

Review of the Use of Geomembranes in Water Resources Sector

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Abstract

Geomembranes are widely used in water resources engineering because of their very low hydraulic conductivity, adaptability to varied foundation conditions, and ability to reduce seepage losses from hydraulic structures. Over time, their application has expanded from canal and reservoir lining to dams, tunnels, pumped-storage systems, wastewater lagoons, irrigation ponds, and rehabilitation of aging hydraulic infrastructure. Their performance in service depends not only on material selection and construction quality, but also on laboratory characterization of hydraulic, mechanical, interface, and durability properties. This paper reviews the principal uses of geomembranes in water resources applications and synthesizes the laboratory tests commonly used to assess their suitability. Particular attention is given to permeability, tensile behavior, puncture resistance, seam performance, interface shear strength, creep, oxidative degradation, ultraviolet resistance, and long-term durability. The review shows that geomembranes can deliver major technical and economic benefits in seepage control and asset rehabilitation, but successful implementation requires careful matching of polymer type, surface texture, support conditions, and exposure environment to the demands of each hydraulic application. Laboratory testing remains central to design, quality assurance, and service-life prediction.

Keywords: Geomembranes, Water Resources applications, canal lining, hydraulic tunnels, embankment dams

Disclaimer: The views expressed in the paper are those of the authors and do not in any way represent the views of the organisation where they are presently working.

I. Introduction

Control of seepage is one of the central concerns of water resources engineering. Excessive seepage from canals, reservoirs, ponds, dams, and hydraulic conveyance structures causes water loss, slope instability, internal erosion risks, deterioration of adjacent soils, and reduced operational efficiency. In regions facing water scarcity, seepage reduction is also directly linked to resource conservation. Among available lining systems, geomembranes have become particularly important because they provide an engineered barrier with extremely low permeability compared with compacted soil liners and many concrete-based systems.

Geomembranes are polymeric sheets manufactured from materials such as high-density polyethylene (HDPE), linear low-density polyethylene (LLDPE), polyvinyl chloride (PVC), ethylene propylene diene monomer (EPDM), and bituminous formulations. Their selection depends on project geometry, expected stresses, exposure conditions, and the required balance among flexibility, strength, chemical resistance, and durability. Early hydraulic applications centered on canals and reservoirs, but more recent practice includes dams, hydraulic tunnels, surge shafts, pressure waterways, and pumped-storage hydropower reservoirs (Vorlet et al. 2024). This broader adoption reflects both advances in materials and increasing pressure to rehabilitate aging infrastructure rather than replace it.

At the same time, field performance has shown that the success of geomembrane systems cannot be judged only by nominal impermeability. Failures or underperformance may arise from puncture during placement, inadequate support, poor seam quality, low interface shear strength, weathering, oxidative aging, or creep under sustained load. For that reason, laboratory testing is fundamental in evaluating whether a geomembrane is suitable for a given water resources application and how it is likely to perform over its design life.

This paper presents a literature review of the uses of geomembranes in water resources applications and the laboratory tests most relevant to their design and assessment. The review is organized around application areas first and testing requirements second, so that the relationship between functional demand and material characterization remains clear.

II. Geomembranes in Water Resources Sector

Geomembranes act primarily as seepage barriers. In hydraulic works, they are usually installed either as exposed liners, buried liners, or components of composite systems combined with geotextiles, drainage layers, concrete, or protective soils. Their attractiveness lies in the very low rate of water transmission through intact sheets, rapid installation compared with thick mineral liners, and ability to conform to complex shapes.

The broader literature shows that geomembranes are especially valuable where conventional clay barriers are unavailable, where seepage losses are high, or where rehabilitation must proceed with limited interruption of service. Review work on hydraulic and hydropower applications notes that geomembrane systems improve watertightness, support structural rehabilitation, and can extend the service life of aging hydraulic assets (Vorlet et al. 2024). Similar conclusions appear in studies of reservoirs and pumped-storage systems, where liner systems are assessed as practical tools for reducing water loss and managing difficult geological settings (Hedien et al. 2023).

III. Uses of Geomembranes in Water Resources Sector

3.1 Canal lining

One of the oldest and most widespread uses of geomembranes in water resources engineering is the lining of irrigation and water conveyance canals. Unlined canals may lose substantial amounts of water through seepage, particularly in permeable alluvial soils. Geomembrane liners reduce these losses dramatically and can be installed either beneath concrete panels or as exposed systems with protective cover where hydraulic and operational conditions permit.

Canal lining applications benefit from the very low permeability of geomembranes and the relatively fast construction process compared with extensive concrete rehabilitation. However, the design challenge is not purely hydraulic. Canal linings must tolerate subgrade irregularities, repeated wetting and drying, flow-induced stresses, and in some cases maintenance traffic. Thus, puncture resistance, seam integrity, and interface behavior with subgrade or concrete are often as important as the intrinsic impermeability of the membrane.

3.2 Reservoirs, ponds, and water storage basins

Geomembranes are extensively used in irrigation reservoirs, municipal water storage ponds, wastewater lagoons, and evaporation-control basins. In these systems, the liner's main role is to minimize seepage into the foundation and prevent loss of stored water. Flexible geomembranes are particularly advantageous where the reservoir geometry is irregular or where differential settlement is expected.

For storage facilities, geomembranes may be exposed to sunlight, thermal cycling, fluctuating water levels, and local stresses caused by wind action or anchorage details. These service conditions make durability, weathering resistance, and anchorage design especially important. In mining-related water containment structures, geomembranes are also used to limit seepage of contaminated water, though those applications may impose chemical resistance requirements beyond ordinary water supply structures (Tuomela et al. 2021).

3.3 Embankment dams and rehabilitation of existing dams

Geomembranes are increasingly used in dam engineering, especially for rehabilitation of embankment dams with seepage problems or aging upstream facings. Rather than reconstructing the whole dam, engineers may place a geomembrane lining on the upstream face or within a rehabilitation system to restore watertightness. This can be especially useful where the embankment remains structurally adequate but seepage control has deteriorated.

In dam applications, stability and long-term reliability are crucial. The liner must withstand hydraulic loading, subgrade movement, temperature variation, and often decades of service. Interface shear strength becomes a critical parameter where the membrane is placed on slopes or against supporting geotextiles, drainage composites, or concrete facings. Laboratory and field experience have shown that these interface properties may govern design in steep or highly stressed configurations more than the tensile strength of the membrane sheet itself (Vorlet et al. 2024; U.S. Bureau of Reclamation 2014).

3.4 Hydraulic tunnels, surge shafts, and pressure waterways

More specialized water resources uses include hydraulic tunnels, surge shafts, and pressure conveyance systems in hydropower. In these applications, geomembranes may serve as waterproofing barriers or rehabilitation

systems for structures affected by cracking, leakage, or aging concrete. Their role is not merely to reduce seepage losses, but also to protect the surrounding rock mass or structure from water ingress and pressure-related deterioration.

The hydropower literature shows an expansion of geomembrane use in these settings, especially where rehabilitation is more feasible than full replacement (Vorlet et al. 2024). Design demands are more severe here than in shallow canals or ponds because of confinement conditions, pressure fluctuations, and in some cases restricted access for inspection and repair. Consequently, seam reliability, creep resistance, and durability under mechanical confinement become especially important.

3.5 Pumped-storage hydropower reservoirs

Pumped-storage hydropower has drawn renewed attention to geomembrane liners because upper reservoirs are often constructed in locations with poor natural watertightness. Reservoir liner systems can reduce seepage losses and improve project feasibility where geology would otherwise require expensive ground treatment. A recent scoping study concluded that geomembrane lining systems are a viable option for pumped-storage reservoirs, provided that site conditions, support layers, and long-term durability are adequately addressed (Hedien et al. 2023).

This application is significant because it combines traditional reservoir-lining functions with modern energy infrastructure needs. It also highlights a key point from the broader literature: geomembranes are no longer limited to conventional irrigation or municipal storage systems, but are increasingly integrated into strategic infrastructure for energy and water management.

3.6 Tailings and water-retaining containment structures relevant to water resources

Although tailings ponds are often discussed in mining rather than classical water resources engineering, they are highly relevant where water containment, seepage control, and groundwater protection are involved. Reviews of basal geomembrane liners in tailings ponds emphasize both the effectiveness of geomembranes in seepage reduction and the importance of integrated design to prevent damage, leakage, and interface instability (Tuomela et al. 2021). These findings matter for water resources engineers because many of the same mechanisms—puncture, differential settlement, interface sliding, and durability loss—apply to reservoirs and other hydraulic structures.

IV. Material Types Used in Water Resources Sector

HDPE remains one of the most commonly used geomembrane materials because of its chemical resistance, relatively high strength, and favorable long-term durability. However, its stiffness can be a limitation on highly irregular foundations or in applications requiring frequent folding or high flexibility. LLDPE offers greater flexibility, while PVC geomembranes are often selected where conformability is important. EPDM is valued in some exposed water-retention applications for flexibility and weather resistance. Bituminous geomembranes are also used in hydraulic works and are often noted for favorable interface behavior and accommodation of foundation irregularities in some project settings (Hadj-Hamou 2018).

Material choice is therefore application-specific. No single geomembrane type is optimal for all water resources structures. A canal with concrete cover, an exposed irrigation pond, a steep dam slope, and a pressure tunnel impose very different demands on the barrier system.

V. Laboratory Tests for Geomembranes in Water Resources Sector

Laboratory testing provides the bridge between material specification and field performance. For water resources applications, the most relevant tests can be grouped into hydraulic, mechanical, interface, seam, and durability categories.

5.1 Hydraulic impermeability and leakage-related tests

The primary functional requirement of a geomembrane in water resources engineering is very low permeability. Strictly speaking, intact geomembranes are essentially impermeable to liquid water for most engineering purposes, so the practical issue is often not bulk permeability through the polymer sheet but leakage through defects, seams, penetrations, or damaged zones. Even so, water transmission and related hydraulic behavior remain central to product qualification and comparative assessment.

In special situations, laboratory permeation testing is also used to study migration of contaminants or other fluids through geomembranes. McWatters et al. (2016) reported laboratory permeation tests for aromatic hydrocarbons through geomembranes, showing that transport behavior depends strongly on material type and temperature. Although this is not a standard clean-water application, it illustrates the broader principle that barrier performance must be assessed under realistic environmental conditions.

For reservoir and pond systems, leakage detection is also a practical concern. Poulain et al. (2011) discussed methods for locating leaks in water reservoirs lined with geomembranes, demonstrating that system performance must be considered at the scale of the installed barrier and not only at the material-sheet level.

5.2 Tensile properties

Tensile testing is among the most fundamental geomembrane laboratory evaluations. Tensile strength, elongation at yield, elongation at break, and modulus are used to characterize how the membrane responds to installation stresses, differential settlement, anchorage forces, and in-service strain. These properties are particularly relevant in reservoirs, canals, and dam facings, where the membrane may span minor voids, deform over subgrade irregularities, or accommodate localized movements.

Tensile testing also plays a major role in durability assessment. When geomembranes are subjected to weathering or aging, retained tensile properties provide an important measure of degradation. For example, ultraviolet exposure studies have evaluated changes in tensile behavior alongside oxidation and thermal indices to assess material deterioration over time (Lavoie et al. 2021). Exhumed-field studies similarly use tensile tests to estimate the remaining performance margin after years of service (Urashima et al. 2024).

5.3 Puncture and indentation resistance

In many water resources projects, puncture resistance is one of the most practically important properties because geomembranes are vulnerable to damage from angular subgrade particles, construction traffic, dropped tools, or overlying protective layers. A membrane with excellent intrinsic impermeability can fail in practice if it is punctured during installation or early service.

Experimental work has shown that puncture susceptibility remains significant across geomembrane types and thicknesses, although greater thickness usually improves resistance to some extent (AbdelRazek et al. 2012). For hydraulic applications built on coarse or irregular foundations, puncture-related testing helps define required cushioning geotextiles, bedding preparation standards, and acceptable construction methods.

5.4 Interface shear strength tests

Interface shear strength is critical in sloping installations such as canal side slopes, reservoir embankments, dam facings, and composite liner systems. A geomembrane usually does not act alone; it interacts with soil, geotextiles, concrete, drainage composites, or no-fines concrete. Sliding may occur at one of these interfaces if the available shear resistance is insufficient under self-weight, hydraulic loading, or seismic action.

Large direct shear testing is the standard laboratory approach for evaluating such behavior. Cen et al. (2018) conducted large-scale direct shear testing on several geomembrane interfaces, including contacts with fine sand, sandy gravel, geotextiles, and concrete, in accordance with ASTM D5321. Their work illustrates that interface strength depends strongly on the nature of the opposing material, membrane texture, and loading path. For water resources applications, such tests are often indispensable because the governing failure mode may be interface sliding rather than rupture of the membrane itself.

Recent work continues to confirm the importance of interface behavior, especially where textured geomembranes or unconventional support materials are involved (Attique et al. 2025). Although that study is more recent and not limited to classical water infrastructure, its conclusions align with long-established design practice in hydraulic systems.

5.5 Seam strength and peel tests

Field seams are often the weakest or most uncertain part of a geomembrane lining system. Since most hydraulic liners are fabricated from multiple panels, the finished barrier depends on consistent welding or seaming quality. Destructive seam testing, including peel and shear tests, is therefore central to both quality control and design assurance. Guidance documents for hydraulic geomembrane systems emphasize that destructive laboratory or field testing should include shear and peel evaluation to verify seam integrity (U.S. Bureau of Reclamation 2014).

For water resources structures that are difficult to dewater or access after commissioning, seam reliability is especially important because repairs may be disruptive and costly. This is one reason why laboratory qualification of seaming procedures and materials is typically performed before large-scale installation begins.

5.6 Creep and stress-relaxation behavior

Geomembranes subjected to sustained tensile load may exhibit creep, meaning time-dependent deformation under constant stress. Creep is relevant in anchored liners, steep slope installations, and any application where the membrane carries persistent stresses over long durations. Excessive creep can affect anchorage performance, strain distribution, and long-term serviceability.

Wang et al. (2024) investigated creep failure characteristics of HDPE geomembranes under different tensile stress levels, showing the importance of stress magnitude in long-term deformation and failure behavior. For water resources applications with long design lives, creep testing contributes to service-life evaluation and helps avoid designs that rely too heavily on short-term tensile strength.

5.7 Weathering, ultraviolet resistance, and oxidative stability

Exposed geomembranes in reservoirs, ponds, and some canal systems are vulnerable to solar radiation, oxygen, and thermal cycling. Accelerated weathering tests are therefore widely used to assess resistance to ultraviolet degradation and oxidation. Lavoie et al. (2021) studied ultraviolet effects on HDPE geomembranes using xenon-arc and ultraviolet-fluorescent weatherometers and assessed degradation through melt flow index, oxidative induction time, tensile testing, differential scanning calorimetry, and Fourier transform infrared spectroscopy. This combination of methods is valuable because no single test captures the whole degradation process.

Oxidative induction time testing is particularly common in polyethylene geomembranes because antioxidant depletion is a key stage in long-term aging. Once antioxidants are consumed, the polymer becomes more vulnerable to oxidative chain scission and embrittlement. For water resources engineers, these results matter most in exposed or partially exposed applications and in hot climates.

5.8 Long-term durability and exhumed-sample evaluation

Accelerated aging tests are useful, but exhumed-field studies provide particularly valuable evidence because they show how geomembranes perform under real service conditions. Urashima et al. (2024) examined HDPE geomembranes exposed for 7 and 11 years at a tailings dam and evaluated retained properties and probability of nominal failure. Although the project context was mining-related, the findings are relevant to hydraulic applications because they demonstrate how long-term exposure history affects retained mechanical performance.

Similarly, Luciani et al. (2020) studied long-term durability of PVC-P geomembranes using accelerated aging and mechanical tests, emphasizing that different polymers degrade through different mechanisms. This has direct implications for material selection in water resources projects, especially where membranes are expected to remain exposed or partly exposed for long periods.

VI. Relationship Between Application Demands and Test Requirements

A useful conclusion from the literature is that laboratory testing must be tailored to the application rather than treated as a generic checklist. For example, a buried basal liner beneath a water storage basin may prioritize puncture resistance, seam quality, and subgrade compatibility. An exposed irrigation reservoir liner may place greater emphasis on ultraviolet resistance and oxidative stability. A steep dam-facing rehabilitation system may be governed primarily by interface shear strength and long-term anchorage behavior. A pumped-storage reservoir may require a balanced assessment of hydraulic barrier performance, durability, construction damage resistance, and slope stability.

This application-based view is essential because the same geomembrane product may perform well in one setting and poorly in another. The literature repeatedly shows that failures are often not caused by the concept of geomembrane lining itself, but by a mismatch between material/system design and project-specific demands (Vorlet et al. 2024; Tuomela et al. 2021).

VII. Advantages and Limitations

The literature identifies several major advantages of geomembranes in water resources engineering. They provide highly effective seepage control, reduce water loss, support rehabilitation of aging infrastructure, can be installed comparatively quickly, and may lower costs relative to massive structural reconstruction. In areas where water conservation is critical, these benefits are especially important.

At the same time, geomembranes are not maintenance-free or failure-proof. Their successful use depends on subgrade preparation, protection against puncture, reliable seaming, interface stability, and consideration of long-term degradation. Thin liners may be vulnerable to construction damage, while stiff polymers may be difficult to place on irregular foundations. Exposed liners require attention to weathering and anchorage, and steep-slope systems demand careful interface shear evaluation. Thus, performance depends on the lining system as a whole rather than the geomembrane sheet alone.

VIII. Research Needs

Although the literature is substantial, several gaps remain. More long-term field studies are needed for water-specific applications such as irrigation reservoirs, canals in hot climates, and pumped-storage systems. There is also a need for improved service-life models that connect accelerated aging results with field exposure conditions more reliably. Interface behavior under cyclic hydraulic loading and thermal variation remains an area where additional research would be valuable, especially for steep and exposed systems. Better integration of leak-detection methods, condition monitoring, and rehabilitation planning would also strengthen lifecycle management of geomembrane-lined hydraulic assets.

IX. Conclusions

Geomembranes have become an important technology in water resources engineering because they provide an effective and versatile barrier against seepage in canals, reservoirs, ponds, dams, tunnels, and pumped-storage systems. Their role has expanded significantly from traditional lining applications to the rehabilitation and modernization of critical hydraulic infrastructure. Recent review studies confirm that geomembrane systems contribute to improved watertightness, resilience, and service-life extension in hydropower and related hydraulic works (Vorlet et al. 2024; Hedien et al. 2023).

The literature also makes clear that successful use of geomembranes depends on more than low permeability alone. Laboratory tests for tensile behavior, puncture resistance, seam strength, interface shear strength, creep, oxidative stability, and weathering resistance are all essential for determining whether a geomembrane system is suitable for a given application. Different hydraulic structures impose different demands, so laboratory characterization must be linked directly to field function.

Overall, geomembranes offer major advantages for seepage control and water conservation, but their long-term performance depends on integrated design, appropriate material selection, rigorous testing, and quality installation. Future progress in the field will likely come from better durability prediction, broader field monitoring, and closer alignment between laboratory testing programs and the actual stress environments encountered in water resources applications.

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