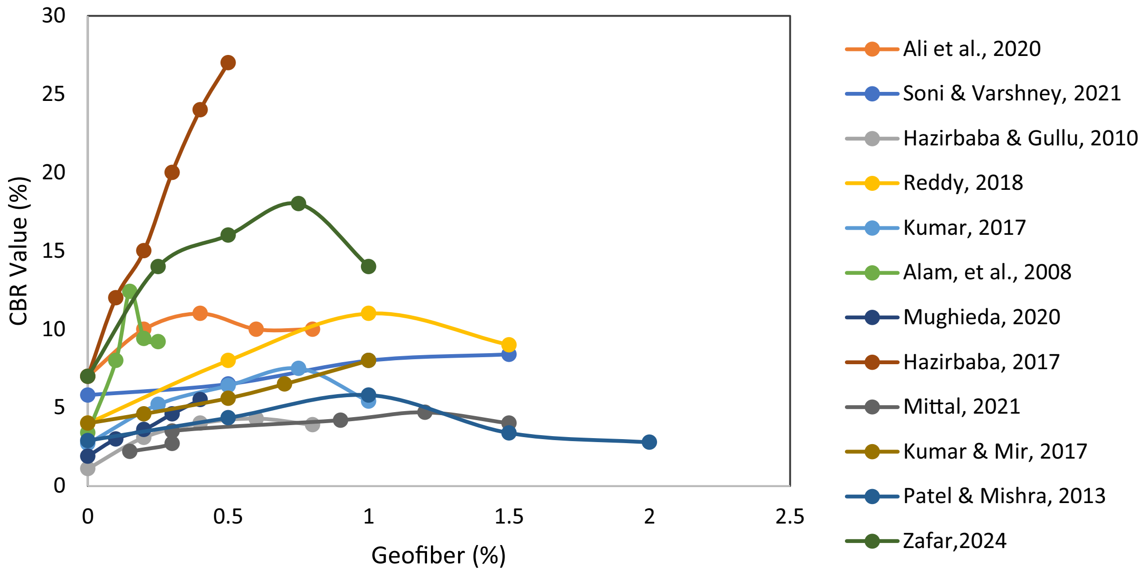


Fig. 4 Relationship between geofibers and CBR values

is placed then soil as shown in Fig. 5, either naturally available soil or soil transported from other sources filled in the geobag the geobag is stitched so that soil does not escape from the filled geobags are placed in desired locations.

5.7 Geopipes

It is a type of geosynthetic material that is in a circular shape. They are flexible conduits made of materials such as high-density polyethylene (HDPE) and used to transport fluids or gasses through the soil. Perforated pipes include small holes along their length, which aids drainage in applications such as highway subsurface systems, whereas non-perforated geopipes are solid and suitable for culverts or sewage systems. Their installation consists of trenching, laying, and back-filling, with geotextile wraps used to prevent soil incursion. Geopipes provide several advantages, including flexibility, corrosion resistance, cost-effectiveness, and environmental benefits. Geopipes are widely used in drainage, sewerage, and environmental projects. They provide sustainable solutions for water management, gas extraction, and leachate collection.

5.8 Geosynthetic clay liners (GCLs)

Geosynthetic clay liners (GCLs) are composite materials used for environmental containment that consist of layers of geotextile fabric encasing a core of sodium bentonite clay. It is a type of geosynthetic material that is made into layers, it consists of two layers of geosynthetic sandwiched with a layer of bentonite clay. This specific architecture forms a highly effective barrier to the movement of liquids and gasses. GCLs provide various advantages over standard compacted clay liners, such as speedier installation, lower costs, and better hydraulic performance. They are widely used in landfill liner systems, canal liner systems, landfill caps, mining operations, and containment ponds to prevent contaminants from

Fig. 5 Geobags in frames

migrating into the surrounding environment. GCLs play an important role in current environmental engineering by providing long-lasting and efficient solutions for hazardous material containment and management.

5.9 Geofoam

Geofoam is a lightweight fill material composed of expanded polystyrene (EPS) or extruded polystyrene (XPS) foam blocks used in a variety of construction applications as shown in Fig. 6. These blocks, made by expanding and moulding polystyrene beads, have low-density and excellent compressive strength, making them perfect for lowering earth pressures, minimizing settlement, and providing thermal insulation. Geofoam, which is commonly used in road embankments, slope stabilization, and lightweight fill applications, has various advantages over typical fill materials such as dirt or gravel [55].

These include ease of handling, reduced construction time, and less environmental impact. Geofoam research is ongoing, with a focus on its performance under varied stress circumstances, long-term durability, and seismic applications. Ongoing efforts focus on enhancing geofoam's design and installation processes to increase and broaden its effectiveness.

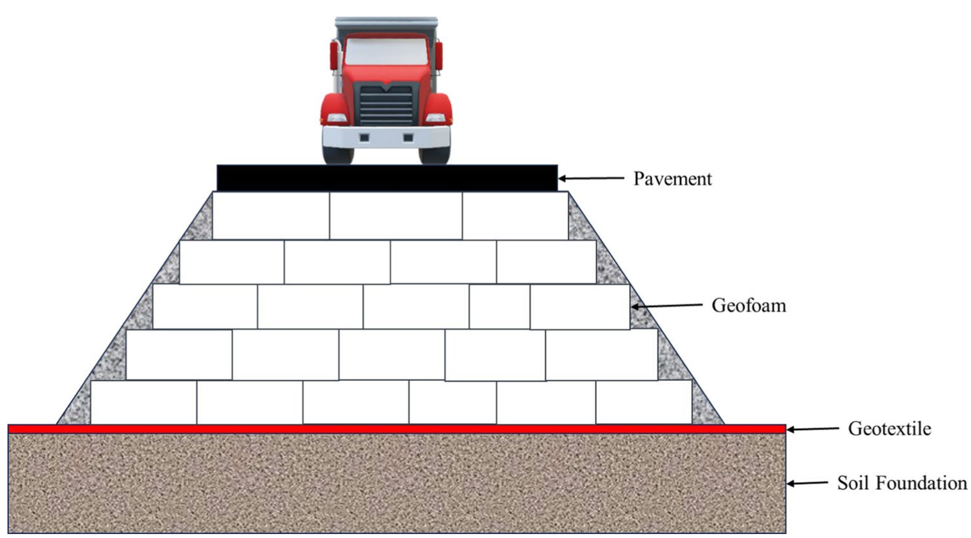
5.10 Geocells

Geocells, also known as cellular confinement systems, are three-dimensional honeycomb-like structures composed of high-density polyethylene (HDPE) or other polymers that are utilized in a variety of civil engineering applications, including soil stabilization, erosion control, and load support [56]. These constructions are made up of interconnected cells that provide a solid framework when filled with earth, aggregate, or concrete. Geocells are lightweight yet provide great strength and stability, spreading loads more evenly over a larger area and reducing soil erosion. They are widely utilized in road and railway construction to increase load-bearing capacity, reduce soil settlement, and improve overall pavement performance. Geocells are also used in slope stabilization projects to reduce soil erosion and landslides, as well as retaining walls to improve stability and prevent lateral soil movement. Nowadays, research is focused on improving design parameters such as cell size, cell wall height, and material qualities to enhance performance and durability while minimizing environmental effects. Studies also look at the mechanical behaviour of geocells under various loading circumstances, as well as novel applications including green infrastructure and coastal protection [57]. Overall, geocells provide long-term, cost-effective solutions to a variety of geotechnical difficulties, and ongoing research intends to further increase their effectiveness and adaptability.

5.11 Geocomposite

Geocomposite are materials that have been designed to blend two or more geosynthetic components to create a single product with improved characteristics and functions. Geotextiles, geogrids, geomembranes, and other specialist geosynthetic materials are commonly used as these components. Improved filtration, drainage, reinforcing, and barrier

Fig. 6 Use of geofoam in road embankment



functions are just a few of the advantages that geocomposite offers. They are engineered to meet specific engineering difficulties in civil and environmental applications [58]. Geotextile-geomembrane composites, drainage geocomposite, and geotextile-geonet composites are examples of common geocomposite. For instance, geotextile-geonet composites offer efficient drainage solutions for a range of soil and water management applications by combining the filtering capabilities of geotextiles with the drainage qualities of geonets. Combining the filtration and protective capabilities of geotextiles with the mechanical strength of geomembranes, geotextile-geomembrane composites are utilized for lining systems in containment applications. Prefabricated vertical drains, sometimes referred to as wick drains or drainage geocomposite, help soft soils quickly release pore water pressure, which speeds up soil consolidation and increases soil stability. To improve performance, durability, and sustainability, geocomposite are being researched with an emphasis on material selection, installation techniques, and design optimization. Modern geotechnical engineering and environmental protection depend heavily on geocomposite because they provide flexible solutions for groundwater management, waste containment, infrastructure construction, and erosion control [59, 60].

6 Functions of geosynthetics

Geosynthetics serve a variety of essential functions in civil engineering, construction, and environmental applications. Their versatility makes them valuable components in addressing various challenges. ISO 10318-1:2015 provides standard definitions of the functions of geosynthetic materials which includes terms related to definitions, functions and products. Here are the key functions of geosynthetics:

6.1 Filtration

Geosynthetic function as filter material, it allows the flow of liquid and holds soil particles in them. It acts as a filter to prevent soil particles from migrating into drainage systems while allowing water to pass through. When geosynthetic material is used in soil surface discontinuity arises between the soil and geosynthetic layer in which some soil partic0les that have less diameter than geosynthetic flow in seepage. Geosynthetic to act as filter equilibrium condition should be maintained. At equilibrium, three zones are made first one is undisturbed soil then the soil filter layer at last the bridging layer. With this, there is a large number of applications such as Highway drainage, retention wall landfill, and leachate collection system. This function is crucial for maintaining the integrity of structures and preventing clogging.

6.2 Separation

Geosynthetics create a barrier between different soil layers with distinct properties, preventing mixing and maintaining the desired characteristics of each layer. This separation enhances the stability of construction elements. It is defined as the placement of flexible geosynthetic material between two similar materials so that the integrity and function ability are improved, its working is shown in Fig. 7. They can be used on paved or unpaved roads, railroads etc. Usually, geotextile, geomembrane, and geogrid are used.

This property is mainly used in roadway construction in which geosynthetics are used to control the mixing of material of different particle size distribution.

6.3 Reinforcement

Soil reinforcement is one of geosynthetics' main purposes. They strengthen the soil's tensile strength and load-bearing capability by enhancing its mechanical characteristics. This is especially crucial for applications such as slope stabilization and retaining walls which are given in Table 2.

It is the improvement of total soil strength by the addition of geotextile, geogrid and geocells which are the good intention for the soil and is good in compression but poor in tension. Enforcement can be used as a mechanical stabilizer for retaining walls and steep slope stabilization [11]. Geosynthetic material in soil reinforces or adds strength when used in layers, as depicted in Fig. 8. Where the soil has low angular bonding and shear strength in those loose soils strength needs to be improved.

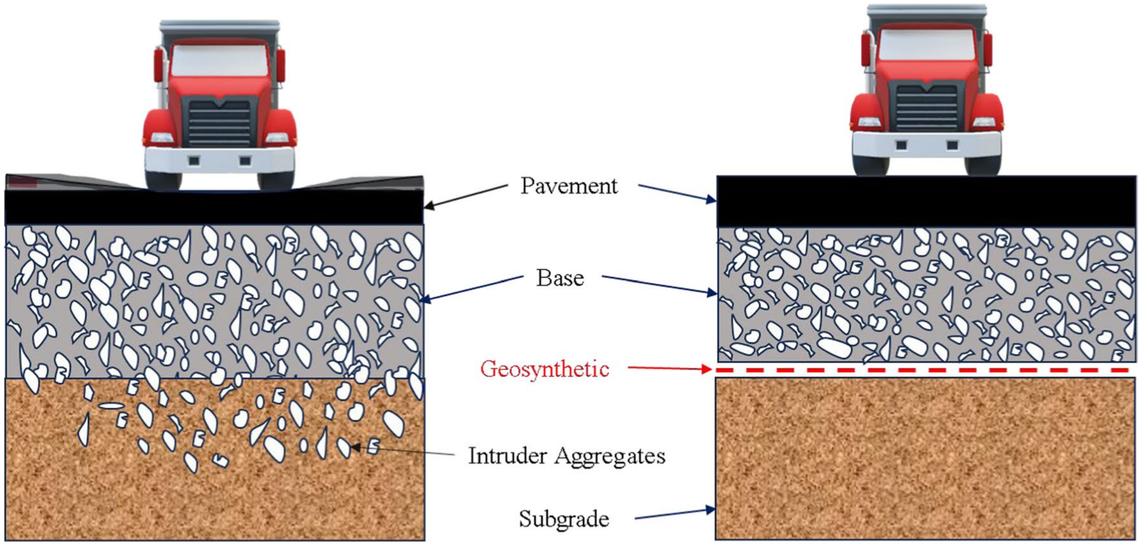


Fig. 7 Use of geosynthetics as separator

6.4 Drainage

Geosynthetics facilitate efficient drainage by providing pathways for the flow of water within the soil structure. They help control pore water pressure, reduce the risk of soil erosion, and contribute to the stability of structures.

Geosynthetic material helps in drainage, as given in Fig. 9. It allows the flow of liquid from soil particles. It is generally designed near large water bodies like ponds, lakes, and river basins. The types of geosynthetics used are geometry, geocomposite and geotextile it has many applications such as retaining walls, sports fields, dams, canal reservoirs and capillarity breaks.

6.5 Surface erosion control

Surface erosion control plays an important role in many engineering applications because it prevents soil from eroding and keeps slopes, embankments, and other earth constructions stable. Geosynthetic materials contribute significantly to surface erosion management by providing reinforcement, filtration, and protection against hydraulic stresses. Geosynthetic material like geogrids reinforce soil and improves resistance to erosion, Geotextile act as filter that prevent soil from being carried away along with flow of water, it traps soil and maintain integrity. Geocell a three-dimensional honeycomb structure stabilize soil surface by holding soil in its pockets. Geotextile along with vegetation cover is used to retain seeds, moisture and helps in reduction of erosion. These methods contribute to long-term erosion control, silt fences, sediment control, protection of slopes and channels. Their adaptability, durability, and efficacy make them indispensable components of erosion control methods in many infrastructure projects.

6.6 Protection

Geosynthetics provide protective layers to shield vulnerable surfaces from mechanical damage or environmental factors. They can be used to protect geomembranes, liners, and other sensitive components.

Geosynthetic material when placed between different materials, acts as a protection layer by uniform distribution of stress. geosynthetics allow the stress to distribute evenly on the soil surface. By serving as shields, barriers, or reinforcements, geosynthetics improve the stability, lifespan, and functionality of engineering projects. By offering a long-lasting buffer layer, geosynthetic materials like geotextiles are frequently utilized to shield geomembranes from abrasion or punctures. Furthermore, slopes, shorelines, and embankments are stabilized with the use of geosynthetic products such as geogrids and geocells, which reduce the danger of erosion and structural failure brought on by soil

Table 2 Application of Reinforcement Function

Author	Country	Area	Function	Type	Outcome
Neves et al., 2016 [61]	Portugal	Subgrade reinforcement	Reinforcement	Geogrid	Because of the geogrid subgrade reinforcement, there was a decrease in strains and displacements in the model
Ikbarieh et al., 2023 [81]	USA	Embankment	Reinforcement	Geotextile	Geosynthetics in many layers help in reducing settlement of embankments
Hung, et al., 2023 [44]	Taiwan	Reinforced soil wall	Reinforcement	Geotextile	The accumulated normalized horizontal movement of narrow GRS walls can be decreased by 30–80% through mechanical connection
Carlos, et al., 2016 [2]	Portugal	Pavement	Reinforcement	Geocomposite	In comparison to unreinforced soil, geocomposite increased the strength parameters and bearing ratio of the soil-reinforcement composite material
Huang, et al., 2015 [37]	USA	Roadway subdrain	Reinforcement	Geotextile	To maintain the overlying soil mass, geosynthetics are utilized as reinforcement layers to span over subterranean voids, sinkholes, and trenches
Hassan, et al., 2023 [45]	Kuwait		Reinforcement	Geotextile, Geocomposite, Geogrid	Because of their greater tensile strength and interface frictional resistance, soils reinforced with woven geotextile exhibit better shear strength than soils reinforced with other reinforcements
Liu, et al., 2022 [94]	United States	Approach of bridge	Reinforcement	Geogrids	The backfill's settlements away from the abutment, which were mostly brought on by traffic loading, may be greatly reduced with geogrids
Chenari & Bathurst, 2023 [38]	Canada	Shallow footings	Reinforcement	Geotextiles, geogrid	The carrying capacity of strip footings on thin reinforced granular layers over undrained soft clay is positively impacted by geosynthetic stiffness
Zhou, et al., 2024 [90]	China	Liquefaction	Reinforcement	Geogrid, geotextile,geotextile-geogrid	The suggested geotextile-geogrid composite works more effectively to increase the calcareous sand's resistance to liquefaction
Zhang, et al., 2019 [71]	China	Reinforced soil	Reinforcement	Geogrid	wall models with inadequate toe restraint circumstances may encounter (or be near reaching) a state of limit equilibrium, wall models with typical toe restraint conditions are probably operated under working stress conditions

Table 2 (continued)

Author	Country	Area	Function	Type	Outcome
Rahmaninezhad, et al., 2021 [70]	USA	Reinforced retaining walls	Reinforcement	Geotextiles	Compared to walls with shorter reinforcement, those with wrap-around facing and longer reinforcement had greater FS
Ding, et al., 2023 [9]	China	Reinforced embankment	Reinforcement	Geogrid, geocell	The usage of geocell can greatly minimize the deformation of the pavement structure layer under the same movement loads as an embankment reinforced with geogrid
Chawla and Shahu, 2016 [73]	India	Railway tracks	Reinforcement	Geogrid, geotextile	When Delhi silt was utilized as the subgrade soil, the model tracks reinforced with a geotextile outperformed the ones reinforced with a geogrid in terms of decreased tie displacement, subgrade displacement, and sub-ballast strain
Kilic, et al., 2021 [69]	Turkey	Retaining walls	Reinforcement	Geotextile	The cohesive, fine-grained clay-sand soil mixture backfilled the geosynthetic-reinforced modular block retaining walls, ensuring its seismic performance. demonstrating geotextile's exceptional reinforcing
Singh, et al., 2019 [32]	India	Road pavements	Reinforcement	3D Grid	Tenax 3D grid outperforms other geosynthetics utilized in this study for single-layer reinforcement, whereas Tenax multimat works best for double layers
Oyegbile, et al., 2017 [67]	Nigeria	Coastal protection	Reinforcement, protection	Geotextile	Advancements in their fabrication techniques and technical features, and the use of geosynthetics in coastal engineering are growing and getting better
Rajabian, et al., 2012 [68]	India	Stability of slopes	Reinforcement and filtration,	Geogrid, non-woven geotextile	When compared to an unreinforced slope, stability study on AGS slope models was found to be in good condition
Lu, et al., 2021 [24]	China	Reinforced soil walls	Reinforcement, separation	Geonets	Under differential settlement, geosynthetic deformation exhibits the concave curve's nonlinear property
Robinson & Howard, 2021 [86]	United States	Airfield pavements	Reinforcement, separation	Geotextiles	In airport damage restoration or as a crack mitigation approach, geosynthetic inclusion might be more advantageous than aggregate base reinforcement in new construction

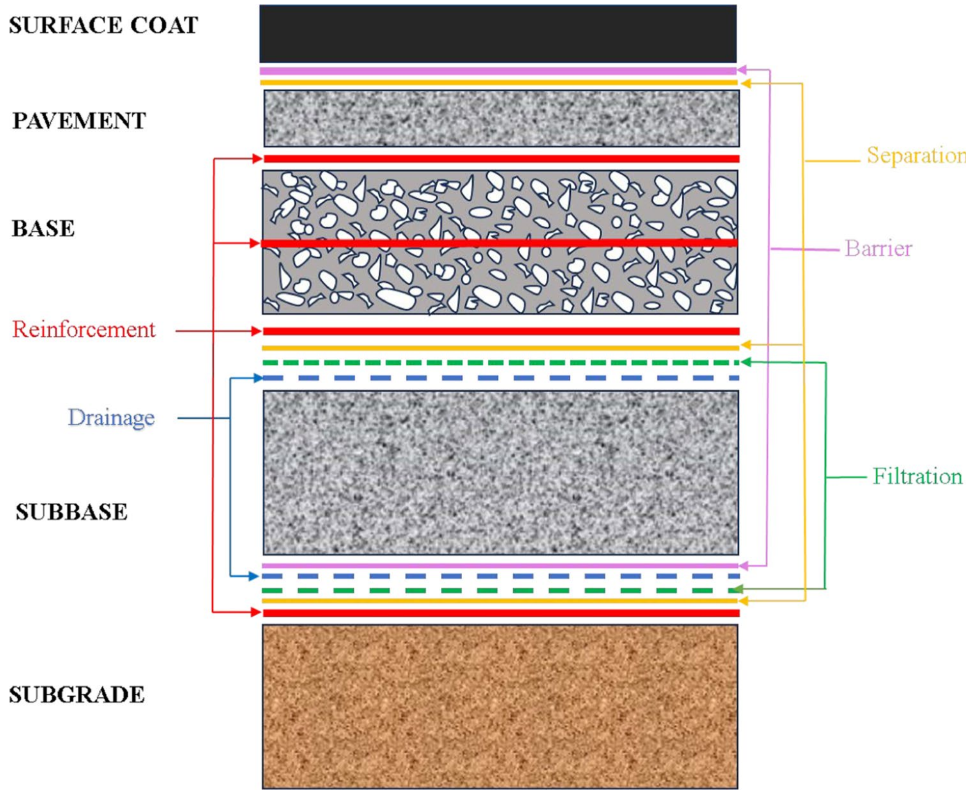


Fig. 8 Multiple functions of geosynthetic in pavement

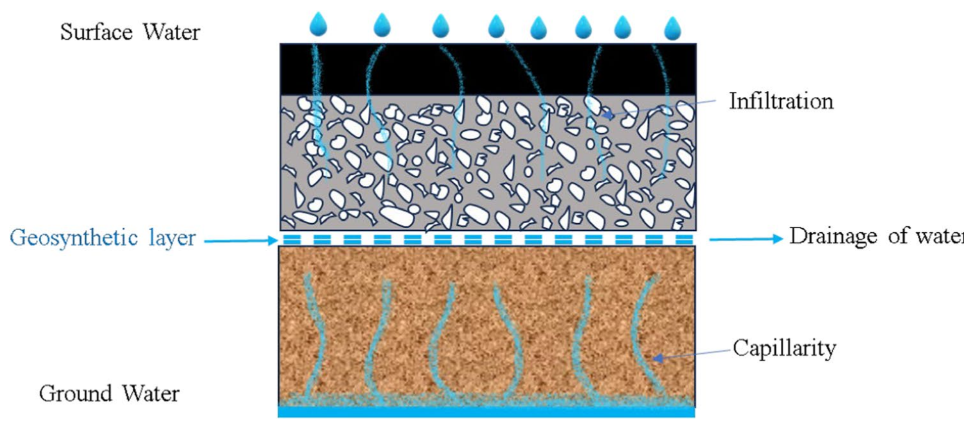


Fig. 9 Application of geosynthetics for drainage

movement. In addition to protecting groundwater supplies and separating hazardous chemicals from the surrounding environment, geosynthetics are also used as protective covers or liners in reservoirs, containment ponds, and landfills. Additionally, geosynthetics provide defence against biological deterioration, UV rays, and chemical deterioration.

6.7 Barrier

Geosynthetics create impermeable barriers, preventing the movement of fluids or gases. This function is crucial in applications where containment and environmental protection are paramount, such as in pond liners and waste disposal sites. Understanding these functions allows engineers and researchers to strategically incorporate geosynthetics into construction projects to enhance performance, durability, and sustainability. The swelling characteristics of bentonite clay are utilized by geosynthetic clay liners (GCLs) to form an impermeable barrier against water and pollutants. Similar to this, geotextile-geomembrane composites offer efficient containment and barrier solutions for a range of engineering tasks by combining the filtering powers of geotextiles with the impermeability of geomembranes. To control the movement and spread of fluids and contaminants in soil and geotechnical systems, geosynthetics with barrier functions are crucial for environmental protection, waste containment, groundwater management, and infrastructure development. They provide long-lasting, economical, and sustainable solutions.

6.8 Stress relief

Geosynthetics play an important role in stress relief for asphalt overlays by absorbing and spreading stresses, improving the structural integrity and performance of the pavement. Their smart integration can help to increase the lifespan of existing pavements and improve the overall sustainability of transportation infrastructure. Geotextile and Geogrids serve a multidimensional function in stress relief for asphalt overlays, including advantages such as crack avoidance, rut reduction, temperature stress management, increased load transfer efficiency, environmental sustainability, cost-effectiveness, and compatibility with diverse pavement types. Their strategic integration improves the structural integrity and performance of pavement systems, eventually contributing to the long-term viability and sustainability of transportation infrastructure.

7 Challenges in geosynthetics

Although geosynthetics provide flexible options for civil engineering and construction, there are drawbacks and restrictions. To use these materials effectively and intelligently, one must be aware of these concerns. These are some of the main obstacles and restrictions related to geosynthetics.

Installation quality: Correct alignment, placement, and connection by design specifications are essential for optimum geosynthetic performance. This is achieved through skilled and informed installation techniques.

Long-term durability: To improve longevity, geosynthetics must be designed with protective coatings, carefully chosen materials, and careful attention to temperature swings, chemical exposure, and UV radiation.

Quality assurance: Strict testing, certification, and conformity to industry standards are all necessary components of consistent quality control procedures that preserve material integrity between batches.

Interface shear strength: Achieving the ideal interface shear strength between nearby materials and geosynthetics is crucial for stability, requiring sophisticated testing techniques and taking compaction and material qualities into account.

End-of-life disposal: The environmental problems associated with the disposal of geosynthetics have prompted studies into more sustainable disposal options, such as recycling and biodegradable materials.

Chemical resistance: To achieve sufficient chemical resistance, geosynthetics must be tested for compatibility with contaminants particular to the site. This testing should involve barrier layers and protective coatings in harsh environments.

Lack of design standards: To provide engineers with guidance, research is being done to develop empirical models and performance-based specifications, as there are currently no standardized design standards for some geosynthetic applications.

Initial cost perception: Although geosynthetics may initially cost more, their adoption is justified by long-term financial advantages including shortened building times and lower maintenance expenses.

Thermal stability: Research into material changes and preventative measures to promote thermal stability is necessary since extreme temperatures might have an impact on geosynthetic performance.

Difficult soil conditions: In extremely variable soils, geosynthetics may be less successful, necessitating design adjustments for differential setting and soil movement.

Frictional resistance: Considering material attributes and using cutting-edge testing techniques is essential to achieving the required frictional resistance between geosynthetics and neighbouring materials.

Limited Understanding: Despite progress, there are still unanswered questions about the behaviour of geosynthetic organisms. This has led to further study to improve field investigations and predictive models.

Addressing these challenges requires ongoing research, advancements in material science, and collaboration between researchers, engineers, and industry stakeholders. Mitigating these limitations ensures the effective and sustainable use of geosynthetics in diverse construction and environmental applications.

8 Application of geosynthetics in real life

Geosynthetics find diverse applications across various civil engineering, construction, and environmental projects, as depicted in Fig. 10. Their versatility and beneficial properties contribute to solving a range of engineering challenges. Here are common applications of geosynthetics:

Geosynthetics are becoming modern materials as the demand for versatile needs is growing in civil engineering, as shown in Fig. 11. It is one of the most economical methods available as compared to other materials. Nowadays it is used in geotechnical, environmental, hydraulic and erosion control fields. There are some fields in which geosynthetic materials are used, its type, properties, functions and usage are given in Table 3.

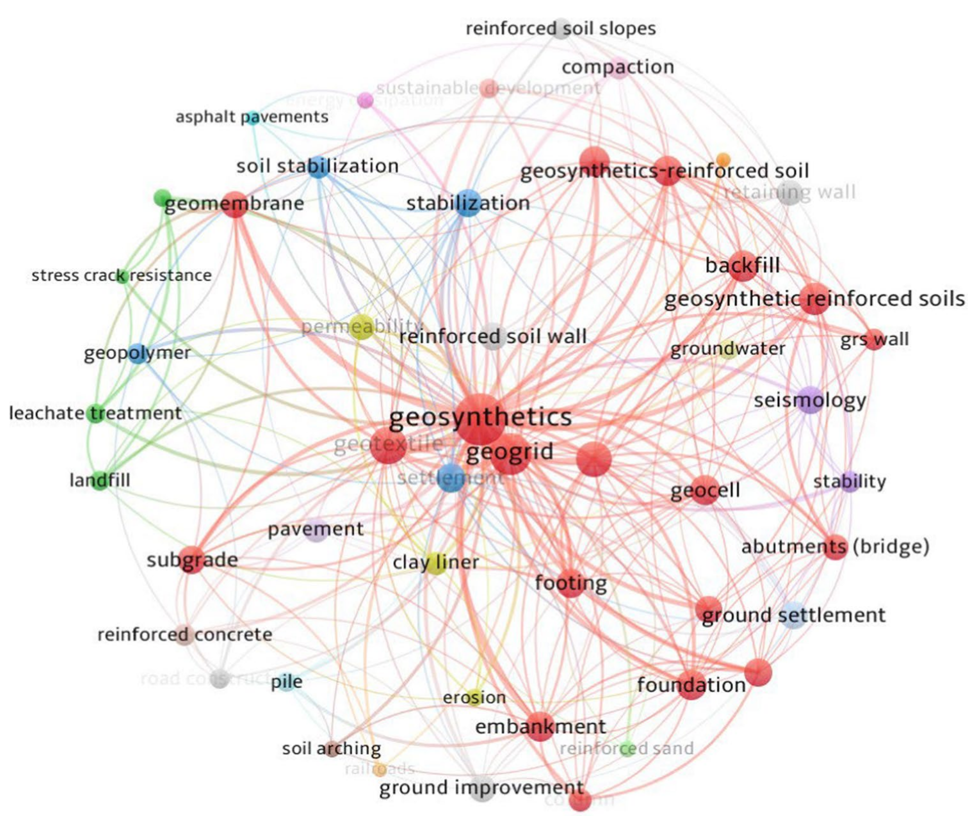
8.1 Drainage systems

Geosynthetics play a vital role in drainage systems by facilitating efficient water flow, preventing soil erosion, and controlling pore water pressure. They are commonly utilized in various drainage applications to enhance the performance and longevity of infrastructure projects. Geocomposite are effective in drainage systems due to their ability to provide both filtration and drainage functions. Geotextiles act as filters, allowing water to pass through while preventing soil particles from clogging drainage channels. Geonets provide structural support and promote rapid water flow within drainage systems.

8.2 Landfill liners and covers

The landfill is a facility to contains solid waste. Wastes are typically municipal generated and need to be dumped. Landfill has many components a liner system consists of multiple barrier and drainage layers and it is placed at the base, slope and top of the landfills liner system is responsible for the containment of leachate. Leachate collection and removal system: it is a system designed to deal with leachate, leachate is the water that is formed by the decomposition of soil waste known as primary leachate and water that infiltrates into landfill and seeps into waste is called secondary leachate. The Leachate collection system collects leachate generated from landfill and sends it to the wastewater treatment plant. This system must be made from highly impervious material like geomembrane. Upon decomposition, waste releases some gas like methane which has a bad odour and is highly inflammable so to deal with it a gas collection and control system is designed that uses the generated methane to produce energy [66]. To prevent water from seeping and infiltrating, in a landfill a barrier-like top cover is designed. The barrier for landfill liner and a cover system can be made from compacted clay liner. In landfills, the geotextiles are replaced

Fig. 10 Uses of geosynthetics as eco-friendly construction material



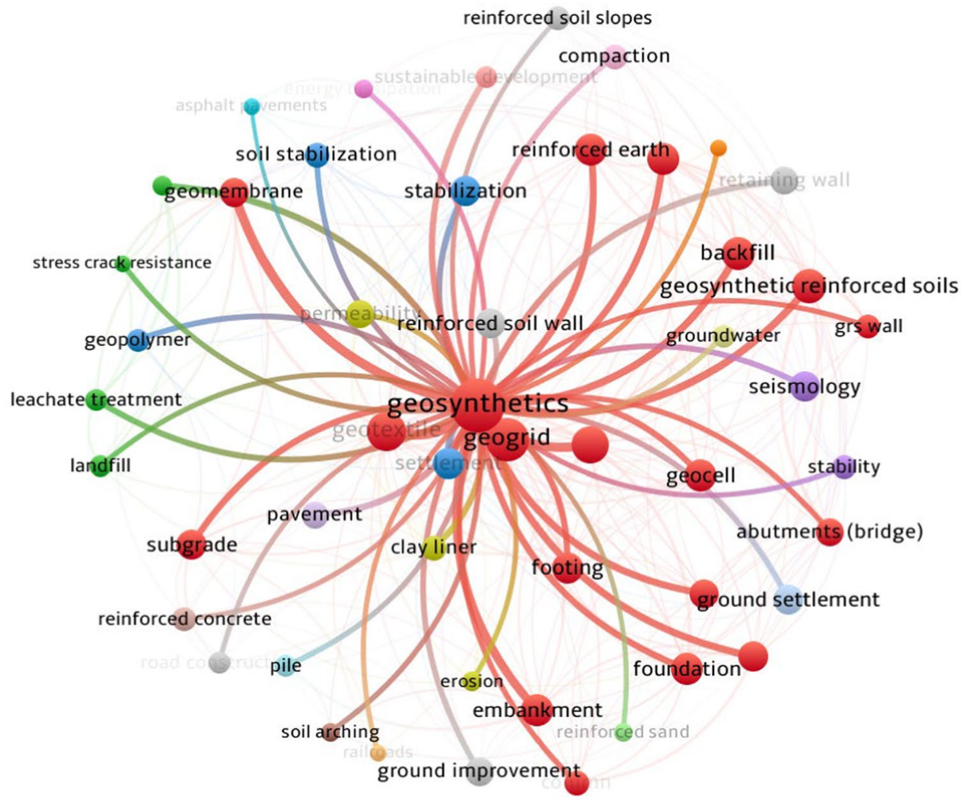


Fig. 11 Application of geosynthetics in different structures

with traditional granular soil layers which leads to a decrease in weight and a reduction in landfill settlement. They are helpful to prevent puncture damage to the geomembrane liner by acting like a cushion [67].

Geosynthetics play a critical role in containing and managing waste materials to prevent environmental contamination. Geomembranes and GCLs are key components used in landfill construction to create impermeable barriers that prevent the leaching of contaminants into the surrounding soil and groundwater. Geomembranes are used as primary liners at the base and sides of landfills. They effectively isolate waste materials from the environment and provide long-term protection against pollution.

GCL consists of a layer of bentonite clay sandwiched between two geotextiles, offering an additional barrier to fluid migration and enhancing the containment capabilities of landfill liners. Additionally, geosynthetics are used in landfill covers to control odours, manage gas emissions, and prevent the infiltration of precipitation into the landfill. Geosynthetics contribute to the safe and environmentally responsible management of solid waste in landfill facilities, reducing the risk of contamination and protecting human health and natural resources.

8.3 Erosion control

Geosynthetics are vital components that stabilize soil surfaces, lessen erosion, and provide protection from wind and water. In erosion control applications, geotextiles, blankets, and mats are frequently used. They encourage filtration, which stops erosion by letting water through while holding onto soil particles. The natural or synthetic fibers in erosion control blankets and mats are secured together by synthetic or biodegradable netting. These materials are spread out over sloping areas to encourage the growth of flora and offer instantaneous erosion prevention. Geosynthetics assist lessen the negative consequences of erosion, such as soil loss, sedimentation in water bodies, and damage to infrastructure, by stabilizing soil surfaces and encouraging vegetative growth. They are extensively utilized in many locations that are vulnerable to erosion, such as building sites, riverbanks, and highway embankments, to maintain soil stability, preserve ecological habitats, and protect against property damage.

Table 3 Area of geosynthetic application

Broad area	Area	Sub-area
Infrastructure development	Road construction	Pavement construction
		Base course stabilization
		Drainage system
	Railways	Track stabilization
		Railway ballast reinforcement
		Subgrade reinforcement
	Tunnel engineering	Tunnel construction
		Ground stabilization
	Retaining structures	Reinforced soil walls
		Mechanically stabilized earth walls
	Pipeline protection	Protection of buried pipelines
Environmental protection	Landfill engineering	Liner systems
		Landcover cap
		Leachate collection
	Erosion control	Slope stabilisation
		Riverbank protection
	Coastal engineering	Shoreline protection
		Beach erosion control
	Wastewater treatment	Lagoon liners
		Secondary containment
	Green infrastructure	Green roofs
		Vegetated slopes
Natural hazard mitigation	Avalanche protection	Snow nets
		Avalanche barriers
	Landslide mitigation	Slope stabilization
		Debris flow barriers
	Flood management	Flood barriers
		Erosion control measures
Resource extraction and mining	Tailings management	Tailings pond liners
		Containment systems
	Mine reclamation	Erosion control
		Habitat restoration
Industrial and commercial facilities	Oil and gas infrastructure	Containment ponds
	Gabion structures	Gabion walls
		Revetments
	Industrial facility protection	Protective liners
		Erosion control
Agriculture and landscaping	Agricultural erosion control	Reinforced soil systems
		Erosion blankets
	Water management	Irrigation canal liners
		Pond liners
	Landscaping	Turf reinforcement
		Golf Course Construction
		Tree root protection

8.4 Pavement construction

To improve the functionality, robustness, and lifespan of roads and other paved surfaces, geosynthetics have several uses. In reinforcement, where materials like geogrids and geotextiles are utilized to strengthen the structural integrity of the pavement layers, geosynthetics play a crucial role [61–63]. To distribute loads more efficiently, minimize rutting, and increase pavement life, geogrids are usually positioned between the layers of pavement, as in Fig. 12. Conversely, geotextiles are frequently employed as filtration and separation layers between various pavement components, avoiding material mixing and facilitating appropriate drainage. To stop water from penetrating the pavement layers and weakening the subgrade, which might result in pavement failure, geotextiles can also be utilized as a moisture barrier. Additionally, geocomposite can be used to improve pavement. and reduce the risk of water-related damage [64].

By using these materials engineers could reduce the thickness of the pavement, improving traffic conditions. It acts as a buffer zone that reduces the stress or impacts of cracking. Geosynthetics helps to resist cracks like reflective cracks, it waterproofs the layers and resists fatigue cracks. These act as a fluid barrier, which protects the underneath layers of pavement by blocking infiltration of surface moisture from the top and from the bottom it protects from capillarity water and groundwater.

8.5 Coastal protection

Protecting coastal areas from erosion, wave action, and other environmental variables is a critical function of geosynthetics. In coastal protection constructions, geotextiles and geocells are frequently utilized to stabilize sandy soils, stop erosion, and lessen the effects of waves and currents [65]. Along beaches, dunes, and shorelines, geotextiles are frequently placed as soft armouring to lessen wave energy and disperse erosive effects. They encourage the growth of vegetation, which stabilizes the shoreline by stabilizing the soil and lessening the effect of waves. Geocells are three-dimensional structures that resemble honeycombs and are constructed from synthetic materials such as HDPE [66]. They are used to strengthen coastal infrastructure and slopes. Revetments or erosion control barriers can be created by filling them with soil or aggregate and then planting vegetation to give them a natural appearance. To establish barriers or refill degraded beaches, geosynthetic tubes and bags are also used for shoreline protection and beach nourishment projects [67]. They are filled with sand or other materials. Additionally, to stabilize coastal infrastructure and provide protection from tidal forces and storm surges, geosynthetics are used in the building of seawalls, groins, and breakwaters [68].

8.6 Retaining walls

Geosynthetics play several significant roles in retaining wall construction, helping to improve performance, durability, and stability. For soil stabilization and reinforcement in retaining wall systems, geogrids and geotextiles are frequently utilized. Installed within the soil mass, geogrids are high-strength materials, usually composed of steel or polymers, that increase the soil mass's resistance to lateral stresses and tensile strength. Geogrids contribute to the increased stability

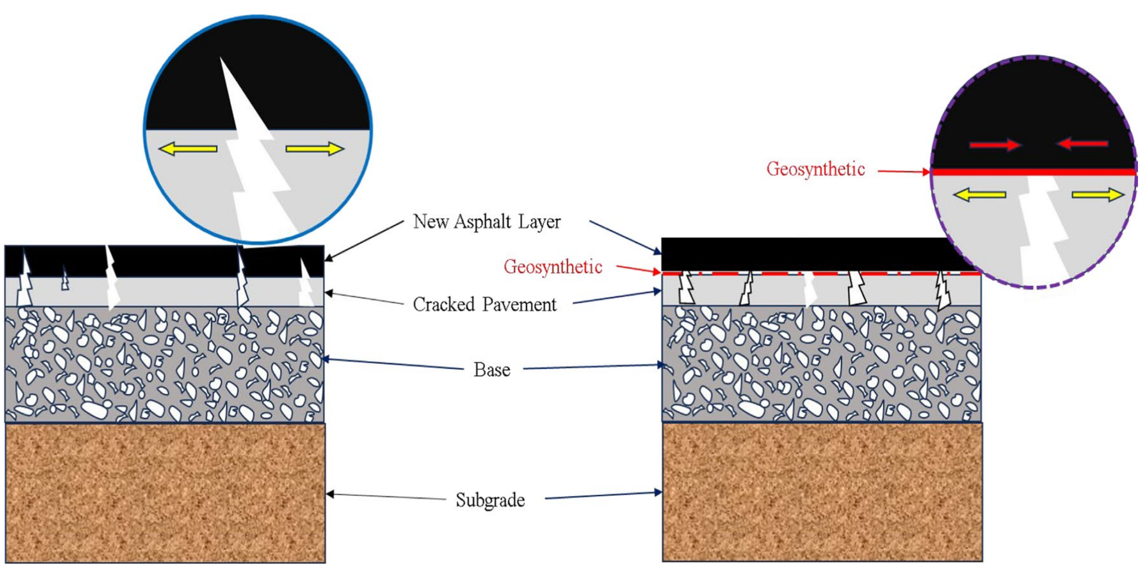


Fig. 12 Use of geosynthetic in the prevention of crack

and structural integrity of the retaining wall by more uniformly distributing loads and limiting soil movement [69, 70]. To stop soil erosion and water accumulation behind the retaining wall, geotextiles are utilized as filtering and drainage layers. They also act as a layer of isolation between the wall's structural elements and the backfill soil, reducing soil migration and preserving the structure's integrity over time. Furthermore, geocomposite materials, such as geocomposite drains, can be integrated into the designs of retaining walls to improve drainage and lower the hydrostatic pressure behind the wall [71].

8.7 Railway track stabilization

Railway tracks must sustain the huge loads and vibrations produced by trains, they are extremely robust and long-lasting. Each part, including the ballast, tracks, and sleepers, must work correctly when the weight is applied to achieve it. Geosynthetics are essential for increased efficiency and performance. Certain places, such as curves, switches, and railroad crossings, must be taken into account. Separation is the fundamental idea behind how geosynthetics work; they function as a barrier to prevent fresh ballast and soil from combining. Ballast seeps into subgrade soil as a result of vibration, which reduces track efficiency [72]. The drainage feature is appropriate for stability over the long run. Because of the capillary action that causes soil pore water to rise and reach the soil subgrade, there is a possibility that the moving wheel would pump mud [73], reducing the soil's strength and load-bearing capability. Water can drain away from geosynthetic and into side drains.

8.8 Tunnel construction

Geosynthetics serve to improve structural integrity, waterproof surfaces, and ensure long-term durability. Geotextiles and geomembranes are often utilized in geosynthetics in tunnel construction projects. Geotextiles are commonly used as separation and filter layers between different construction materials within a tunnel, avoiding material mixing and promoting correct drainage [74]. They also act as protective layers, preventing damage to waterproofing membranes and other tunnel components during construction. Geomembranes serve as key waterproofing barriers, preventing water infiltration into the tunnel structure [75]. They are placed on tunnel walls, floors, and ceilings to provide a continuous impermeable barrier that inhibits groundwater intrusion and protects against water damage.

8.9 Gabion wall construction

Gabion wall construction uses gabion baskets, which are wire mesh containers filled with stones or other durable materials, to build retaining walls, erosion control structures, and architectural features. Geosynthetics contribute significantly to gabion wall construction by improving stability, durability, and performance. Geotextiles are frequently utilized as a lining layer behind gabion walls to aid with soil retention, filtration, and drainage. Geotextiles are placed between the backfill soil and the gabion baskets to prevent soil erosion, retain fine particles, and allow water to pass freely through the structure, decreasing hydrostatic pressure and preventing water buildup behind the wall. Geogrids can also be used in gabion wall designs to give further reinforcement and stability.

8.10 Pipeline protection

Geotextiles and geomembranes serve as protective layers, shielding pipelines from external elements such as rocks, sharp objects, and abrasive soil particles, lowering the risk of physical damage and corrosion to pipeline coatings [76]. Geocomposite materials cushion pipes by spreading external loads, reducing stress concentrations and preventing structural damage. Geosynthetics also reinforce the surrounding soil to improve bearing capacity, stabilize soil surfaces to prevent erosion, and shield the pipeline from corrosive soils and electrolytes, extending its service life [77]. Geosynthetics play important roles in the resilience, dependability, and cost-effectiveness of pipeline infrastructure, guaranteeing safe and efficient transit of fluids and energy supplies. Geogrids are horizontally installed between layers of gabion baskets to enhance load distribution, reduce settlement, and boost overall structure strength [78–80]. Geosynthetics, when used in conjunction with gabion baskets, improve the performance and endurance of gabion walls, making them excellent solutions for numerous civil engineering and landscaping applications, such as slope stabilization, riverbank protection, and coastal erosion management.

8.11 Wastewater treatment

Geomembranes are often employed as liners in containment facilities such as wastewater ponds, lagoons, and landfills, forming impermeable barriers that prevent toxins from seeping into the surrounding soil and groundwater. GCLs are also used because of their low permeability and high hydraulic conductivity, which improve wastewater containment and allow for effective leachate collection and management. Geotextiles are also used in wastewater treatment systems for filtration and separation, which aids in the removal of suspended materials, the filtering of impurities, and the effective drainage of treated water. Geocomposite materials, which combine several geosynthetic components, can be used to provide multifunctional solutions like drainage and reinforcement in wastewater treatment infrastructure.

8.12 Agricultural applications

Geosynthetics are widely used in a variety of agricultural applications to combat soil erosion, increase soil stability, improve water management, and promote sustainable farming. Geotextiles are widely used for erosion control on slopes, embankments, and riverbanks, where they stabilize soil surfaces, reduce erosion, and stimulate vegetation growth. Geomembranes and GCLs are used in pond liners and reservoirs to prevent seepage, retain water, and allow for efficient irrigation and storage. Geocells and geogrids are used to stabilize soil in erosion-prone or compacted areas, as well as to provide structural support for access roads, parking lots, and agricultural tracks. Geotextile fabrics are also used in landscaping applications, such as weed control, mulching, and root protection, to increase soil health and plant growth. Geosynthetics help to promote sustainable agricultural practices, soil conservation, and crop yield by providing solutions for erosion control, soil stability, water management, and vegetative support.

8.13 Avalanche control

Geosynthetics serve an important role in avalanche control measures by providing new solutions to reduce avalanche danger and protect infrastructure, transit routes, and communities in avalanche-prone locations. Snow nets, snow fences, and avalanche barriers made of geosynthetic materials are strategically placed along avalanche pathways to intercept and restrict snow movement, minimizing the risk of devastating avalanches. These geosynthetic structures are intended to disperse the energy of snow masses, initiate controlled snow releases, and deflect avalanche debris away from sensitive regions. Geotextile mats or blankets are also used to stabilize slopes and strengthen vegetation, minimizing the risk of snow buildup and avalanche initiation. Geosynthetics offer cost-effective, ecologically friendly avalanche hazard mitigation methods, improving safety and resilience in mountainous and alpine environments.

8.14 Embankments

They are masses of soil made to elevate roads, highways and railway tracks. When loose soil is explored in an area various soil stabilization methods are adopted to make soil bear the loads either by replacing soil or improving by adding additives like lime, cement, and fly ash or using processes like grouting, compaction and sand drains [81, 82]. The problem is that it is time-consuming and expensive, on the other hand using geosynthetic materials like geotextile, geogrids and geomembrane in foundation embankment can be directly constructed over it. It serves as reinforcement, drainage and separation. Reinforcement function improves its slope stability, drainage improves the consolidation of soil particles by reducing pore water pressure. Separation helps in the prevention of the mixing of different layers.

8.15 Shallow foundation

Geosynthetics is gaining popularity for its application in shallow foundations that have less depth. There are many types of soil present some are either hard or loose. So, to construct a foundation soft soil must be stabilized. Usually, one or more layers of geosynthetic material are used [83–85]. This soil with geosynthetic material acts as reinforcement which improves load-carrying capacity. Geosynthetics used are mainly of geotextile, geocell, geocomposite and geogrid, they act as separators between soft soil and foundation base. To get maximum efficiency geosynthetic layers are placed horizontally concerning the foundation base [86]. Geosynthetics act as a water repulsion method, due to high precipitation

Table 4 Application of geosynthetic in various fields

Author	Country	Area	Function	Type	Outcome
Abbas, et al., 2024 [88]	South Korea	Sinkhole	Reinforcement	Geogrid	Geosynthetic reinforcement to significantly reduce sinkhole deformations
Babagiray, et al., 2023 [76]	Turkiye	Pipelines	Protection	Geocell, geogrid, strip geogrid,	The most effective reinforcing material in terms of pressure absorption (46.6%) and acceleration reduction (83.3%) was geotextile
Banerjee, et al., 2023 [56]	India	Railway tracks	Confinement	Geocells	The findings of the cyclic loading test showed that substituting coal mine OB for the conventional sub-ballast aggregates and combining it with geocell reinforcement produced positive results
Bi, et al., 2023 [5]	China	Crack propagation	Monitoring	Geogrid	Strain-self-sensing geogrid to monitor the performance of expansive soil slopes in alternate wetting–drying cycles
Chen, et al., 2023 [89]	Singapore	Land reclamation	Separation	Geotextiles	When using the HDeG sheet with vacuum preloading method, the transmissivity of geotextile has a major impact on the consolidation of soft soil
Dassanayake, et al., 2023 [36]	Sri Lanks	Landfill caps	Reinforcement, drainage	Geotextile	For the non-woven needle-punched geotextile and the non-woven needle-punched geotextile with band drains, the RMSEr values rose to roughly 15% and 19%, respectively
Eskandarni, et al., 2023 [43]	Iran	Permeability	Hydraulic properties	Geotextile	Geotextiles can facilitate fluid movement both through-plane (TP) and in-plane (IP)
Hegde & Sitharam, 2015 [77]	India	Protection of pipelines	Protection	Geogrid, geocell	When compared to other types of reinforcements, the usage of geocells with additional basal geogrid significantly minimizes the deformation of the pipe
Heibaum, 2014 [92]	Germany	Waterways and flood protection	Separation	Geobags, geotextiles, geosynthetic clay liner	To ensure the optimal construction of rivers and flood protection systems, geosynthetics can be engineered to regulate the interaction between water and soil to specific local needs

Table 4 (continued)

Author	Country	Area	Function	Type	Outcome
Jang, et al., 2015 [74]	Republic of Korea	Tunnels	Filtration, drainage	Nonwoven geotextile,	Comparing the geocomposite to nonwoven needle-punched geotextiles of comparable thickness, the geocomposite has a substantially higher discharge capacity
Junqueira, et al., 2006 [59]	Brazil	Leachates control	Drainage	Geotextile	When paired with geotextiles, tyres can provide an affordable drainage solution in areas where typical materials are expensive or hard to come by
Lamont-Black, et al., 2015 [93]	U. K	Dewatering	Filtration	Geotextile	By decreasing the volume of the contaminated waste, electrokinetic geosynthetics (EKG) technology offers an alternate dewatering treatment technique
Li, et al., 2023 [65]	China	Coastal protection	Separation, Drainage	Geobags, geogrids	Based on the two-year in-situ data gathered from the field experiments, the protection cost, structural stability, material durability, and design feasibility of the coastal geotextile sandbag protection performance were quantitatively assessed
Long, et al., 2007 [66]	Vietnam	Coastal areas	Protection, mitigation and rehabilitation	Geotextiles	Crucial responsibilities for geosynthetics can be played in the mitigation, protection, and restoration of impacted coastal areas
Mandhaniya, et al., 2022 [72]	India	Rail transportation	Shock absorbent	Geogrid	The GRE foundations function better when the facing wall is incorporated, according to the lateral response based on vertical acceleration computed at nodes. As speed increases, the improvement from the least reinforced to the most reinforced part ranges from 30 to 60%
Raja & Shukla, 2021 [85]	India	Foundation	Separator	Non-woven geotextile	When compared to the unreinforced model, the wraparound reinforced model has an average total settlement that is almost 45% lower

Table 4 (continued)

Author	Country	Area	Function	Type	Outcome
Scheiner, et al., 2006 [79]	Austria	Pipelines	Wear Protection	Geotextiles	Sand coating the pipeline reduces abrasion force, which the pipeline's outer anti-corrosion film can withstand without the need for extra protection. Sand leaching can be prevented by covering the sand body with geosynthetic materials
Sheng, et al., 2021 [87]	China	Isolating foundation near metro	Confinement, shock absorbent	Geobags	Building foundation isolation near metro transportation can be achieved with a geosynthetic isolator
Solatiyan, et al., 2021 [62]	Canada	Road pavements	Separation	Geogrid	The size of the aggregates used in high-strength grids' surrounding mixtures has a significant impact on the grids' ability to mitigate cracks
Sürer, et al., 2024 [23]	Turkiye	Leachates control	Barrier	Geosynthetic clay liners	After examining sodium's hydraulic conductivity, it was found that the GCLs had a low flow rate, which made them an effective barrier
Tafreshi, et al., 2020 [55]	Iran	Pipeline Protection	Protection	Geocell, geofoam	By reducing the pressure applied to the pipe, the use of geofoam and geocell helps reduce pipe deformations
Tupa & Palmeira, 2007 [80]	Brazil	Protection of buried pressurised pipes	Protection, reinforcement	Woven geotextiles, geogrid	When an underground pressurized pipe collapses, geosynthetic reinforcement can effectively fortify the soil and lessen the impact on nearby structures
Vorlet & Cesare, 2014 [19]	Switzerland	Hydropower plants	Barrier	Geomembrane	It provides an efficient system for water barriers in hydraulic structure
Watanabe, et al., 2020 [82]	Japan	Tsunami resistance embankments	Erosion	Geotextile	The GRS method was found to be very effective for resisting the erosion of embankments due to overflowing
Wu, et al., 2023 [57]	China	Machine foundation	Shock absorbent	Geocell	At high strain amplitudes, geocell reinforcement can improve the specimen's damping ratio by preventing the formation of local shear bands

Table 4 (continued)

Author	Country	Area	Function	Type	Outcome
Yang, et al., 2023 [95]	Taiwan	Reinforced soil walls	Drainage	Geogrid	Quantitative analysis was done to determine the impact of sand cushion thickness and reinforcing spacing on wall performance. Wall distortion was substantially decreased and wall stability was improved by increasing the thickness of the sand cushion and decreasing the space between reinforcements
Yu & Rowec, 2020 [18]	China	Waste containment	Containment, reinforcement	Geomembrane	Stability research demonstrates that there is a critical relationship between the width of the top of the waste pile and the overall thickness of the waste during waste-filling activities under a particular factor of safety
Zhang, et al., 2023 [6]	China	Roadway	Wicking	Geosynthetic	When geosynthetic was placed at the interfaces, the wicking effect of the paved roadway contributed 18–30% and the strengthening effect contributed 8–11%
Zhang, et al., 2023 [63]	China	Road construction	Monitoring	Printed geogrid	In a model test on geogrid-reinforced subgrades with an underlying karst cave, a self-sensing geogrid that can track strain in real time was created
Zornberg, et al., 2017 [64]	USA	Lateral drainage in roadway	Drainage	Geotextiles	When improved lateral drainage is included in roadway systems, pavement performance is improved in several ways

or an increase in groundwater level water reduces the strength of soil just below the foundation resulting in either failure, sinking, tilting or differential settlement, all these can be avoided by geosynthetics. To investigate the effect of woven geotextile in improving load carrying capacity of the foundation upon weak soil many factors are examined the size of the geotextile, number of geotextiles, layers of geotextile, width of geotextile and spacing between geotextile layers [87].

8.16 Filters and drains

There are many areas for geosynthetics to act as filter material which include drains of roadways, seepage water transfer systems, retaining wall drainage, slope drainage, landfill leachate collection systems, drainage columns in embankments and dams. Traditionally for filtration graded granular stone filters were used but in the modern era geotextile fibre has taken its place, because geotextile is easy to install, economical, cheap, light in weight, stable, durable and easy to maintain [88–90]. To use geotextile three phenomena, affect the filtration capacity they are blocking the pore of geotextile which will affect its effectiveness. decrease binding [91] and clogging both reduce the capacity of geotextile.

8.17 Earthen dams

Earthen dams are massive structures built with soil and stones to store water. Soil and stones used are locally available and are placed and compacted and this process is continued till it reaches a sufficient height [92]. It is a very old method to store water it has very little efficiency because soil allows water to percolate out of it. So, geosynthetic materials are used to improve their efficiency. It may serve many functions like a water barrier system, filtration, drainage, and reinforcement. Geosynthetics are soft and flexible so they can be used in any shape and formed into different sizes. It also has mechanical strength that helps it to bear tension and deformation. Geomembrane, geotextile has low permeability that is used in dams that restrict the infiltration of water in the soil. Reinforcement can be achieved by geogrid, geotextile which helps in slope stabilization [93–95]. For old-constructed dams, it can be used as a temporary method to limit cracks and provide free board, which contributes to increasing its safety.

The broad application of geosynthetics is given in Table 4.

These applications showcase the versatility of geosynthetics across various industries and illustrate their role in addressing engineering challenges, improving infrastructure resilience, and promoting sustainable practices in diverse real-life scenarios.

9 Conclusion

In this review, a detailed overview of geosynthetic material utilized as an alternative to traditional construction material in soil stabilization is done. Geosynthetics have emerged as indispensable materials in modern construction and environmental management. Their multifaceted roles contribute to the resilience, efficiency, and sustainability of diverse projects. Many research illuminates the pivotal role that geosynthetics play in contemporary civil engineering, construction, and environmental applications. By meticulously exploring the various types, functions, and real-world uses of geosynthetics, this study underscores their versatility and effectiveness in addressing a wide array of engineering challenges.

The implications of this research extend to engineering professionals seeking innovative and cost-effective solutions, with identified research gaps providing fertile ground for future exploration and advancements in the field. As we navigate the complexities of modern construction and environmental management, geosynthetics stand out as indispensable tools, offering resilient and sustainable solutions.

The findings of this research have practical implications for engineers and construction professionals, offering innovative and cost-effective solutions to engineering challenges. Future studies may focus on addressing challenges, refining design guidelines, and investigating new applications for geosynthetics.

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Declarations

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