

Applications of Geosynthetics in Tunnels Construction: A Sustainable Approach to Carbon Footprint Reduction

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REVIEW ARTICLE

Applications of Geosynthetics in Tunnels Construction: A Sustainable Approach to Carbon Footprint Reduction

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ABSTRACT

The use of geosynthetics has transformed tunnelling practices by enhancing structural integrity, durability, and environmental sustainability. This review adopts a systematic literature review design, covering publications from 2000 to 2025 sourced from Scopus, Web of Science, ScienceDirect, and Google Scholar. The selected studies were screened based on relevance, quality, and focus on tunnelling applications, then thematically analyzed into four domains: geosynthetic types, applications, sustainability, and performance evaluation. This review focuses on the applications of various geosynthetics, including geotextiles, geogrids, geocomposites, geocells, and geomembranes, in tunnelling projects. These materials play crucial roles in reinforcing tunnel walls and slopes, improving load distribution, and controlling deformation. Additionally, geosynthetics contribute to effective drainage and filtration, reducing water-related hazards and preventing soil erosion, while geomembranes offer protection against water ingress, chemical exposure, and abrasive damage. The integration of geosynthetics supports safer construction and extends the service life of tunnels. Selecting appropriate geosynthetics based on project-specific conditions, such as soil type and environmental factors, is essential for optimal results. While their benefits are substantial, challenges like maintaining performance under harsh conditions and ensuring proper installation require attention. Ongoing research and field studies are needed to advance understanding and improve practices. The future of tunnelling engineering will benefit from innovations in bio-based and smart geosynthetics, promising greater adaptability, sustainability, and efficiency. Overall, the strategic use of geosynthetics is pivotal in modern tunnelling, offering solutions that align with the demands of safety, performance, and environmental responsibility.

Keywords: Geosynthetics, Tunnelling, Tunnel lining, Drainage systems, Environmental sustainability

1. Introduction

Geosynthetics play a pivotal role in modern civil engineering and construction, particularly in tunnel engineering, where they enhance soil stability, drainage, and environmental sustainability [1–5]. The underground structure (tunnels, bunkers, etc.) should be stable against different types of extreme loading [6–11]. These synthetic materials, including

geotextiles, geogrids, and geomembranes, serve as essential components in reinforcing and stabilizing soil and rock masses, preventing erosion, and improving the durability of underground structures [12]. Their applications extend across various infrastructure projects such as roadways, railways, and waste containment systems [13–16]. Over recent years, research has increasingly focused on improving the performance, durability, and sustainability of geotechni-

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cal and tunnelling systems, including advancements in material technologies, underground construction practices, groundwater management, and structural monitoring, to enhance long-term infrastructure reliability and reduce environmental impacts [17–23]. The integration of geosynthetics in tunnelling and civil infrastructure projects offers significant engineering, environmental, and economic benefits by improving ground performance, supporting erosion control and drainage functions, reducing dependence on conventional construction materials, and promoting sustainable construction practices [24–35]. The use of geosynthetics and improved geotechnical engineering practices can enhance soil performance, facilitate the utilization of locally available materials, and reduce excavation, stabilization, and transportation requirements, thereby contributing to more cost-effective and sustainable construction practices [36–40]. In tunnel engineering, geosynthetics provide several advantages, including enhanced structural stability, extended service life, and reduced maintenance costs. Their reinforcement capabilities help mitigate risks such as ground settlement and structural instability by improving load distribution and support conditions within the surrounding ground. Previous studies have highlighted the importance of factors such as soil layering, groundwater variation, and superstructure interaction on tunnel performance and settlement behaviour during tunnel construction [22, 41–43]. Their lightweight and flexible nature enable easy installation, making them a practical alternative to traditional reinforcement techniques [44–48]. The use of geomembranes and geosynthetic clay liners in tunnel waterproofing ensures protection against chemical degradation and leakage, thereby enhancing the overall resilience of underground infrastructure [48–51]. Additionally, geosynthetics contribute to effective water drainage and filtration, preventing excessive moisture buildup and minimizing the risks associated with water infiltration, such as structural weakening and corrosion [50, 52]. By improving structural stability, reducing ground deformation, and enhancing the durability of tunnel support systems, geosynthetics contribute to extending the service life of tunnel structures and minimizing the need for frequent maintenance and rehabilitation activities [53–58]. Furthermore, their role in reducing the carbon footprint of construction projects aligns with global efforts to promote sustainable development [52, 59–62]. One of the key aspects of sustainability in tunnel engineering is the ability of geosynthetics to mitigate environmental degradation. The incorporation of recycled materials in geosynthetics manufacturing reduces dependence on

virgin resources, thus promoting resource efficiency [48, 52]. Additionally, their application minimizes construction waste generation, contributing to a more environmentally responsible approach to infrastructure development [63–67].

The application of geosynthetics in tunnel engineering aligns with the United Nations' 17 Sustainable Development Goals (SDGs), particularly those related to sustainable infrastructure development and environmental conservation, as illustrated in Fig. 1 [68]. Their use supports SDG 9 (Industry, Innovation, and Infrastructure) by promoting resilient, resource-efficient, and sustainable infrastructure systems with reduced embodied environmental impacts [69]. Additionally, geosynthetics contribute to SDG 11 (Sustainable Cities and Communities) by enhancing the durability and efficiency of underground transportation infrastructure, minimizing environmental disturbances, and supporting safer and more sustainable urban development practices [70]. These contributions highlight the important role of geosynthetics in advancing long-term sustainability objectives in civil engineering and infrastructure construction.

Despite these advancements, the literature still lacks a comprehensive and focused review addressing the combined technical performance and sustainability aspects of geosynthetics specifically in tunnelling applications. Most previous studies have concentrated on isolated functions such as reinforcement or drainage, while their cumulative impact on environmental performance and carbon footprint reduction remains underexplored. Recognizing this research gap, the present study aims to synthesize and critically evaluate existing knowledge on the use of geosynthetics in tunnelling, emphasizing their role in achieving structural efficiency, durability, and sustainability.

The purpose of writing this review paper is to comprehensively cover the use of geosynthetics in tunnelling projects. This will include examining various applications, such as reinforcement of tunnel walls and slopes, drainage and filtration systems, and protection against corrosion and abrasion. It will also discuss the advantages and challenges associated with using geosynthetics and their contribution to sustainable and environmentally friendly tunnelling practices. By focusing on sustainability, this paper will highlight how geosynthetics can significantly reduce the environmental impact of tunnelling projects by minimizing waste generation, lowering carbon emissions, and promoting the use of recyclable materials. Moreover, the long-term durability and performance of geosynthetics contribute to sustainable construction by reducing the frequency



Fig. 1. The 17 United Nations (UN) Sustainable Development Goals (SDGs) [68].

of maintenance and the need for extensive repairs, leading to reduced resource consumption and waste production. Ultimately, this review will emphasize the importance of geosynthetics in achieving sustainable tunnelling practices and advancing the goals of sustainable development in the civil engineering and infrastructure sectors.

1.1. Aims of the study

The main aim of this review is to provide a comprehensive synthesis of the use of geosynthetics in tunnelling from both engineering and sustainability perspectives. Specifically, the study seeks to:

- Summarize the various types of geosynthetics used in tunnelling and describe their mechanical and functional properties relevant to underground construction.
- Evaluate their applications in reinforcement, drainage, filtration, and protection systems within tunnel environments.
- Examine the contribution of geosynthetics to sustainability and carbon footprint reduction in tunnelling projects.
- Discuss laboratory and field performance evaluations to understand durability and long-term behaviour under harsh environmental and loading conditions.
- Identify existing challenges and propose strategies for effective material selection, design, and installation.

- Highlight research gaps and future directions for innovation in sustainable tunnel engineering.

2. Methodology of the review

To ensure a comprehensive and systematic review, a structured methodology was adopted for collecting, screening, and synthesizing relevant literature. The search primarily focused on publications from the years 2000 to 2025, including peer-reviewed journal articles, conference papers, and technical reports; however, a few seminal studies published as early as 1995 were also included due to their foundational relevance to the topic. The literature search was conducted using databases such as Scopus, Web of Science, ScienceDirect, and Google Scholar. A total of approximately 430 studies were initially identified through database searches using Scopus, Web of Science, ScienceDirect, and Google Scholar. After removing duplicate and unrelated records during title and abstract screening, 230 studies were retained for full-text assessment. Following detailed evaluation based on the predefined inclusion and exclusion criteria, 155 studies were finally selected and included in the thematic review and analysis.

The screening process was conducted in multiple stages:

- Initial screening based on titles and abstracts to filter out irrelevant studies,
- Full-text review to assess detailed relevance and data quality,

Table 1. Comparative characteristics of general polymer families [80].

Comparative Properties	Group of Polymer			
	Polyester	Polyamide	Polypropylene	Polyethylene
Strength	High	Medium	Low	Low
Elastic Modulus	High	Medium	Low	Low
Strain at Failure	Medium	Medium	High	High
Creep	Low	Medium	High	High
Unit Weight	High	Medium	Low	Low
Alkalis	Low	High	High	High
Fungus, Vermin, Insects	Medium	Medium	Medium	High

- Inclusion criteria: relevance to geosynthetics in tunnelling, English language, and a focus on sustainability or infrastructure durability.
- Exclusion criteria: non-peer-reviewed materials, duplicates, and studies unrelated to underground structures.

The final set of studies was thematically categorized into major focus areas, including:

- Types of geosynthetics,
- Applications in tunnelling,
- Sustainability and environmental performance,
- Performance evaluation and innovations.

This structured methodology ensured objectivity, transparency, and reproducibility in the literature review. The process is visually summarized in Fig. 2.

3. Types of geosynthetics used in tunnelling

The primary geosynthetics used in tunnelling include geotextiles, geogrids, geocomposites, geocells, and geomembranes (Fig. 3). These materials may be used individually or in combination to improve reinforcement, drainage, filtration, and waterproofing performance in tunnel construction [71–79].

Four primary polymer families serve as raw materials for geosynthetics: polypropylene, polyester, polyamide, and polyethylene. Table 1 presents the comparative characteristics of the polymer families utilized in geosynthetics [80].

3.1. Geotextiles

Geotextiles are permeable synthetic fabrics widely used in tunnelling for reinforcement, filtration, separation, and drainage applications. Fig. 4 shows the different types of geotextiles [81]. They are commonly used to separate different soil layers and prevent the intermixing of fine and coarse particles, thereby improving filtration efficiency and maintaining the stability and performance of tunnel ground systems [81–83]. Fig. 5 illustrates a standard classi-

fication of geotextile manufacture [82]. Geotextiles can also be used to control erosion and prevent the loss of fine soil particles during tunnel excavation.

Key engineering properties include tensile strength, puncture resistance, and filtration capacity. vary depending on factors such as the polymer type, manufacturing process, and the specific application it is intended for [80].

3.2. Geogrids

Geogrids are polymeric reinforcement materials with apertures that interlock with surrounding soil or rock, thereby improving load transfer and ground stability [84]. Geogrids are often constructed from polyester, high-density polypropylenes (PP), or high-density polyethylene, although alternative materials are generally utilized as indicated in Table 2. Fig. 6 depicts the different varieties of geogrids. In tunnelling, geogrids are primarily used to stabilize weak ground and limit excessive deformation [85].

3.3. Geocomposites

Geocomposites are combinations of different geosynthetic materials such as geotextiles, geogrids, and geomembranes. In tunnelling, geocomposites are employed for integrated drainage, filtration, separation, and reinforcement functions. The versatility of geocomposites allows for tailored solutions to suit specific ground conditions and project requirements, making them an essential component in tunnel construction [52, 86, 87].

3.4. Geocells

Geocells are three-dimensional honeycomb-like structures made of perforated panels that are interconnected to form a flexible and stable confinement system as shown in Fig. 7 [88, 89]. Table 3 shows the typical properties of Geocell. In tunnelling projects, geocells are used for slope protection, load support, and erosion control. Their confinement mechanism

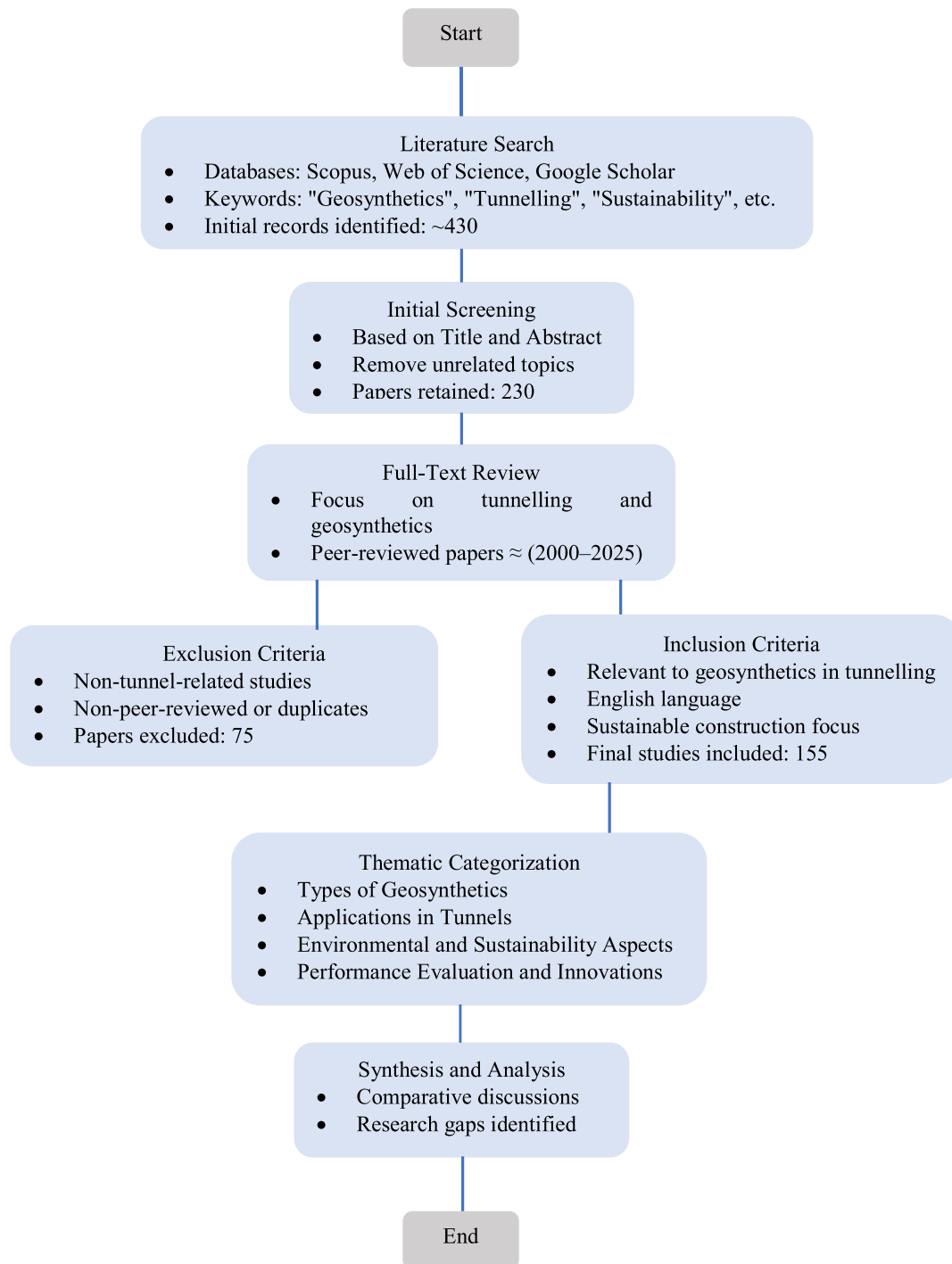


Fig. 2. Flowchart of the review methodology for selecting and analysing literature on geosynthetics in tunnelling.

improves soil stability and reduces erosion around tunnel structures.

3.5. Geomembranes

Geomembranes are impermeable polymeric barriers used to control fluid and gas migration.

Geomembranes can be categorized into two primary types based on their thermal properties: thermoplastics, which can be remelted, and thermosets, which are crosslinked or cured and cannot be remelted without degradation [96]. In tunnelling projects, geomembranes are employed to provide waterproofing and chemical protection to

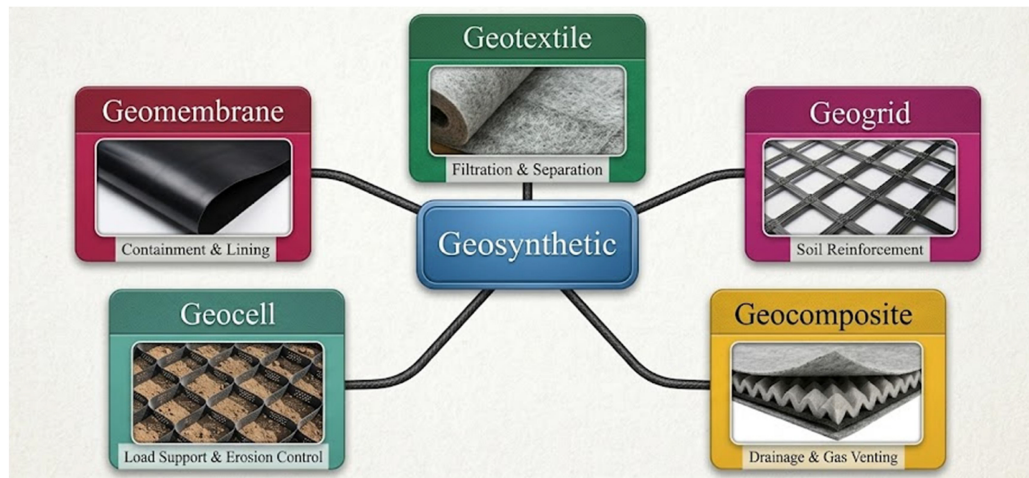


Fig. 3. Common types of geosynthetics used in tunnelling applications.

Table 2. Properties of polymers often employed in geogrid materials [84].

Type of Polymer	Glass Transition Temperature, T _g (°C)	Density (kg/m ³)	Modulus of Elasticity (MPa)	Tensile Strength Ultimate, (MPa)
Polyethylene Terephthalate (PET)	71-81	1380	2760-4140	85
High-Density Polyethylene (HDPE)	-125	930-970	650-1500	26
Low-Density Polyethylene (LDPE)	-125	910-940	190-520	10
Polypropylene (PP)	-20 to -6	920-980	1140-1550	9-80
Polyvinyl Chloride (PVC)	86	1400	3-4140	0.00123-60.8

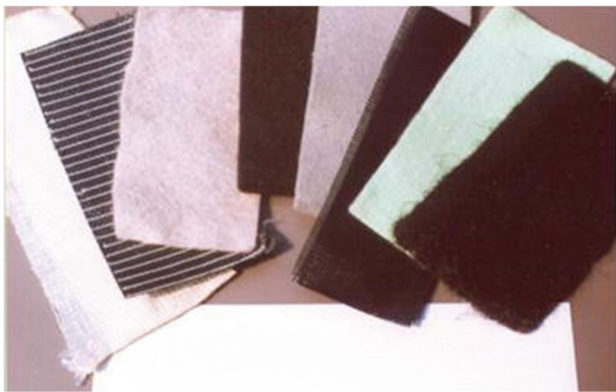


Fig. 4. Different types of geotextiles [81].

the tunnel structure as shown in the Fig. 8 [97]. They protect tunnel linings against water ingress, chemical exposure, and gas penetration [98, 99].

4. Functions and application of geosynthetics in tunnelling

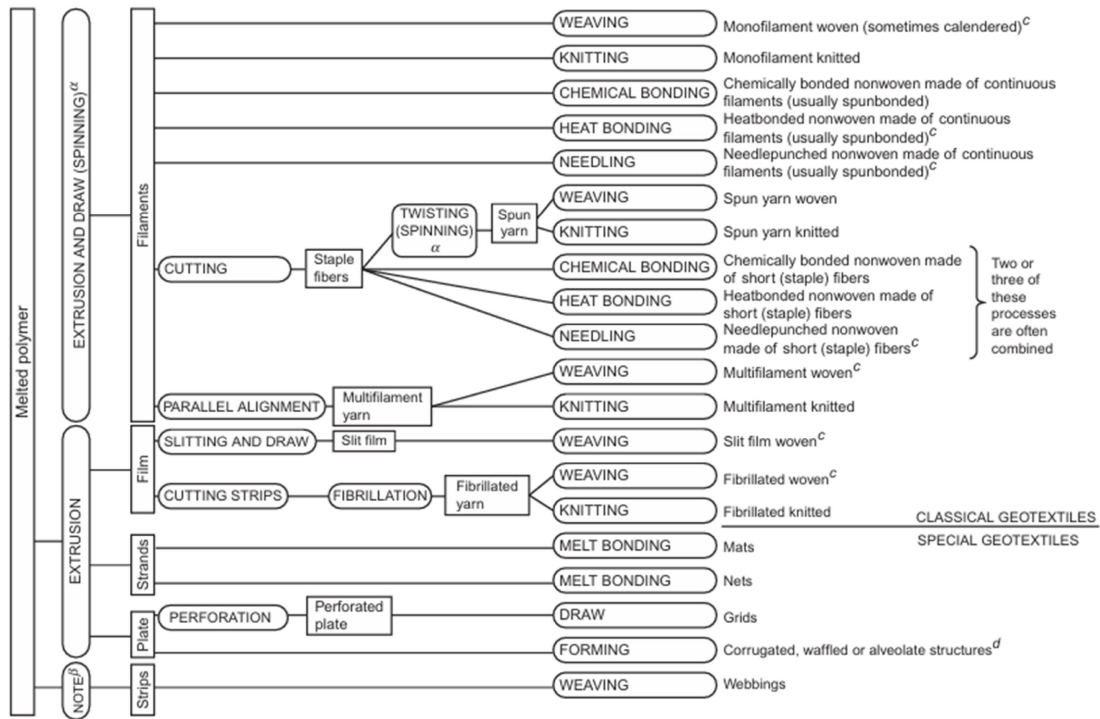
Geosynthetics play a vital role in various aspects of tunnelling projects, including reinforcement of tunnel walls and slopes, drainage and filtration systems, and protection against corrosion and abrasion as shown in Fig. 9.

Table 3. Typical properties of the novel polymeric alloy geocells [88].

Properties	Values	Test Method
Density (g/cm ³)	0.95	ASTM D1505 [90]
Strip thickness (mm)	1.53	ASTM D5199 [91]
Tensile strength (N/mm)	> 20	-
Creep reduction factor	> 2.7	ASTM D6992 [92]
Environmental Stress-Cracking Resistance (ESCR) (hr)	> 3000	ASTM D1693 [93]
Coefficient of Thermal Expansion (CTE) (Ppm/°C)	< 80	ISO 11359-2 [94]
Durability to UV Degradation (min)	> 100	ASTM D5885 [95]

4.1. Reinforcement of tunnel walls and slopes

Geotextiles and geogrids are extensively utilized in tunnelling projects to reinforce the walls and slopes of the underground structures. These geosynthetic materials are strategically incorporated to provide substantial additional tensile strength, significantly improving the overall structural stability of the tunnel. This reinforcement approach is particularly crucial in areas with weak or unstable soil conditions, where the geosynthetic reinforcement can effectively prevent the occurrence of slope failures and substantially limit the potential deformations within the tunnel structure. Faleih et al., [100] investigated the



- (^a) The term 'spinning' encompasses two definitions: the extrusion through a spinneret to produce a filament and the creation of yarns from staple fibers.
- (^b) Strips can be produced utilizing various suitable methods, including extrusion, calendaring, weaving, yarn production, and fabric coating.
- (^c) Certain traditional geotextiles (as specified) are utilized more frequently than others.
- (^d) Corrugated, waffled, or alveolate structures are typically not employed independently.

Fig. 5. Production of geotextiles (Products are denoted in lowercase characters; processes are represented in uppercase letters) [82].

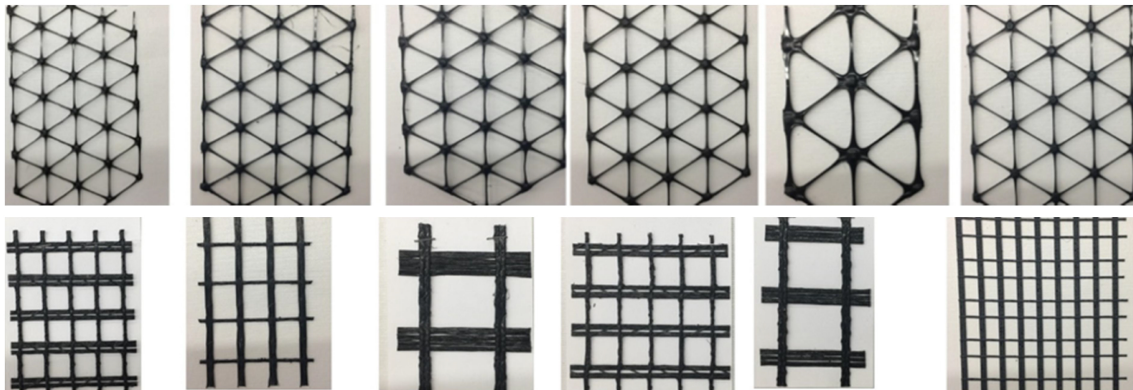


Fig. 6. Different types of geogrid materials used for soil reinforcement applications [84].

reinforcement of tunnels in soft soil using geogrids under axial loading conditions using laboratory model as shown in Fig. 10. Tests were performed at two depths; 1.5D and 2.5D (D is the diameter of tunnel) with different geogrid configurations. Results showed that two-layer geogrid reinforcement

significantly enhanced tunnel stability by improving load distribution and reducing pressure and surface settlement. Reinforced tunnels exhibited reduced deformation, contributing to greater structural integrity and sustainability. The study concluded that geogrid layers provide an effective, cost-efficient

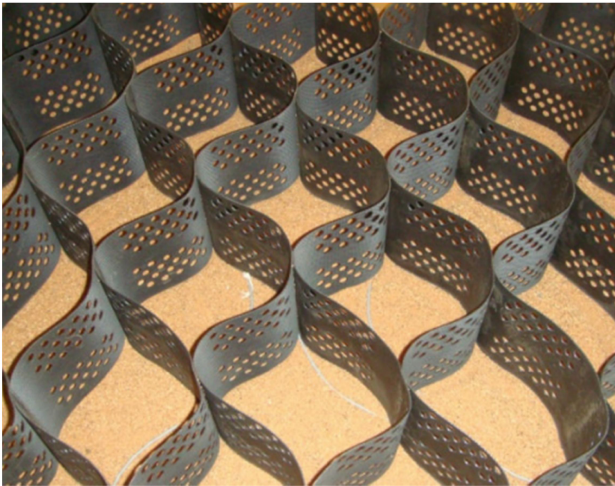


Fig. 7. Typical geocell structure used for soil confinement and stabilization [89].



Fig. 8. Geomembrane waterproofing system used in the Helms penstock access tunnel [97].

method for increasing the load-bearing capacity of soil-tunnel systems. By leveraging the robust tensile properties of geotextiles and geogrids, engineers can enhance the long-term performance, reliability, and safety of the overall tunnelling infrastructure.

4.2. Drainage and filtration systems

Geosynthetics, such as geotextiles and geocomposites, are widely employed in tunnelling projects to establish effective drainage and filtration systems. Geotextiles are used as permeable barriers to separate soil layers, preventing the migration of fine particles while allowing for the controlled flow of water as shown in Fig. 11 [101]. This approach helps maintain the integrity of the tunnel structure by mitigating

the risk of soil erosion and ensuring proper drainage [102, 103]. Additionally, geocomposites, which combine geotextiles with other geosynthetic materials, are utilized to provide comprehensive drainage solutions, efficiently managing the flow of groundwater and reducing the potential for water buildup within the tunnel. Fig. 12 shows the geotextile used in tunnel drainage system [104].

4.3. Protection against corrosion and abrasion

Geomembranes, which are impermeable and highly durable geosynthetic sheets, play a crucial role in protecting the tunnel structure from a wide range of environmental threats and deteriorating factors. These specialized materials serve as a robust and reliable barrier against the ingress of water, the intrusion of harmful chemicals, and the abrasive forces that can act upon the tunnel over time [105, 106]. Brummermann and Schlütter [107] investigated the geomembrane sealing systems in tunnel construction, which apply to both trenchless two-shell tunnels (Fig. 13) and cut-and-cover methods (Fig. 13). The recommendations emphasize the importance of effective waterproof sealing for ensuring longevity and low maintenance costs. They detail the design fundamentals, installation practices, and quality assurance measures necessary for successful implementation. Fig. 14(a) and 14(b) illustrate the structures of geomembrane sealing systems in vault tunnels and cut-and-cover tunnels, respectively, highlighting the arrangement of protective layers and drainage elements [107]. By effectively preventing the penetration of water and corrosive substances, geomembranes significantly enhance the structural integrity and long-term performance of the tunnel, helping to extend its lifespan and minimize the need for costly maintenance and repair operations. The incorporation of these impermeable geosynthetic layers is essential in ensuring the overall durability, resilience, and service life of the tunnelling infrastructure.

Through the strategic application of various geosynthetic materials, including geotextiles, geogrids, geocomposites, and geomembranes, engineers and construction professionals can address a wide range of challenges encountered in tunnelling.

5. Performance evaluation of geosynthetics in tunnelling

Evaluating the performance of geosynthetics in tunnelling projects is crucial to ensuring the long-term reliability and safety of the underground infrastructure. One key aspect of this performance evaluation

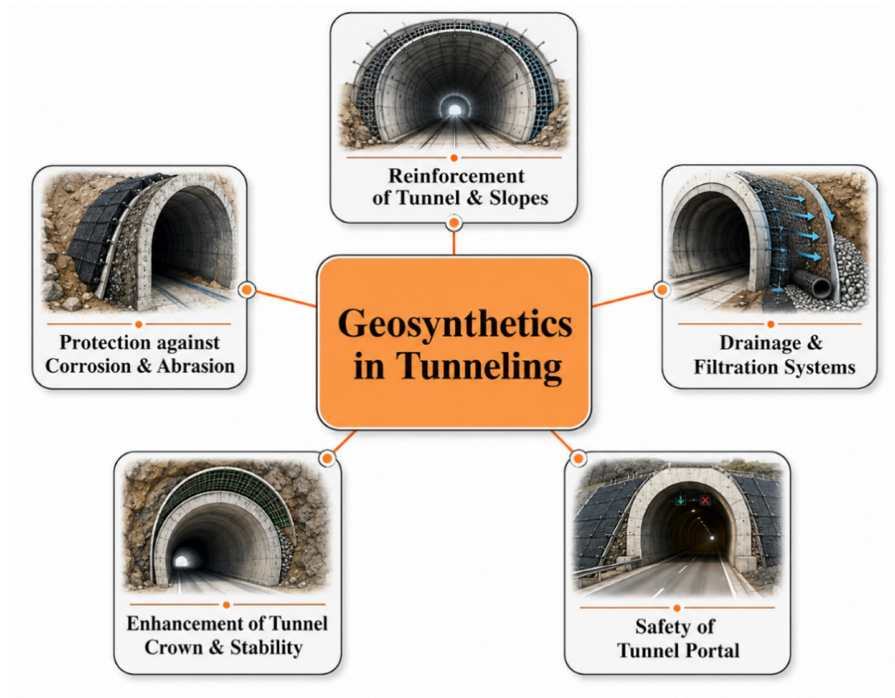


Fig. 9. Major applications of geosynthetics in tunnelling engineering.

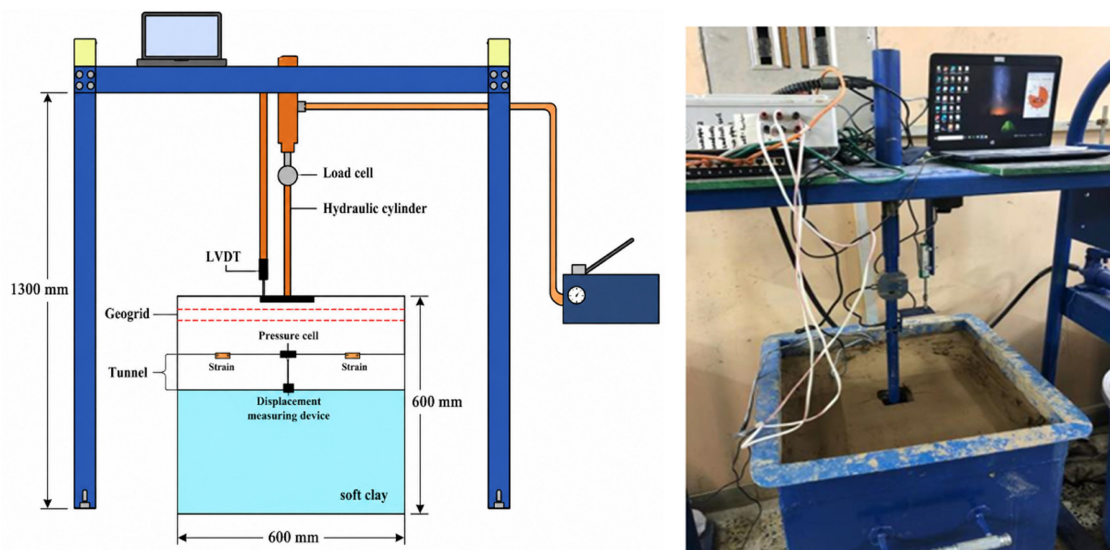


Fig. 10. Experimental setup and loading arrangement for geogrid-reinforced tunnel testing under axial loading conditions [100].

is the assessment of the geosynthetic materials' resistance to degradation and deterioration under the specific environmental conditions encountered within the tunnel.

5.1. Laboratory testing methods

To assess the durability and long-term performance of geosynthetics in tunnelling applications, a range

of laboratory testing methods are employed. These include: tensile strength tests to measure the materials' ability to withstand tensile stresses, elongation tests to determine their deformation characteristics, and other specialized assessments to evaluate the geosynthetics' resistance to chemical and biological degradation, as well as their ability to maintain their structural integrity under various environmental conditions [108, 109]. Almeida et al.,

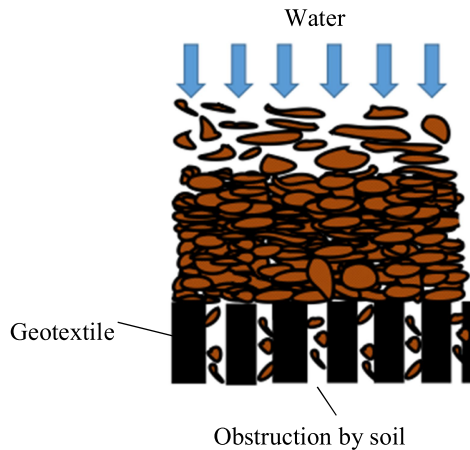


Fig. 11. Illustration of soil particle obstruction caused by geotextile [101].

[110] examined the mechanical damage and abrasion resistance of five geosynthetics (three geotextiles and two geogrids) under repeated loading. Fig. 15 shows the equipment setup for mechanical damage tests, where geosynthetics are placed between layers of corundum and subjected to cyclic loading to simulate stress during installation. Fig. 16 depicts the abrasion test setup, where geosynthetics are attached to a stationary platform and rubbed by an abrasive sheet under controlled pressure to assess surface wear. Mechanical loading caused filament cuts and punctures in the geotextile specimens, as observed in Fig. 17(a–d) and 18(a–d), whereas abrasion produced noticeable surface wear and fibre detachment in the geogrid specimens, as presented in Fig. 19(a–d) and 20(a–d). Almeida et al., [110] reveals that significant tensile strength loss for Geotextile W180 (35.6% reduction from mechanical damage) compared to 86.1% from abrasion. Nonwoven Geotextiles NW300 and NW500 exhibited retained tensile strengths of 69.8% and 86.0%, respectively, while Geogrid GG40I had minimal loss (1.6%) versus GG40II (40.3%). Table 4 highlighted the tensile properties, showing a greater loss in woven geotextiles after mechanical damage, while abrasion severely impacted geogrids as shown in Table 5. Table 6 indicated nonwoven geotextiles were more resistant, with higher mass per unit area enhancing survivability [110]. The analysis highlights the intricacy of geosynthetic durability in actual degrading conditions, such as tunnels.

5.2. Field monitoring and observation

In addition to laboratory testing, field monitoring and observation of geosynthetic performance in actual tunnelling projects are essential to validating the materials' effectiveness and identifying any

Table 4. Tensile properties of the woven geotextile W180 [110].

Degradation Test	Tensile Strength (T) (kN/m)	Maximum Load (EML) (%)
Undamaged	24.80	52.7
Mechanical Damage	8.84	17.2
Abrasion	21.36	34.2
Mechanical Damage + Abrasion	6.90	13.2

potential issues or degradation over time. Tunnel drainage systems are essential design elements in tunnels, as the buildup of groundwater behind linings can compromise tunnel safety. Geotextiles are employed to enhance the dissipation of pore-water pressure. Chemical compounds in the water can cause clogging when tunnels deteriorate over time [111]. Jo et al., [111] evaluated geosynthetic materials for tunnel drainage, focusing on discharge capacity and resistance to clogging by calcium carbonate (CaCO_3). Four geocomposites were evaluated based on the types of drainage core and geotextile filter, as detailed in Table 7. The study examined three geocomposite configurations: harmonica shape (GC-1 and GC-2), castle shape (GC-3), and retiform shape (GC-4). Two filter types were used: thermal heat-bonded type for GC-1, GC-2, and GC-3, and needle-punched type for GC-4. Tests were conducted under various confining pressures using a three-layered Non-Woven Needle-Punched (NWNP) geotextile. Fig. 21 shows a cylindrical chamber setup used for discharge testing, including a CaCO_3 generation device. Fig. 22(a–e) demonstrates the decline in discharge capacity over time under different pressures, highlighting the adverse effect of CaCO_3 on performance. Results show that while all geosynthetics experienced reduced discharge capacity due to pressure and clogging, GC-3 proved most effective in maintaining performance, whereas the NWNP geotextile was the most susceptible to degradation due to the absence of a core [111]. This comprehensive approach allows engineers to develop a thorough understanding of the long-term behavior and performance of geosynthetics in the unique and challenging tunnelling environment.

Laboratory testing and field monitoring play an important role in tunnel design and geosynthetic selection. Parameters such as tensile strength, creep resistance, abrasion resistance, hydraulic conductivity, and durability help evaluate material suitability under different loading and environmental conditions. Field observations related to tunnel drainage, lining deformation, and groundwater behaviour further support the validation of laboratory findings and improve design reliability. Therefore, integrating laboratory and field performance assessments is essential for developing durable and sustainable tunnel support systems.

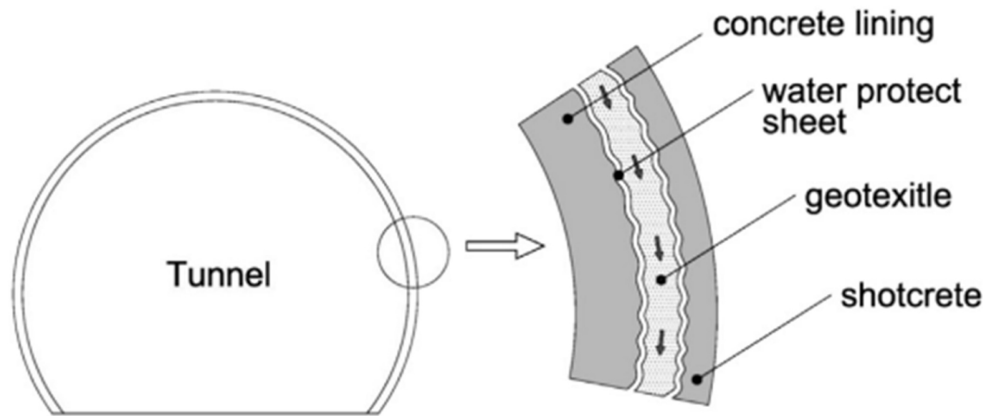


Fig. 12. Application of geotextiles in tunnel drainage and groundwater control system [104].

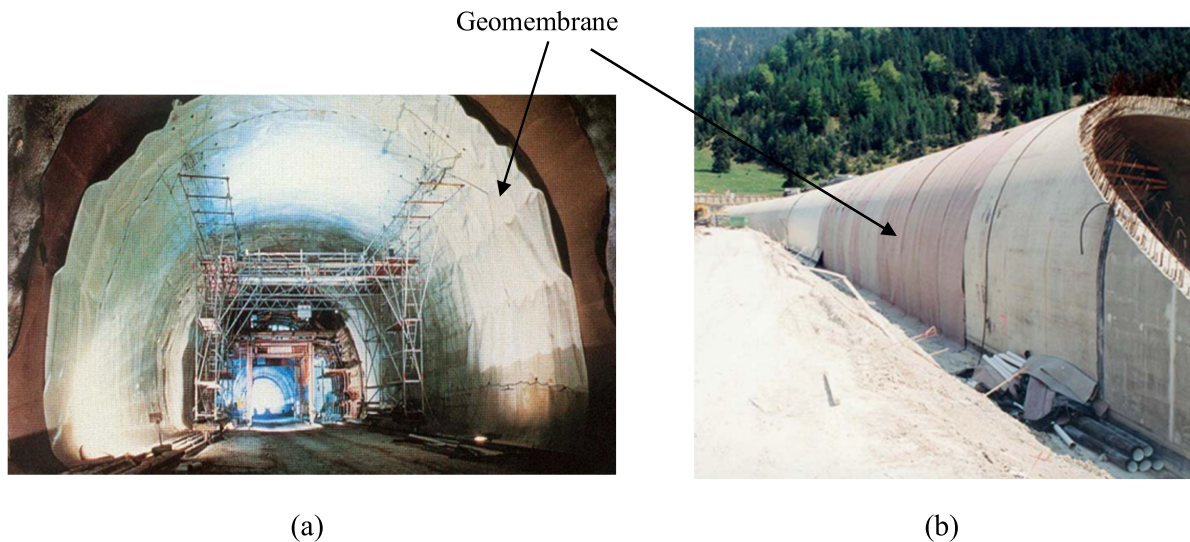


Fig. 13. Geomembrane sealing systems used in tunnel construction: (a) trenchless two-shell tunnel and (b) cut-and-cover vault tunnel [107].

Table 5. Tensile properties of the woven geogrids GG40I and GG40II [110].

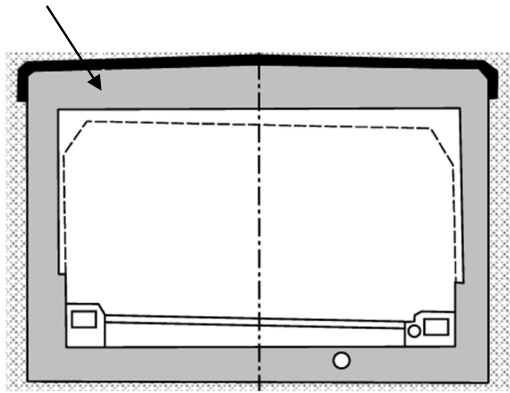
Degradation Test	GG40I		GG40II	
	Tensile Strength (T) (kN/m)	Maximum Load (E _{ML}) (%)	Tensile Strength (T) (kN/m)	Maximum Load (E _{ML}) (%)
Undamaged	44.36	12.1	39.83	17.6
Mechanical Damage	43.63	10.6	23.76	12.3
Abrasion	16.37	6.5	14.50	11.4
Mechanical Damage + Abrasion	14.75	6.3	7.52	10.4

Table 6. Tensile properties of the nonwoven geotextiles NW300 and NW500 [110].

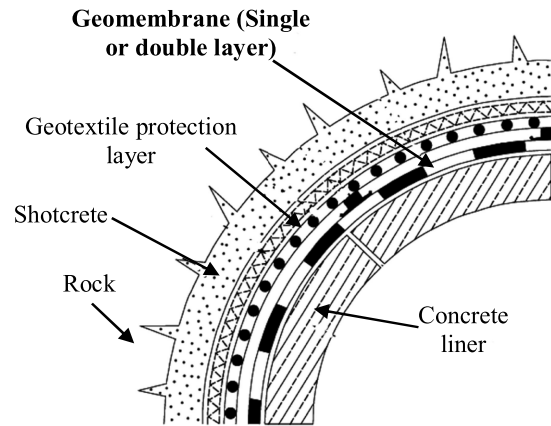
Degradation Test	NW300		NW500	
	Tensile Strength (T) (kN/m)	Maximum Load (E _{ML}) (%)	Tensile Strength (T) (kN/m)	Maximum Load (E _{ML}) (%)
Undamaged	23.44	138.4	33.61	135.9
Mechanical Damage	16.36	81.0	28.92	104.0
Abrasion	20.21	101.7	32.25	104.7
Mechanical Damage + Abrasion	11.86	58.9	28.40	95.6

Sealing System Consisting of:

- Protection/Drainage Layer
- **Geomembrane**
- Geotextile protection



(a)



(b)

Fig. 14. Structures of geomembrane sealing systems (a) Tunnel via cut and cover method (umbrella geomembrane lining) (b) Vault section of tunnels via mining construction method [107].

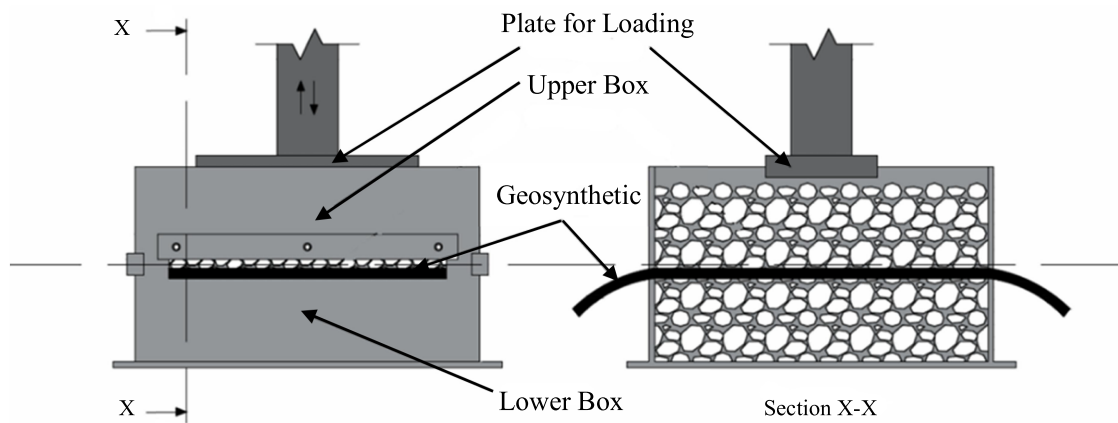


Fig. 15. Schematic illustration of the apparatus for mechanical damage assessment under repeated loading tests [110].

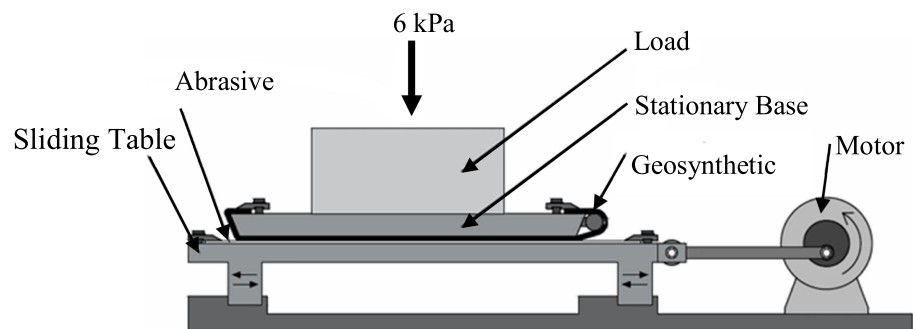


Fig. 16. Schematic configuration of the abrasion resistance test apparatus for geosynthetics [110].

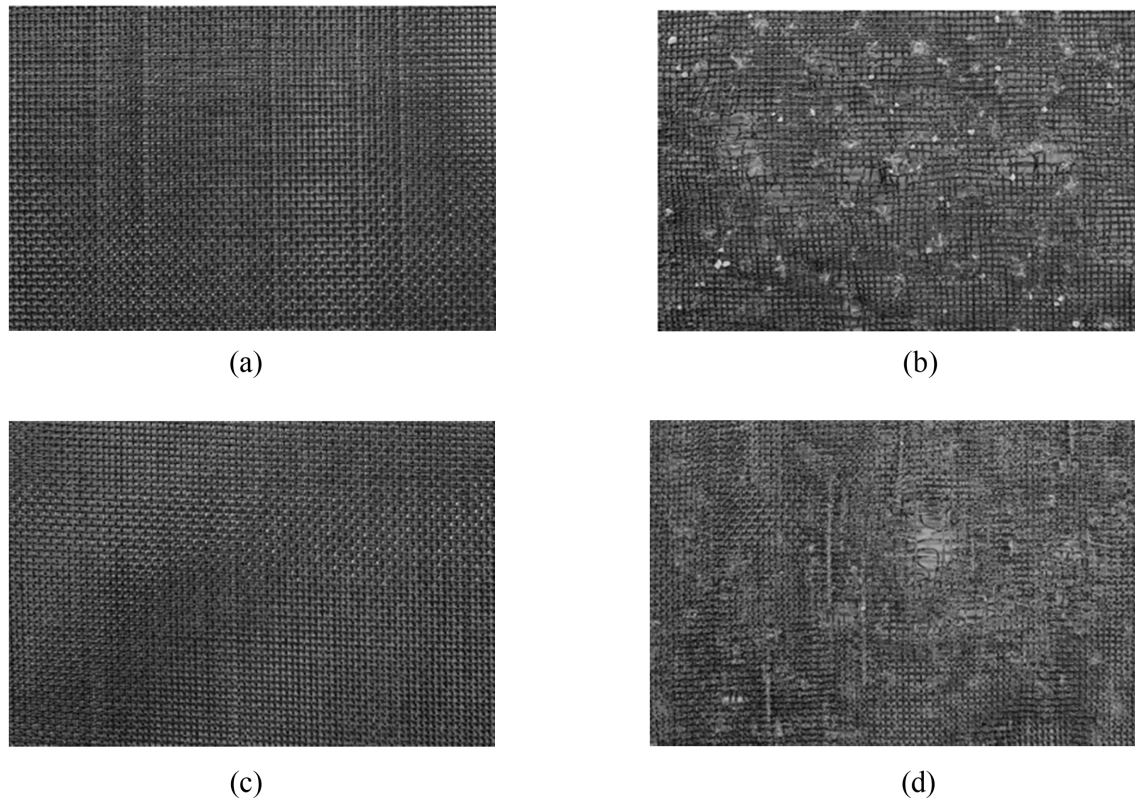


Fig. 17. Examination of Geotextile W180 using visual assessment (a) undamaged sample (b) after mechanical damage under repeated loading (c) after abrasion (d) after successive exposure to mechanical damage under repeated loading and abrasion [110].

Table 7. Specifications pertaining to geosynthetic materials utilized in laboratory evaluations [111].

Geosynthetic Materials	NWNP Geotextile	GC-1	GC-2	GC-3	GC-4
Figure of Cross Section					
Cross-Sectional Area, (A)	8.2 cm ²	4.0 cm ²	11.0 cm ²	3.0 cm ²	4.5 cm ²
Permeability	0.29 cm/s	16.56 cm/s	3.44 cm/s	24.00 cm/s	13.81 cm/s
Core Shape	-	Harmonica	Harmonica	Castle	Retiform
Core Thickness	8.2 mm	4.0 mm	11.0 mm	3.0 mm	4.5 mm
Filter Thickness	8.2 mm	0.2 mm	0.6 mm	0.35 mm	1.0 mm

5.3. Challenges and limitations

While the use of geosynthetics in tunnelling has demonstrated numerous benefits, there are also some challenges and limitations that must be addressed. One key challenge is the complex and variable nature of the geological conditions encountered in tunnelling projects, which can significantly impact the performance and effectiveness of the geosynthetic materials. Additionally, the harsh environmental conditions within the tunnel, such as the presence of chemicals, high temperatures, and abrasive forces, can lead to the degradation and deterioration of the geosynthetics over time [101, 112]. Yoo, [101] investigated how the hydraulic deterioration of

geosynthetic filter drainage systems in tunnels affects the structural performance of tunnel linings. This study examined several tunnel building scenarios including the construction of a 7 m diameter circular drained tunnel under diverse boundary circumstances. To encompass a broad spectrum of tunnel scenarios, the tunnel cover depth (H_c) and the hydraulic head above the tunnel crown (H_w) were adjusted to $H_c = 3D, 5D, \text{ and } 10D$ and $H_w = 1D, 2.5D, 3D, 4D, \text{ and } 5D$, where D represents the tunnel diameter. Three soil classifications were evaluated, encompassing degraded granitic soil (GT-I), low quality rocks (GT-II), and fair quality rocks (GT-III), according to the engineering classification of rocks. Fig. 23 presents a schematic representation of the

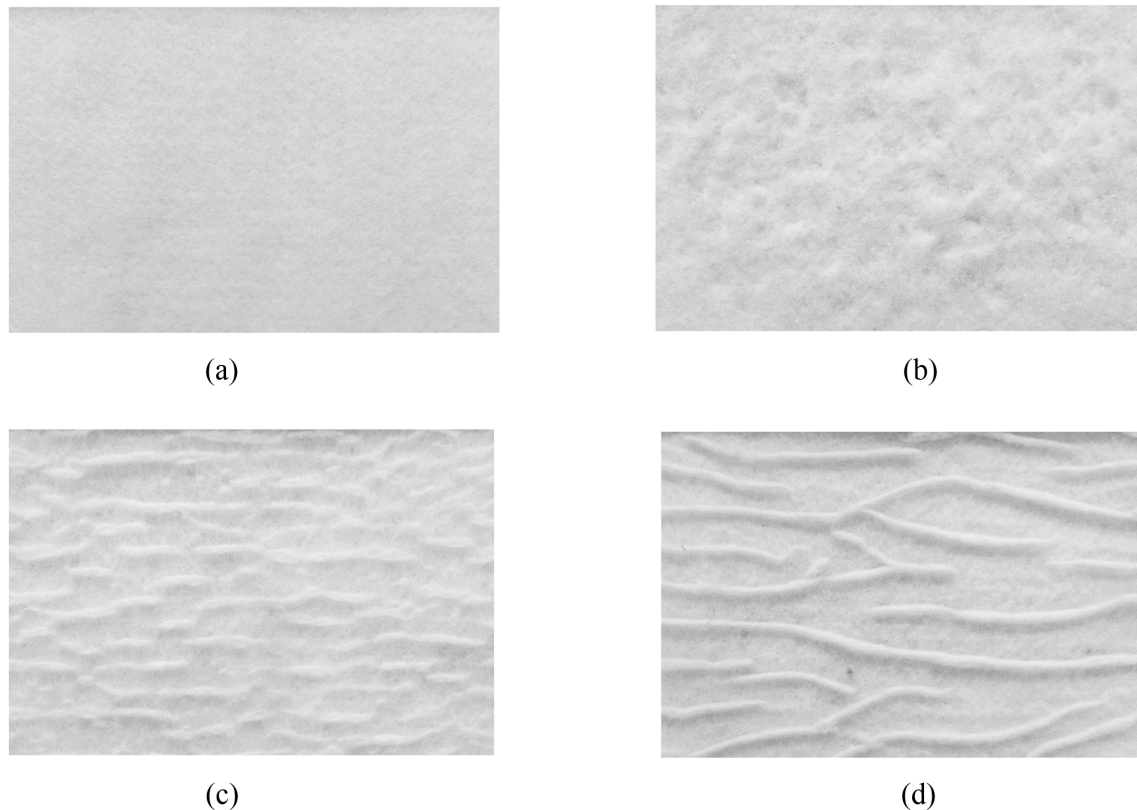


Fig. 18. Examination of Geotextile NW300 using visual assessment (a) undamaged sample (b) after mechanical damage under repeated loading (c) after abrasion (d) after successive exposure to mechanical damage under repeated loading and abrasion [110].

tunnelling circumstances examined in this study. The results show that reduced drainage leads to increased axial thrust and bending moments in the tunnel lining, especially at higher hydraulic heads. The graph in Fig. 24(a–c) shows how the additional lining forces, specifically axial thrust (ΔSF) and bending moment (ΔSM), change as the relative permeability (RP) between the ground and the drainage layer varies. The RP range from 1 to 1000 is studied, representing different levels of hydraulic deterioration. The graph indicates that as RP increases (indicating more severe hydraulic deterioration), both ΔSF and ΔSM increase, particularly beyond $RP = 100$. This suggests that reduced drainage capacity significantly impacts the structural stress on tunnel linings [101]. The deterioration-induced forces tend to decrease with increased cover depth and are more significant in weaker ground conditions. These findings highlight the importance of proper design and maintenance of drainage systems.

To overcome these challenges, ongoing research and development efforts are focused on improving the durability and performance of geosynthetic materials, as well as enhancing the design and installation methodologies to better accommodate the unique requirements of tunnelling applications.

Previous studies have demonstrated the effectiveness of geosynthetics in improving tunnel performance under various ground conditions. Faleih et al. [100] reported that geogrid reinforcement improved load distribution and reduced settlement in soft soil tunnels. Similarly, Ghoreishi Tayyebi et al. [57] observed reduced displacement and improved soil–structure interaction in geosynthetic-reinforced tunnel systems. In drainage applications, Jo et al. [111] found that drainage performance decreased under confining pressure and calcium carbonate clogging, while Yoo [101] showed that hydraulic deterioration can increase tunnel lining forces. Regarding sustainability, Raja et al. [69] discussed embodied carbon assessment, whereas Touze [70] highlighted the environmental benefits of geosynthetics in infrastructure systems. Overall, these studies confirm that geosynthetics can enhance reinforcement, drainage, durability, and sustainability in tunnelling applications.

6. Design considerations for geosynthetics in tunnelling

The effective incorporation of geosynthetics in tunnelling projects requires a comprehensive design

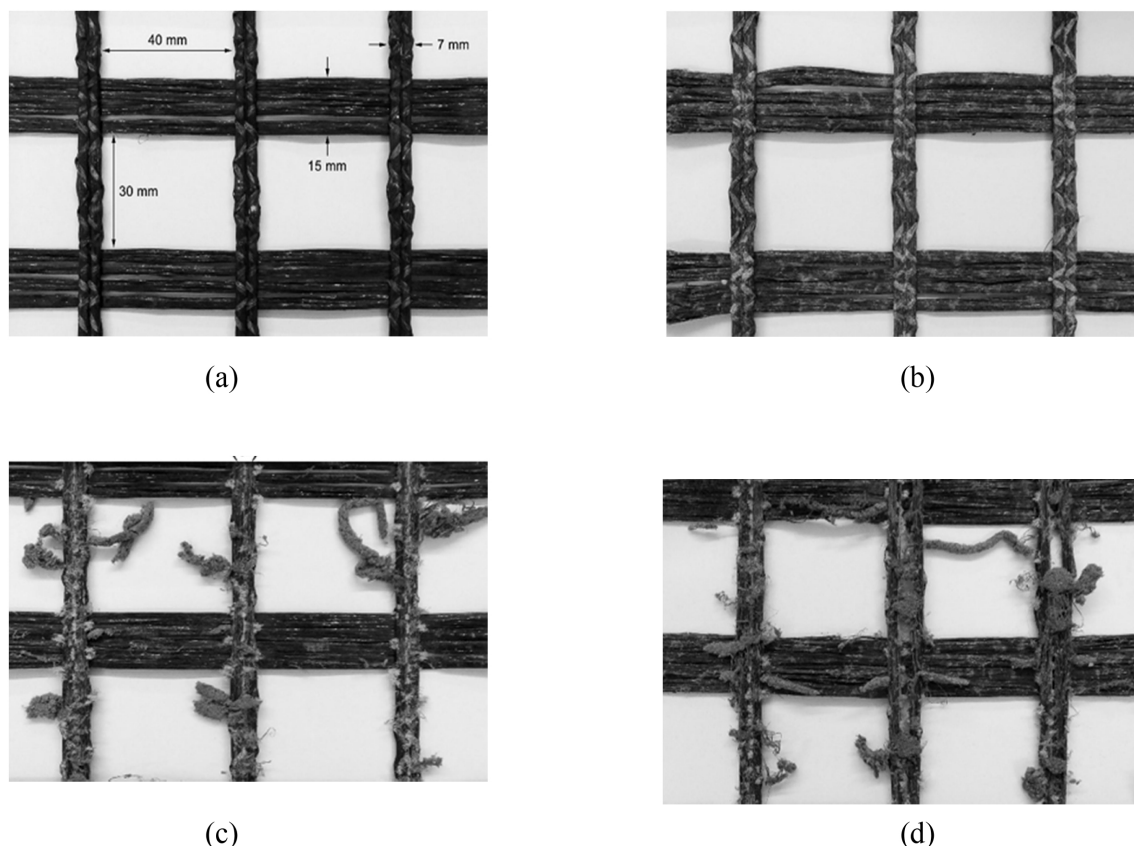


Fig. 19. Examination of Geogrid GG40I using visual assessment (a) undamaged sample (b) after mechanical damage under repeated loading (c) after abrasion (d) after successive exposure to mechanical damage under repeated loading and abrasion [110].

approach that takes into account a wide range of factors. These include the specific geological and environmental conditions of the site, such as the soil composition, groundwater levels, and potential chemical or biological threats. Additionally, the structural requirements of the tunnel, including load-bearing capacities and anticipated stresses, must be carefully considered. Furthermore, the long-term performance and durability of the geosynthetic materials themselves are crucial, as these specialized materials must be able to maintain their integrity and functionality over the lifespan of the tunnelling infrastructure.

6.1. Selection criteria based on site conditions

The selection of appropriate geosynthetic materials for a tunnelling project should be based on a thorough assessment of the site-specific conditions. This includes evaluating the soil characteristics, such as grain size distribution, permeability, and shear strength, as well as the presence of groundwater and any potential chemical or biological threats [113, 114]. Additionally, the anticipated loading conditions and the required performance criteria, such as tensile strength, puncture resistance, and

durability, must be carefully evaluated in order to select the most suitable geosynthetic materials [110]. Table 8 presents some standard tests conducted on geogrid and geotextile prior to selection for tunnelling projects or other applications.

6.2. Installation techniques and quality control

The proper installation of geosynthetics in tunnelling applications is crucial to ensure their long-term performance and effectiveness. Careful attention must be paid to factors such as site preparation, material handling and storage, and the installation process itself to minimize the risk of damage or degradation [79, 144]. Rigorous quality control measures, including on-site inspections and testing, are essential to verifying the integrity of the installed geosynthetic systems and ensuring their compliance with design specifications.

6.3. Suitability of geosynthetics under different tunnel conditions

The suitability of geosynthetics in tunnelling depends on geological conditions, groundwater

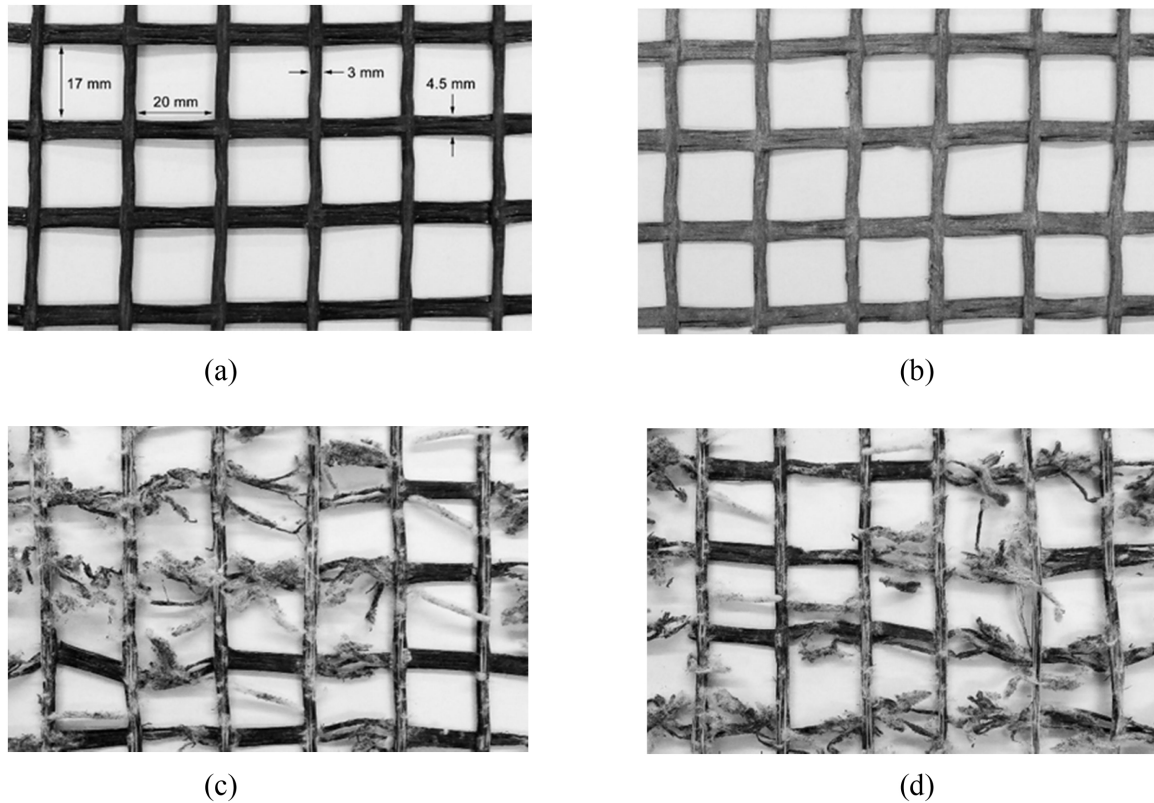


Fig. 20. Examination of Geogrid GG40II using visual assessment (a) undamaged sample (b) after mechanical damage under repeated loading (c) after abrasion (d) after successive exposure to mechanical damage under repeated loading and abrasion [110].

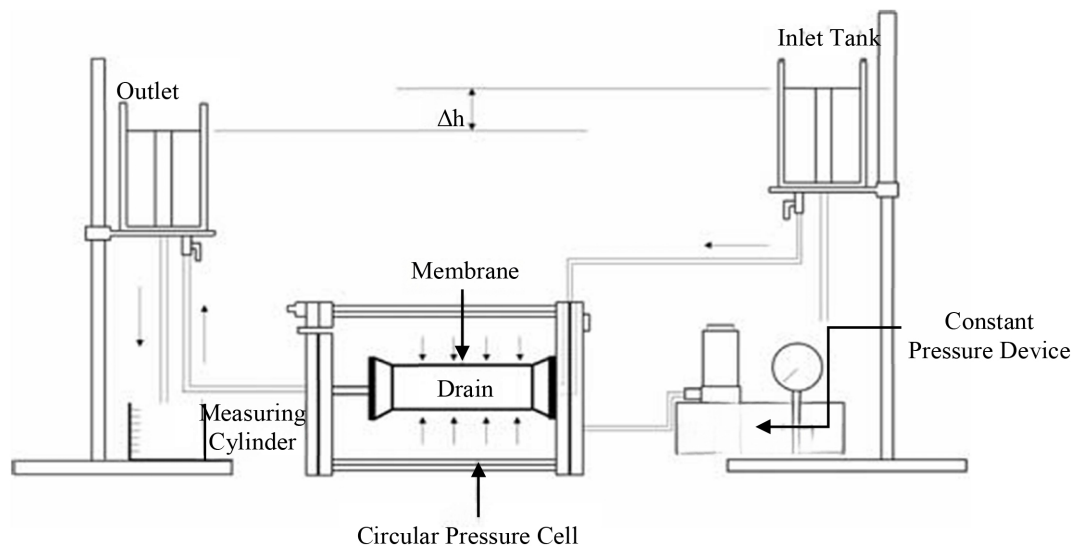


Fig. 21. Schematic layout of the discharge capacity testing apparatus used for evaluating tunnel drainage geosynthetics [111].

environment, loading characteristics, and tunnel construction methods. Different geosynthetic materials provide distinct functions depending on project-specific requirements.

In soft and weak ground conditions, geogrids and geocells are commonly used to improve soil confinement, enhance load distribution, and reduce

excessive settlement and deformation [88]. In tunnel waterproofing and drainage applications, geotextiles, geomembranes, and geocomposites are widely adopted to control groundwater ingress and protect tunnel linings [71, 72, 78, 107]. In cut-and-cover tunnels, geomembranes and drainage geocomposites are frequently incorporated due to

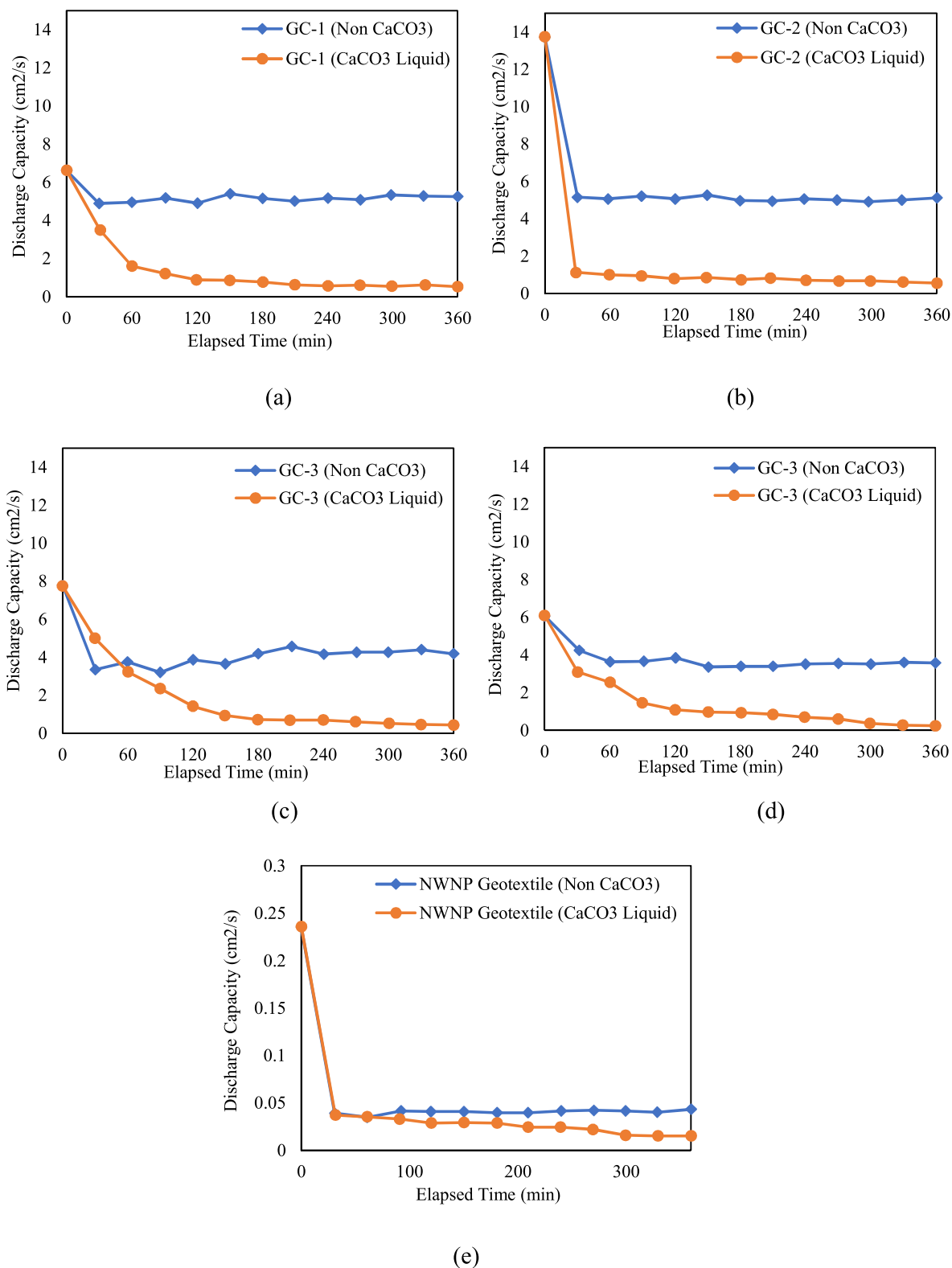


Fig. 22. Variations in discharge capacity over time relative to the presence of CaCO₃ in liquids at a confining pressure of 200 kPa (a) GC-1 (b) GC-2 (c) GC-3 (d) GC-4 (e) NWNP geotextile [111].

Table 8. Standardized tests employed to examine the characteristics of geogrid and geotextile materials.

Standard Test Number	Name of Standard Test	Property
ASTM D4355-21 [115]	Assessment of geotextile degradation under light, moisture, and heat using a xenon arc apparatus	UV resistance
ASTM D6637/D6637M-15 [116–126]	Tensile strength measurement of geogrids using single or multi-rib methods	Mechanical properties
GRI Test Method GG7 and GG8 [127]	Analysis of carboxyl end groups and molecular weight of PET yarns	Hydrolysis resistance
ASTM D5262-07(2016) [120, 122, 128–131]	Evaluation of geosynthetic creep behavior under unconfined tension conditions	Creep properties
ASTM D6992-16 [120, 122]	Accelerated tensile creep testing using stepped isothermal method	Creep properties
ASTM D4595-17 [122, 126, 130, 132–135]	Tensile strength testing of geotextiles via wide-width strip method	Mechanical properties
ASTM D1388-18 [116]	Determination of fabric stiffness	Mechanical properties
ASTM D5199-12 [116, 130]	Measurement of geosynthetic nominal thickness	Index properties
ASTM D5261-10 [116, 120, 122, 130]	Determination of geotextile mass per unit area	Index properties
ASTM D7556-10 [132]	Small-strain tensile properties assessment through cyclic tension tests	Mechanical properties
ASTM D7737-11	Strength evaluation of individual geogrid junctions	Mechanical properties
ASTM D7748-14	Measurement of flexural rigidity in geosynthetics	Flexural rigidity
ISO 10319:2015 [132, 136–140]	Wide-width tensile testing of geosynthetics	Mechanical properties
ISO 10722:2007 [138]	Mechanical damage evaluation of geosynthetics under repeated loading	Fatigue resistance
ISO 11058:2019 [138]	Determination of water permeability characteristics of geotextiles	Durability
ISO 12956:2010 [138]	Measurement of characteristic opening size of geotextiles	Index properties
ISO 13427:2014 [138]	Simulation of abrasion damage using sliding block test	Durability and installation damage
ISO 20432:2007 [138]	Long-term strength assessment of geosynthetics for soil reinforcement	Creep properties
ISO 10722-1:1998 [138]	Geotextile damage simulation during installation in granular materials	Durability and installation damage
ISO 13431:2024 [141]	Creep and creep-rupture behavior analysis of geotextiles	Creep properties
ISO 13438:2024 [141]	Screening test for thermo-oxidation resistance of geotextiles	Thermo-oxidation resistance
BS EN 20139 [142]	Standard atmospheric conditioning for textile testing	Durability
BS 6906 [143]	Tensile property determination for geosynthetics	Mechanical properties

Table 9. Comparative suitability of geosynthetics for different tunnelling conditions based on reported engineering applications and literature findings.

Tunnel Condition	Commonly Used Geosynthetics	Primary Function
Soft and weak ground tunnels	Geogrids, Geocells	Reinforcement and settlement control
Rock tunnels	Geotextiles, Geomembranes	Drainage and waterproofing
High groundwater pressure tunnels	Geomembranes, Geocomposites	Waterproofing and groundwater control
Cut-and-cover tunnels	Geomembranes, Geocomposites	Waterproofing and drainage
Erosion-prone tunnel slopes and portals	Geocells, Geotextiles	Erosion control and slope stabilization

their compatibility with reinforced concrete tunnel systems and their effectiveness in waterproofing applications [107]. Table 9 summarizes the commonly adopted geosynthetic systems for different tunnelling conditions based on reported literature and engineering applications.

Therefore, the selection of geosynthetics should be based on detailed geotechnical investigation, hydro-geological assessment, durability requirements, and expected loading conditions.

7. Environmental and sustainability aspects (carbon footprint reduction)

The incorporation of geosynthetics in tunnelling projects can also have significant implications for the environmental and sustainability performance of these infrastructure systems. Geosynthetics can play a crucial role in mitigating the environmental impacts of tunnelling, such as reducing the risk of ground-water contamination and minimizing the disruption

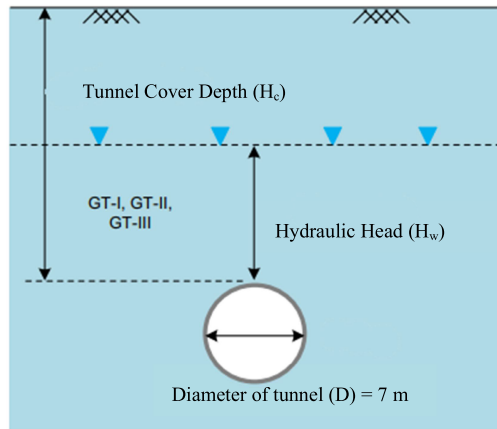


Fig. 23. Schematic cross-sectional representation of tunnel geometry and hydraulic boundary conditions considered in the analysis [101].

to sensitive ecosystems [48, 145]. Fig. 25 illustrates the utilization of geosynthetics as environmentally friendly construction materials. The major environmental and sustainability benefits of geosynthetics in tunnelling are discussed in the following subsections.

7.1. Waste reduction

The integration of geosynthetics in tunnel construction reduces material waste by encouraging the use of locally available soils, minimizing the need for imported aggregates, concrete, and steel. This leads to lower excavation and transportation efforts. Geosynthetics like geogrids and geotextiles enhance in-situ soil properties, reducing landfill waste and overall project costs, while supporting more efficient and sustainable resource utilization in tunnel engineering [146].

7.2. Soil stabilization and erosion control

Geosynthetics improve soil strength and erosion control in tunnel projects by reinforcing the ground with materials like geogrids, geocells, and geotextiles. They help manage water infiltration, reduce settlement risks, and stabilize slopes. By maintaining soil integrity, these materials support vegetation growth and ensure structural safety, especially in erosion-prone or environmentally sensitive areas, making them essential for sustainable and resilient tunnel construction [147].

7.3. Sustainable construction practices

Geosynthetics promote sustainable tunnel construction by reducing reliance on conventional

materials like reinforced concrete and steel. They allow for lightweight, flexible support systems, decreasing excavation and carbon emissions. Geosynthetics also enhance waterproofing and structural durability, reducing the need for chemical sealants. These environmentally friendly practices contribute to long-term sustainability and align with global goals for green construction and reduced environmental footprints [148].

7.4. Recycling and reusability

Geosynthetics offer high recyclability and reusability, often being made from recycled polymers like PE and PP. After use, they can be repurposed in other construction projects, minimizing waste and material demand. Their durability extends infrastructure life and reduces maintenance frequency. This efficient material use aligns tunnel engineering with circular economy principles, reducing environmental impacts and promoting sustainable development across multiple construction cycles [149].

7.5. Energy efficiency and carbon footprint reduction

By reducing material thickness and weight, geosynthetics help lower energy use in production, transportation, and construction processes. Their insulating properties improve tunnel energy efficiency by reducing the need for active ventilation and temperature control. Geosynthetics enhance structural performance while minimizing carbon emissions, supporting energy-efficient design in large-scale tunnels and contributing to climate change mitigation and sustainable infrastructure development [150, 151].

Several studies have quantitatively demonstrated the environmental benefits of geosynthetics in infrastructure applications. Deger and Guler [61] reported that the use of geosynthetic reinforced soil retaining structures enabled the reuse of marginal fill obtained from tunnel excavation, significantly reducing CO₂ emissions associated with hauling and quarry operations from 7,630,000 kg to 477,000 kg. The study also highlighted additional environmental benefits, including reduced quarry activities, lower air and noise pollution, and minimized disturbance to natural habitats. In addition, life-cycle assessment studies on tunnel infrastructure have emphasized the importance of sustainable material selection and energy-efficient design for reducing greenhouse gas emissions during tunnel construction and operation [65]. These findings demonstrate the potential contribution of sustainable construction practices and geosynthetic applications toward environmentally responsible tunnelling infrastructure.

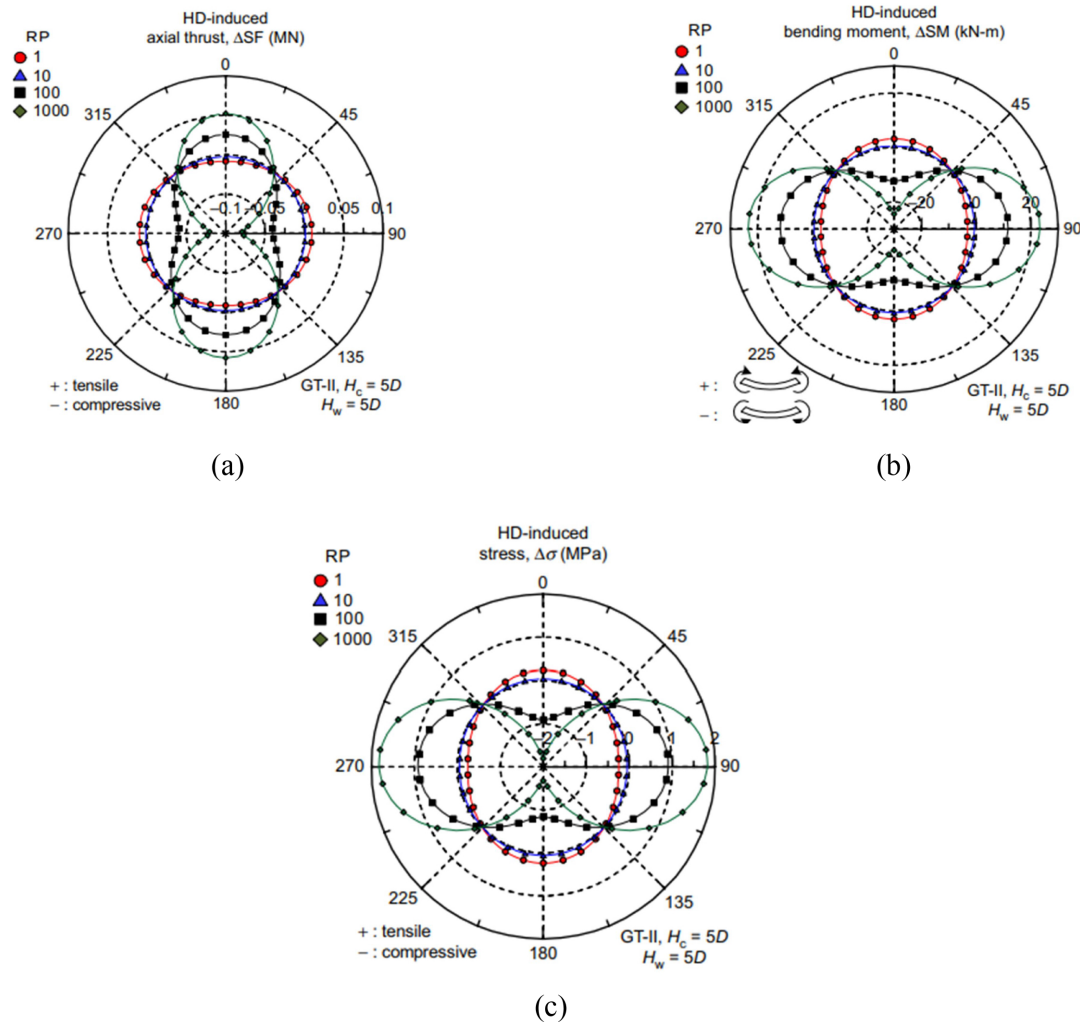


Fig. 24. Stress distributions and lining forces caused by hydraulic degradation for different relative permeabilities (GT-II, $H_c = 5D$, $H_w = 5D$) (a) ΔSF ; (b) ΔSM ; (c) $\Delta \sigma$. HD, hydraulic deterioration [101].

7.6. Environmental performance and certifications

Geosynthetics are assessed through certifications like ISO 14001 to ensure environmental safety and sustainability. They support resilient tunnel structures through applications in drainage, waterproofing, and reinforcement. Their resistance to harsh conditions makes them ideal for climate-resilient designs. Using certified geosynthetics minimizes environmental impact, promotes responsible resource use, and supports long-term performance of underground infrastructure in line with green engineering standards [152].

7.7. Environmental monitoring and remediation

Geosynthetics serve vital roles in environmental protection by acting as barriers to prevent

groundwater contamination and pollutant spread in tunnel construction. Materials like geomembranes and GCLs enable containment and monitoring of hazardous substances. They are also used in rehabilitating disturbed land post-construction. This supports sustainable land use, protects ecosystems, and aligns tunnel engineering with ecological restoration and environmental stewardship goals [152].

8. Advances and innovations in geosynthetics for tunneling

Driven by ongoing research and development efforts, the field of geosynthetics for tunneling is undergoing a rapid evolution aimed at addressing the unique challenges and requirements of this specialized application.

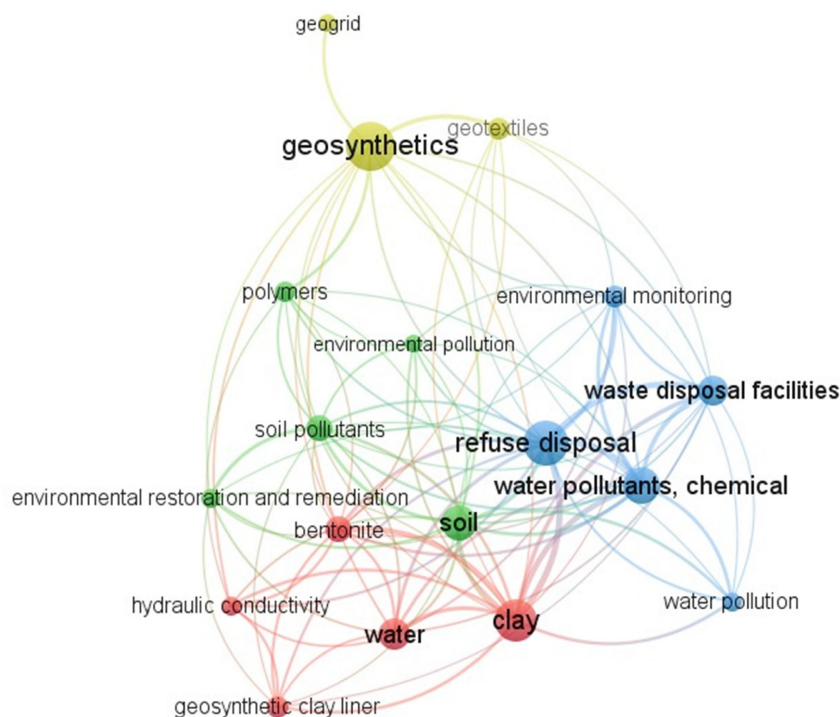


Fig. 25. Utilization of geosynthetics as environmentally friendly construction materials.

8.1. Emerging materials and technologies

One area of particular focus is the development of more durable and resilient geosynthetic materials that can withstand the harsh environmental conditions encountered in tunneling projects. This includes the exploration of new material formulations, as well as the enhancement of existing products through the incorporation of advanced reinforcement, coatings, and other protective measures.

In addition to the ongoing improvements in traditional geosynthetic materials, the field of tunneling is also seeing the emergence of novel materials and technologies that can further enhance the performance and sustainability of these infrastructure systems. For example, the use of recycled and bio-based materials in geosynthetic production is gaining traction, as the engineering community seeks to reduce the environmental footprint of these critical construction components.

8.2. Research and development initiatives

To support the ongoing evolution of geosynthetics for tunneling applications, the engineering community, including both academic institutions and industry practitioners, is actively engaged in a wide range of research and development initiatives. These efforts are focused on exploring the long-term durability and

performance of geosynthetic materials under the extreme conditions commonly encountered in tunneling projects, such as high temperatures, chemical exposure, and significant mechanical stresses [153–155].

8.3. Future trends and prospects

Given the growing importance of underground infrastructure, the role of geosynthetics in tunneling is poised to become increasingly essential. As the demand for tunneling projects continues to rise in response to factors such as population growth, urbanization, and the need for improved transportation and utilities networks, the engineering community will need to stay at the forefront of material innovation and installation techniques to ensure the reliable and sustainable performance of these critical underground systems. The application of geosynthetic materials, in conjunction with other supporting techniques, has become a widely adopted approach to address the significant challenges encountered in tunneling through soft and weak ground conditions.

9. Conclusion

This review synthesizes current knowledge on the use of geosynthetics in tunnelling—covering geotextiles, geogrids, geocomposites, geocells, and

geomembranes—and highlights their combined roles in reinforcement, drainage and filtration, and waterproofing/protection. Across these functions, geosynthetics demonstrably enhance structural stability and durability, support efficient construction, and contribute to sustainable, lower-carbon tunnel infrastructure.

Key conclusions are as follows:

- **Reinforcement and stability:** Properly selected and detailed geosynthetics improve load distribution, limit deformation and settlement, and enhance the integrity of tunnel linings and adjacent ground in weak or layered soils.
- **Drainage and filtration:** Engineered geotextile and geocomposite systems maintain controlled water flow while limiting soil particle migration, thereby reducing hydraulic stresses on linings and mitigating moisture-related deterioration.
- **Waterproofing and protection:** Geomembranes and related barriers provide effective resistance to water ingress, chemical attack, and abrasion, extending service life and reducing maintenance frequency.
- **Sustainability and carbon footprint:** By enabling the use of locally available soils, reducing the need for energy- and carbon-intensive materials, and prolonging service life, geosynthetics support measurable reductions in embodied impacts and operational interventions.
- **Constructability and cost:** Lightweight, flexible geosynthetics can accelerate installation and reduce maintenance interventions over the asset life, improving whole-life value when appropriately specified and quality-controlled.
- **Performance variability:** Material polymer type, product structure, installation damage, boundary conditions, and exposure environment lead to significant variability in performance; project-specific characterization and design verification are therefore essential.
- **Standards and quality control:** Adherence to established test methods and installation QA/QC procedures is critical to realizing the intended mechanical and hydraulic functions over the design life.

Implications for practice

Designers should align geosynthetic selection with site-specific geotechnical and hydrogeological conditions, adopt verified product data, and incorporate durability considerations (e.g., mechanical damage, creep, abrasion, clogging potential, and chemical/thermal exposures). Robust detailing of

drainage and waterproofing interfaces, coupled with construction-stage protection measures and inspection/testing, is essential to preserve function and extend service life.

Research gaps and future directions

Priority areas include (i) long-term durability under harsh underground conditions (high in-situ stress, freeze–thaw, saline or chemically aggressive water, temperature cycles, abrasion, and sustained hydraulic gradients); (ii) field-validated benchmarks that link laboratory indices to in-service performance; (iii) standardized life-cycle and cost–benefit frameworks that account for embodied carbon, reuse/recycling pathways, and maintenance intervals; (iv) evaluation of hybrid systems (e.g., combined reinforcement, drainage, and barrier solutions) and optimization of material architectures; and (v) consistent reporting and data standards to enable comparability across products and projects.

Overall, geosynthetics provide proven, adaptable solutions that align with modern tunnelling objectives of safety, performance, and sustainability. Continued progress will hinge on rigorous durability assessment, robust field evidence, and harmonized evaluation frameworks that translate material functions into reliable, low-carbon tunnel assets.

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Dataset

No dataset was generated or analyzed during the current study.

Data availability

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author contribution

IR and MRS proposed and conceptualized the study. The data collection was conducted by IR under the supervision of AHA. The production of the paper was carried out by author IR, while professional suggestions were made by MRS and SA. The manuscript's final version received approval following comprehensive editing and assessment by each author. The authors have reviewed and sanctioned the final manuscript.

Ibraheem Rais (IR), Abdullah H. Alsabhan (AHA), Md. Rehan Sadique (MRS), Shamshad Alam (SA).

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