E3S Web of Conferences **569**, 08001 (2024) https://doi.org/10.1051/e3sconf/202456908001
GeoAmericas 2024

Protection with reinforced EIA geomembranes

Craig Hoffman*[1], *Warren* Gerhardt[1], and *Jason* Spruell[1]

[1]Seaman Corporation, Technology Department, 1000 Venture Blvd, Wooster, OH, USA

Abstract. Ethylene Interpolymer Alloy (EIA) Geomembranes are a long lasting geosynthetic solution that was developed in response to the Clean Water Act of 1972. This paper discusses the history of EIAs membranes, defines the broad class of materials that are considered EIAs, and delves into the polymer film, reinforcement, other layers, and their respective contributions to the Geomembrane's final properties and performance. With properties and performance in mind, the paper discusses benefits these solutions offer over other geo solutions.

1 Introduction

Polymers have been part of ground water and potable water protection since the mid-20th century, gaining increasing traction as a cost-effective and efficient option as part of the Clean Water Act of 1972.[1] The primary solutions were polymeric films and textile supported/reinforced membranes, which are broadly known as geosynthetics, and they have a dominant role in the larger geoengineering market. Important prerequisites for the polymer coatings are adequate flexibility and strength for the application, chemical resistance to the specifics of the locality, and sufficient exterior/environmental robustness. Despite the range of design possibilities, the final system is often simply defined by the composition of the outer polymer coatings, and the common classes are: high density polyethylene (HDPE), polypropylene (PP), flexible polyvinyl chloride (fPVC), ethylene interpolymer alloy (EIA), and several others.

From this list, EIAs stand out as an alloy of unplasticized polyvinyl chloride (uPVC) and ketone ethylene esters (KEE), which are two distinct polymers. A polymeric alloy is defined as a fully compatible union of dissimilar polymers to give a system with its own unique properties. uPVC is a rigid polymer with an outsized role in the building and construction industry. When well formulated, it has excellent robustness and durability to many environmental insults, but it has little value for geosynthetics where flexibility and toughness are required. When flexibility is needed, low molecular weight liquid plasticizers are compounded into the rigid uPVC matrix to form fPVC. In the early days of geosynthetic, fPVC was one of the few polymeric options available.[2] However, introduction of these plasticizing agents detracts from many of rigid uPVC's positive traits, and these molecules will ultimately exude, evaporate, and extract out. These losses will return the fPVC to uPVC's rigid state. The rate of this inevitable reversion is dependent on the environmental conditions the fPVC experiences. This rigidification leads to embrittlement and stress

---

* Corresponding author: choffman@seamancorp.com

cracking of the once flexible and tough film or membrane and concomitantly pollutes the area in the vicinity. EIAs, resoundingly and permanently, solve this plasticizer dilemma by alloying KEE with uPVC. The KEE portion of this tough alloy is a pliable, high molecular weight polymer, whose polarity and amorphous nature make it particularly compatible with uPVC. The new material possesses the flexibility and toughness of an elastomer, while retaining many of the desirable properties of the rigid uPVC. These immutable features have helped EIAs earn a reputation of long-lasting performance for almost 50 years to the geoengineering market.

Textile reinforcement is an equally important attribute that often gets overlooked. The nature and type of reinforcement will be discussed as well as its importance to the final geomembrane application. This paper will focus on the marriage of design and configuration of EIA films with textile reinforcements to create membranes wherein the emergent properties useful for geoengineered solutions are a result of the composition of the polymeric coating and reinforcement.

2 Membrane Constructions

Reinforced EIA geomembranes were first industrialized in 1975.[1] The first known test site was a liner for solar and wastewater ponds in the late 1970s, and the first commercialized installation was a wastewater lagoon in Mammoth Cave National Park in 1984.[3,4] Details of this test site are limited but the installation at Mammoth Cave National Park is still in service today.[4]

A membrane is designed and constructed to meet the specific properties that the application requires. The simplest geomembrane construction is a monolithic sheet, which is a thick, unsupported film. While this is simple, it does have limitations.

Multiple processes can be employed to produce these unsupported membranes: die extrusion, blown extrusion, or calendering. They are produced in a range of widths that can reach up to seven meters, and the extrusion process can permit multiple layers of films that augment the properties through the cross-section of the full membrane. Economies of scale during manufacturing give wider width, unsupported materials a cost advantage versus multilayer designs. These wider panels will need less welded seams to cover an area, which means reduced fabrication and installation times. Despite these cost advantages, an unreinforced membrane's physical properties are dictated by the polymeric system alone. Their properties are often inferior to reinforced membranes at a similar thickness and this limits their use to specific applications; moreover, the physical properties cannot be tailored in the same way as a reinforced geomembrane.

To avoid the need for thicker single polymer membranes, reinforcement can be added. These reinforcements are often a woven and knitted textile. A reinforcement can be used with any geosynthetic solution but are more prevalent in fPP and EIAs as opposed to HDPE. The polymers used in textile reinforcement are analogous to those used in synthetic fabrics in other markets. Polyethylene terephthalate (PET) and polyamide (PA) are the main polymers used in EIA reinforcement, and PET is the most common reinforcement polymer. It is cost-efficient, reasonably resistant to acid and oxidants, has low water absorption, and good dimensional stability. Polyamides are several times more expensive than PET, but compared to PET, it offers better alkaline resistance, higher elongation, and higher adhesion. The construction of the reinforcement and how the full assembly is adhered together are also critical to the final membrane's physical properties.

3 Compositions and Construction

The textiles used in supported membranes are often wovens or warp-knits. Wovens and warp knits are generally defined by the yarn denier, the pick and end count, and the design pattern. Denier is a yarn value defined as the mass density of a 9000-meter-long length in grams; a thicker yarn will have a higher yarn denier. The pick and end counts are the number of perpendicular yarns in a square inch of the fabric. The end count is the number of yarns in the machine direction, or warp, and the pick count is the number of cross-machine direction yarns, or weft. The physical properties of the textile reinforcement increase proportionally with all these values, but the main properties of interest on a specification sheet are tensile strength and puncture resistance. The decision to use a woven or warp-knitted textile ultimately depends on the movements and stresses that the reinforced membrane is expected to experience after installation.

3.1 Woven Textile Reinforcement

A woven textile has perpendicular yarns interlaced into a pattern. There are a wide range of patterns and permutations. A plain weave, basket weave, and ripstop are popular in geosynthetics, and each have its pros and cons (Figure 1).

A plain weave is when each warp and fill yarn alternate over and under (Figure 1a). This gives a tight and durable construction with a high level of yarn intersection points. A basket weave is a plain weave variation (Figure 1b). It has the same alternating over and under pattern, but with the pick and end yarns doubled, which gives the basket weave a checkerboard pattern. Compared to a plain weave using the same yarns, a basket weave is a tougher construction with better tear strength. A rip-stop is a plain weave that uses a different yarn(s) in prescribed increments in each direction (Figure 1c). This gives a distinctive “box” pattern in the fabric. These different yarns are stronger. They are either a higher denier or spun with different and stronger filaments. This gives the textile higher tear strength along each box’s perimeter that can contain a tear or rip.

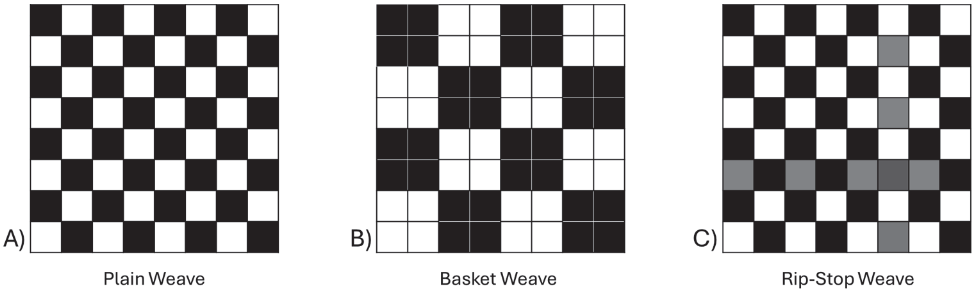

Figure 1. Three representative weaves depicting warp yarns in black and fill yarns in white. Images A) and B) have a warp and fill yarn. The rip-stop weave is represented in C) has a standard warp and fill yarn but also a strong warp yarn and strong fill yarn, shown in shades of gray in weave pattern C).

Yarns in all woven textiles are interlaced in and out of the fabric's X-Y plane. This interlacing in the y-plane causes the woven yarn to be shorter in length than the unwoven yarn in the x-plane. The difference in this length is commonly referred to as crimp (Figure 2). When tensioned or stressed the yarn crimp permits woven fabrics to have greater flex and stretch versus the other dominant method, warp-knitting. Different weaves have different levels of crimp with a plain weave having the most. These features are beneficial in applications with movement and varying stresses, such as a membrane floating on water or in a windy environment.

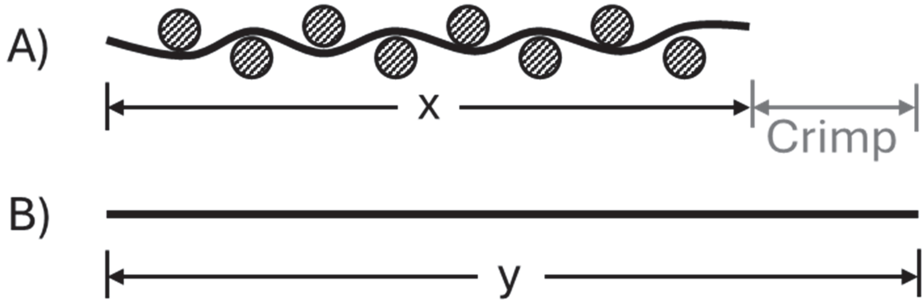

Figure 2. Depiction of yarn length in a A) woven and B) warp-knit depicting and resulting crimp.

3.2 Warp-Knit Textile Reinforcement

Like a woven, a warp-knit has perpendicular warp and fill yarns, but they are not interlaced. The warp yarns are conveyed under tension and flat through the knitting machine with the fill yarns laid over them (Figure 3). Next, a row of needles knits a narrow stitch yarn around each touch point (Figure 3). As a result, warp-knits have a flat construction with no crimp and almost no stretch or flex. Additionally, the relatively unstable textile needs to be handled gently, limiting its value outside of stabilizing composite structures. Despite these limitations, the stitch points in a warp knit allows for more open fabrics and prevents unravelling. A warp-knit of similar yarn and yarn density will usually have higher tear strength when embedded in a membrane when compared to that of a weave. Yarns in a warp-knit can more easily bunch, bundle, and cooperate when torn versus the yarns of a woven fabric.

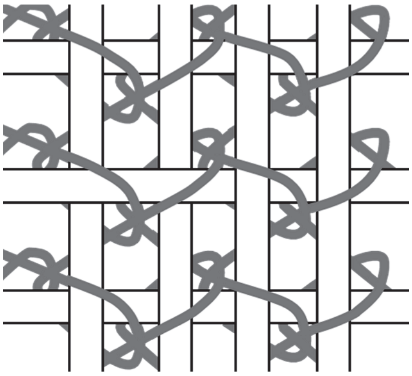

Figure 3. Representation of a warp-knit structure.

3.3 Adhesion Methods

To form a robust composite system, the reinforcing textile and polymer coatings must bond together. Adhering the textile support to the polymer coat is this next step in the geomembrane manufacturing process. The nature of the textile will dictate the consolidation method. The two primary methods are lamination, which is a direct process, and adhesive coating, which requires multiple operations. If it is a light duty textile support with an open construction, then the top and bottom polymer face coatings can be readily laminated together through the openings in the textile with heat and pressure. The opposite polymeric outer layers meet and fuse at these open contact points and is also called "strike through" adhesion Lamination is the most direct way to get to a consolidated structure, but a laminated membrane often has minimal interfacial adhesion of the outer polymer coatings to the reinforcing textile.[5] As a result, the yarns in the textile can move under load and internally separate from the polymer coatings. This is called yarn bundling, and it can beneficially give higher than expected tear strength values be beneficial during a tear event but can concomitantly create undesired wicking channels, or tunnelling, along the yarn bundles. Lamination is an intermediate solution between an unsupported membrane, or film, and a full coated and adhered dense textile reinforcement, or single-ply membrane. The overall properties of a laminate are higher than an unsupported film of similar thickness but usually less than a fully coated fabric.

Most woven textiles and higher density warp-knits do not have adequate areal openness for sufficient strike-through adhesion. Therefore, the textile must first be coated with an adhesive layer, or tie-coat, that can bond to each polymeric face in a second operation. The adhesive is generally coated to each textile face, or it is dipped through an adhesive bath. Either adhesive application provides a primed textile surface.

The adhesive interacts with the textile yarns and filaments through a multitude of weak physical bonding, commonly hydrogen bonding, lesser but stronger permanent chemical bonding, and often a combination of both bonding approaches. While each type contributes to the system's adhesion, chemical bonding increases adhesion to a much greater extent and allows load properties to be transferred across welded seams. Unlike laminated membranes, the adhesive coating limits and constrains the movement of the yarns and filaments in the textile reinforcement. This locked conformation prevents tunnelling at the yarn interfaces and yarn bundling during a tear event. The membrane often has higher tensile values at the expense of tear and flexibility of a comparable laminate. Careful consideration of the installation features, expected service life, and environmental exposures should all be factored into the final design. Illustrations of a supported membrane with either a warp-knit or a woven textile, respectively, are shown in Figure 4.

Figure 4: An image of a warp-knit reinforced membrane is shown on the left. It has a narrow stitch yarn that binds the perpendicularly oriented and heavier warp and fill yarns. The warp-knit is encapsulated with an adhesive layer that bonds the polymer facecoats to the textile reinforcement. This is shown as the translucent middle layer in the left illustration. A membrane with an open weave reinforcement is shown on the right.

4 Properties of Reinforced EIA Geomembranes

The properties of reinforced EIA geomembranes can be separately described as (1) survivability properties which result largely from the textile reinforcement and (2) chemical and environmental resistance which emerge from the nature of the polymer coating and its formulation.[6,7] Design choices must be made based on the expected environmental and chemical challenge scenarios expected during the life of the geomembrane.

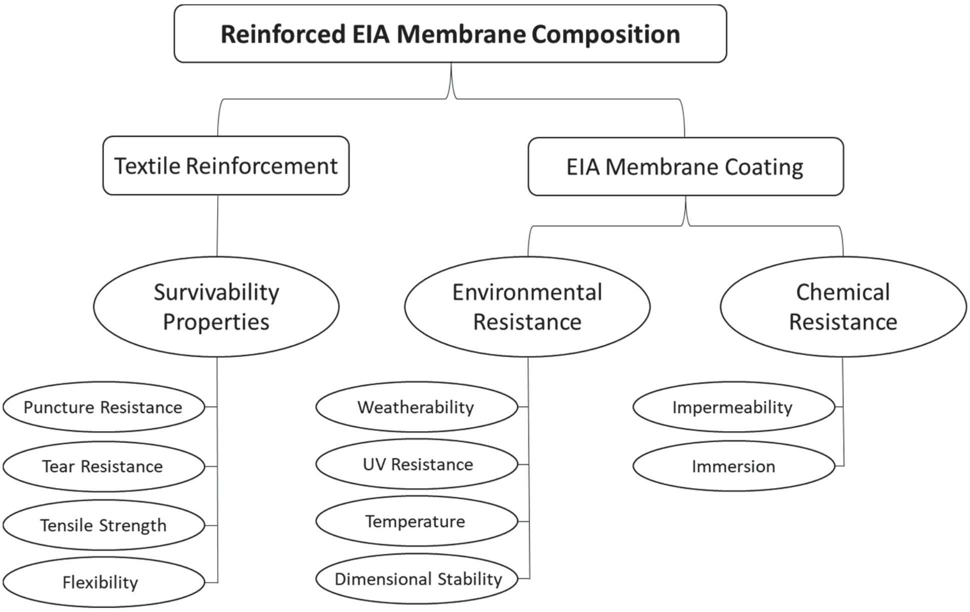

Figure 5: Summary of the composition of reinforced EIA geomembranes and the properties influenced by them. Parts of the EIA are enclosed in a square with the properties they influence in ovals under them.

4.1 Survivability Properties

A geomembrane failure is defined as a fissure in the membrane that allows fluid transmission laterally through the textile reinforcement or transversely to the other side. Survivability emerges from the suitability of the reinforced geomembrane to cope and respond to the environmental conditions it will experience throughout its lifetime. These physical properties of the geomembrane - puncture, tear, tensile strength, and flexibility – largely determine its physical robustness.[7] Manufactures make recommendations to minimize and prevent premature failures. One of these common recommendations is the use of a geotextile under the geomembrane over sharp subgrades to prevent punctures. This recommendation can add cost to the overall system. An alternative approach that a reinforced EIA geomembrane facilitates is the use of a highly puncture resistant single-ply reinforcing layer, which solves the original problem while eliminating the need for an additional layer.

The benefits of textile reinforcements can be seen in Figure 6. Textile base weight and the geomembrane physical properties are correlated. Testing was done on the same warp-knit construction but with the yard denier and density increasing, i.e. the textile's strength properties increased.[8] Unreinforced materials exhibit the lowest physical properties, while reinforcement increases the tensile strength, tear strength, and puncture resistance.

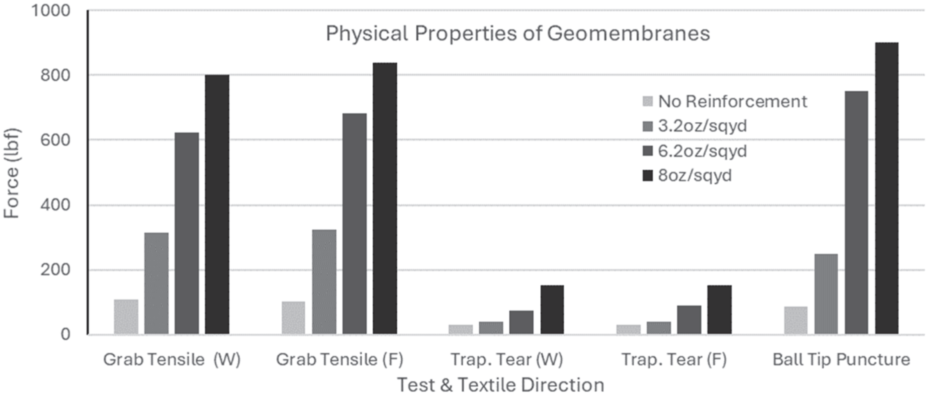

Figure 6: The graph is results of ASTM D751 Grab Tensile, Trapezoidal Tear, and Ball Burst for samples with increasing reinforcement weight. The letters W and F represent warp, machine direction, and fill, cross machine direction. The use of heavier textiles increases survivability properties increase.

The outer polymer coating can erode, abrade, or crack over time. These failure modes would manifest as flex fatigue events and lead to exposure of the textile to the environment. The properties provided by the textile reinforcement are resistance to punctures, tensile strains, and tears. The polymer coating protects the textile from the elements and the textile girds the polymer coating from physical assaults of the elements.

All materials will eventually fail. The cooperation of a properly designed EIA will extend the useful serviceable life of the geomembrane. As forces act on the membrane over this service life a small fissure can become a hole that may become a tear, which can then propagate and become a catastrophic failure. A real-world example of this failure is the constant wind bellowing a secondary containment liner. As the liner flexes and flutters in response to the external stresses, filaments in the yarn can break creating a weak zone. This localized weak zone has essentially become an unsupported membrane. The loss of filaments, and then yarns, the tensile strength of the area is weakened at which the system yields. This scenario is representative of flexibility, puncture, and even tensile strength failing. Other precautions can be taken during installation such as limitation of wrinkles, installing the membrane with a specified tensile load, and proper ballast use. While the modification of survivability properties is possible with the addition of reinforcement all EIAs should have similar environmental and chemical resistance.

4.2 Chemical Resistance

The interior textile reinforcement is the main driver of survivability properties. The polymer coatings encapsulating the textile determines the membranes resistance to chemical exposure and environmental aging.

Modes of chemical failure are permeation, dissolution, and/or degradation. Permeability can be tested in several ways.[9] The test method chosen should reflect the interaction of the membrane and fluid and try to best mimic the expected real-world challenge. A permeability test for secondary containment is the inverted cup method. Is using the geomembrane sample as the seal in a chemical fluid filled cup and inverting the test chamber so that one face of the geomembrane is exposed for a prescribed period. This test quantifies liquid or vapor permeation rate of the chemical fluid through the geomembrane.

Chemical immersion testing is conducted to assess compatibility of geomembrane system with various chemicals of interest.[6] This immersion can be conducted on samples immersed in the specific field application pond of interest. Alternatively, a challenge chemical solution will be prepared in the laboratory that mimics the known field chemical. The test is conducted by fully immersing a sample of geomembrane in the challenge liquid for a prescribed time at a known temperature. Following immersion, the sample is allowed to dry after which changes from the original or noted. Properties typically tested include the survivability properties discussed in section 3.1. 70% property retention is the typical industry benchmark.

4.3 Environmental Resistance

Environmental resistance is the assessment of endurance to environmental challenges of a specific location.[6] Typical environmental challenges include continued and cyclical UV exposure, hot and cold temperature extremes, wind exposure, water erosion, and erosion by sand or soil. Weatherability is the resistance of the geomembrane material to changes in survivability properties and chemical resistance properties in the face of these significant environmental challenges over its expected life.

UV resistance is evaluated by exposing small samples to intense ultraviolet radiation, wherein the higher intensity of light accelerates the aging effect. After exposure, the sample is evaluated for cracking of the coating and physical properties changes. Membranes are evaluated at extreme temperatures by low temperature bend, cold crack, and dead load. Low temperature bend and cold crack evaluates the membrane's performance at a specified arctic temperature. Dead load is an evaluation of a material's ability to hold a load over a weld at elevated temperatures for an allotted time.

Dimensional stability of the geomembrane is an important topic. While low temperature flex testing and dead load are conducted at constant temperature, dimensional stability evaluates the expansion and contraction of a membrane in the transition from hot to cold and vice versa. When a membrane is fastened at all sides, expansion and contraction could lead to premature failures. After installation, a drop in temperature could cause liners to shrink and pull away from the subgrade, inducing additional stresses and loads. Expansion of a fastened membrane causes wrinkle formation. Wrinkles increase risk of flex fatigue and perforation. Reinforced EIA Geomembranes typically have excellent thermal dimensional stability which largely alleviate the problems noted above.

5 Value of Reinforced EIA Geomembranes

Ultimately, the value of reinforced EIA geomembranes is continued protection of the local environment in the face of severe environmental and chemical challenges for prolonged periods of time. This value manifests itself through (1) the ability to contend with variable subgrades, (2) membrane flexibility that enables factory fabrication and the benefits that brings, and (3) excellent survivability properties at lower thickness and weight. These combined properties mean easy installation with lower total cost of ownership compared to other solutions.

Reinforced EIA geomembranes enable security when installed on varied subgrade types. Subgrade is the ground on which the containment is installed. Preparation of the ground is key in longevity for any type of geomembrane installation. Suitable subgrades have little to no debris, such as rocks and organic matter, and is stable. Rocks can puncture the linear and decomposing inorganic matter can react with the liner causing premature failure. Instability can also cause premature failures by overloading the tensile property of the liner. To combat risk of puncture due to poorly prepared subgrade, unreinforced geomembranes with low puncture resistance are installed with geotextile underlayment. While the use of geotextile underlayment is also used with reinforced geomembranes, it is not always necessary.

The manufacturing processes used to produce reinforced EIA geomembranes makes the rolled good at narrower in width than typical processes used to produce unsupported monolithic membranes. This difference arises from limitation to textile reinforcement equipment as well as the available extrusion processes for EIA materials. Typical monolithic geomembranes are produced in a single step through blown film extrusion at wide widths. Due to the narrower widths, more welds are required to create a fabricated panel. Due to their enhanced flexibility, large, fabricated panels may be produced in the factory, folded, and shipped to site [10,11]. Factory fabrication offers consistent welds, larger areas to deploy, and less time in the field. These benefits contribute to long lasting protection and lower installation cost.

To produce high quality fabricated membrane panels, it is important that the welded surfaces are clean, ambient conditions remain consistent, and welding rate and machine settings remain constant[10]. These variables are much easier to control when fabrication takes place in a factory. In contrast, when fabricating in the field, weather can vary dramatically. As temperatures change, some membranes expand and contract which cause wrinkles or the panels to pull apart yielding a weld that lacks the appropriate overlap. Precipitation also increases the chance of a poor weld by introducing moisture into the weld making them inconsistent or incomplete. Inconsistent welds can also be caused by dirt in the weld. Incoming inclement weather can result in rushed welding, which produces variable weld values. Factory fabricated seams have higher rates of success over field seams.[10]

Factory fabrication reduces the time spent on site during deployment or installation. The reduction in time spent on the field can also yield cost savings. This fact is endorsed by the Fabricated Geomembrane Institute and documented by their Installation Cost Comparison Calculator [11,12].The Installation Cost Comparison Calculator accounts for costs of personnel and equipment deployment. The tool illustrates that field fabrication requires more equipment to be deployed, higher cost of labor due to travel, and increased time on a job due to weather shifts all of which can be reduced by fabricating much of the liner before it ever reaches the field.

To demonstrate the cost advantages of factory fabrication with faster installation, the following example is provided. Figure 7 shows a prefabricated reinforced EIA geomembrane, the left image, compared to a field-fabricated one, the right image. The dashed lines on the left image represent factory welds, and the solids lines on the right image represent field welds. Despite having twice the welded seams, the prefabricated EIA geomembrane has a lower fabrication cost of $1.20 less per m^2 (using the Installation Cost Comparison Calculator) [12]. For a panel with the area of 1,858m^2 factory fabrication yields a savings of $2,227 in labor.

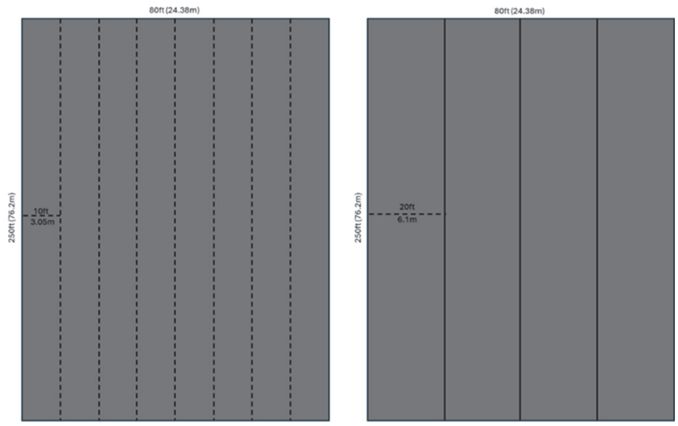

Figure 7: On the left, a prefabricated EIA geomembrane panel. On the right, a field-welded EIA geomembrane.

Labor savings is one cost benefit of EIA geomembranes. Another cost benefit is the elimination of coverage materials, such as: dirt, rock, or sand. The coefficients of thermal expansion and thermo-oxidative sensitivity of other common polymeric coatings require material coverage protection and shielding from the elements. Bulk sand and gravel costs in 2022 were $11 per metric ton, which does not include delivery to the installation site. Furthermore, a geomembrane is often installed for additional security, and if a spill occurs, the now contaminated coverage material will need to be removed, safely disposed or remediated, and potentially replaced, and all in accordance with regulations, which increase the overall cost of ownership. The inherent robustness and protection of a well-designed EIA geomembrane obviates many of these additional concerns and burdens, which are not often communicated to the site manager/owner during the initial phase of the geomembrane's selection.

Membrane coverage not only increases cost but increases the chance of undetected defects. The fill used in covered liners impedes visual inspection and can limit some methods of leak detection used to prevent contamination of surrounding areas. When penetrations are found, the fill then must be moved carefully to not cause more damage to the installation, cleaned, and then repaired. The only containment solutions that do not require coverage are concrete and reinforced EIA geomembranes. If a crack occurs in a concrete containment, the area must be taken out and repoured. Whereas, reinforced EIA correction just requires the area to be clean and dry so that a patch with overlap to already installed good material can be welded to taking less time.

6 Conclusion

Reinforced EIA geomembranes are a compelling protective material class. They have over a forty-year track record of providing robust, protective solutions, with many original installations remaining in place. By combining distinct textile and coating performance properties, reinforced EIA geomembranes have superior survivability and chemical resistance than monolithic materials. These advantages result in higher operational security, lower installation costs, lower service costs, and an overall lower total cost of ownership than many of the other options available to the geomembrane specifier.

References

1. Geosynthetica. Opportunities and Solutions, *Development and Growth of the Geomembranes;https://www.geosynthetica.com/Uploads/KoernerSympGaryKolbasuk.pdf*
2. Fabricated Geomembrane Institute, *Current Overview of EIA Geomembranes, https://assets-global.website-files.com/5977726d80d12837b9592f43/64d556c49febbe6e357b8bb9_FGI-EIA-Guideline-2023-7-22-23-Final-jkm.pdf* (2023).
3. F. Wilson, *XR-5® Takes on the Tough Texas Oilfields.* https://www.xrgeomembranes.com/project-profiles/xr-5-takes-on-the-tough-texas-oilfields
4. F. Wilson, *XR-5® Continues to Protect Mammoth Cave Wastewater Stabilization Pond* https://www.xrgeomembranes.com/project-profiles/mammoth-cave-process-wastewater
5. F. Wilson, *Coated vs. Laminated Geomembranes – Which Are Best for You? https://www.xrgeomembranes.com/blog/coated-vs.-laminated-geomembranes-which-are-best-for-you*
6. F. Wilson, *Identifying Critical Geomembrane chemical and Environmental Resistance Properties.* https://www.xrgeomembranes.com/blog/identifying-critical-geomembrane-chemical-and-environmental-resistance-properties
7. F. Wilson, *Defining the Critical Geomembrane Survivability Properties* https://www.xrgeomembranes.com/blog/critical-geomembrane-survivability-properties
8. Seaman Corporation Internal Lab Report (LR11067)
9. F. Wilson, *How Does Permeability Occur in an Impermeable Geomembrane.* https://www.xrgeomembranes.com/blog/permeability-in-an-impermeable-geomembrane
10. T.D. Stark, M.A. Hernandezb, D.S. Rohec. Geotextiles and Geomembranes **48**, 454-467 (2020).
11. T.D. Stark, G. Farid, S. Medina. *Factory versus Field Fabrication Cost Comparison* (IFAI)
12. Flexible Geomembrane Institute Cost Comparison Calculator https://www.fabricatedgeomembrane.com/protected/pond-liner-calculators
13. https://www.statista.com/statistics/219381/sand-and-gravel-prices-in-the-us/