A Guide to Polymeric Geomembranes

JOHN SCHEIRS

Excelplas Geomembrane Testing Services, Edithvale, Australia

Wiley Series in Polymer Science



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Series Editor

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Series Preface

The Wiley Series in Polymer Science aims to cover topics in polymer science where significant advances have been made over the past decade. Key features of the series will be developing areas and new frontiers in polymer science and technology. Emerging fields with strong growth potential for the twenty-first century such as nanotechnology, photopolymers, electro-optic polymers etc. will be covered. Additionally, those polymer classes in which important new members have appeared in recent years will be revisited to provide a comprehensive update.

Written by foremost experts in the field from industry and academia, these books have particular emphasis on structure-property relationships of polymers and manufacturing technologies as well as their practical and novel applications. The aim of each book in the series is to provide readers with an in-depth treatment of the state-of-the-art in that field of polymer technology. Collectively, the series will provide a definitive library of the latest advances in the major polymer families as well as significant new fields of development in polymer science.

This approach will lead to a better understanding and improve the cross fertilization of ideas between scientists and engineers of many disciplines. The series will be of interest to all polymer scientists and engineers, providing excellent up-to-date coverage of diverse topics in polymer science, and thus will serve as an invaluable ongoing reference collection for any technical library.

John Scheirs

Preface

Geomembranes are flexible polymeric sheets mainly employed as liquid and/or vapour barriers. Polymeric (and elastomeric) geomembranes are designed as relatively impermeable liners for use in a variety of containment situations (e.g. to contain water, process fluids, leachates, mine liquors and contaminated industrial liquid effluents), in applications where natural clay or other containment options are not possible or viable.

Geomembranes are used extensively in a broad array of industries such as water conservation, mining, construction, waste management, agriculture, aquaculture, and wine making. Their diverse applications include: water protection; conveyance and storage; basins and ponds; municipal solid waste (MSW) and hazardous waste (HSW) landfills; process water ponds and leachate collection ponds; storm water collection ponds; evaporation aprons; private and commercial water features; floating covers and other containment facilities. In all of these applications geomembranes intercept the flow path of liquid through soil, performing fluid barrier functions in the containment system.

Geosynthetic engineers, specifiers, designers, facility owners and operators are presented with a diverse range of geomembrane materials which all appear to provide similar benefits, based on basic mechanical properties. The key factor to consider when assessing the suitability of a given geosynthetic product is its performance when it comes to installation, welding, chemical resistance and environmental durability.

This book covers the various types of materials used for geomembranes, their attributes and shortcomings. Each type of geomembrane material has different characteristics which affect installation procedures, durability, lifespan and performance. There are a number of geomembrane types available so it is often difficult to select the geomembrane with the right combination of properties required for a given application. Geomembrane materials are selected for their overall chemical resistance, mechanical properties (elastic modulus, yield strength, puncture/tear resistance), and weathering resistance. Good material selection coupled with excellent design and construction methods could yield a 'theoretically' flawless liner. In practice, however, some degree of installation-related imperfections and applied stress/strain on the liner system is inevitable.

This book is intended to assist project specifiers, engineers and purchasers in their understanding and evaluation of polymeric geomembranes. All aspects of polymeric geomembrane materials, performance, testing, design, engineering, installation considerations, welding practices, case histories and field failures are included in the book. An overview of the manufacture, structure-property relationships, material properties and quality control of geomembrane materials is provided. The material properties covered which relate to the manufacture and quality are referred to as index properties as well as those related to the design and in-service properties are referred to as design or performance properties. Both the index and performance properties are important in specifying geomembranes for containment, liner and cover applications.

Geomembranes have become critical components in the design and environmental performance of mining facilities. The mining industries extensively utilize geomembranes in heap leach pads, solution ponds and evaporation ponds. Due to the enormous size of many of these mining applications, mines have come to represent a significant percentage of geomembrane consumption.

Mining companies stretch the capabilities of geomembranes to their limits and sometimes to the point of failure. For example leach pads are heaps of rocks/ore up to 120–180 m high piled on a geomembrane pad. In addition, there is traffic on the liner leach pad in the form of truck hauls or dozer pushes. Furthermore, the liquors used are highly acidic with pH values of around 1. Thus leach pads present one of the most aggressive service environments for geomembranes.

Due to their functionality geosynthetic liners and membranes are utilized in some of the most demanding applications that synthetic materials have been called upon to perform in. Service environments often combine extreme heat and UV exposure together with high mechanical loading and exposure to aggressive solutions and slurries. In addition, geosynthetic liners are expected to exhibit long-term durability with service lives being measured in decades rather than years. Expected service lives generally range from 20 to >100 years.

Geosynthetic liners are used extensively in critical applications such as protecting the water table from toxic landfill leachates or preventing corrosive mine process solutions from contaminating soil and aquifers. The failure of such geosynthetic barriers can have devastating environmental consequences. Given that they must withstand the extremes of weather and be laid over coarse and soft subgrades it is important that a generous safety factor is employed in their installation designs. Geosynthetic liners such as landfill caps need to have excellent longevity since they are intended to become permanent features of the landscape.

This book discusses the structure-property relationship of various geomembrane materials and compares and contrasts their individual advantages and shortcomings. The geotechnical designer needs to understand the limitations of various geomembrane products – relatively thin materials (0.5-0.75 mm) can be damaged by abrasion, for instance, and the texturing on spray-on geomembranes can be scratched off.

In landfill design, geomembranes are typically used as base liners (or basal liners) which are placed below waste to minimise seepage of leachate into the underlying soil and into the water table. Geomembrane covers are placed over the final waste to keep surface water and rain water from infiltrating the waste and adding to the volume of leachate solution. The geomembrane cover also serves to capture the landfill gas preventing release of methane which is a potent greenhouse gas. Base liners are typically HDPE because of its inherently good chemical resistance and strength, whereas the covers are generally LLDPE, VLDPE or fPP since they are more flexible than HDPE and hence conform better to the underlying decomposing waste and are better able to tolerate the strains associated with waste settlement.

About the Author

Dr. John Scheirs is a polymer technologist with ExcelPlas Geomembrane Testing Services. He specializes in geomembrane properties, polymer selection, failure analysis and testing and evaluation of geomembrane materials. He has extensive experience in durability testing of many polymeric geomembranes, in addition to routine mechanical analysis, forensic investigation and weld testing of geomembranes and polymeric liners. He has worked widely with HDPE, fPP and PVC membranes. Previously he worked with Exxon-Mobil on the stabilization and long-term durability of HDPE polymers.

Symbols Used

Throughout this book a number of symbols are used in the text as an aid to the reader for passages in italics that warrant particular attention because of their importance or relevance to the subject.

The symbols used in this book are:



A drawing pin to highlight interesting or significant facts

- A clipboard to indicate "TAKE NOTE" for important notes to avoid pitfalls
- (An eye to indicate "AT A GLANCE" for summarized information
 - A thumbs up to indicate "RULES OF THUMB" for general (simplified) rules of science or engineering

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1

Introduction to Polymeric Geomembranes

1.1 INTRODUCTION

The large number of commercially available geomembranes (or polymeric geosynthetic barriers) can make it challenging to select which geomembrane has the most appropriate combination of performance properties for a given application. Each type of geomembrane material has different characteristics that affect its installation procedures, durability, lifespan and overall performance. It is therefore necessary to match the project performance criteria with the right combination of properties of a particular geomembrane. Geomembrane materials are generally selected for their overall performance in key areas of chemical resistance, mechanical properties (elastic modulus, yield strength, puncture/tear resistance), weathering resistance, product life expectancy, installation factors and cost effectiveness.

The properties of polymeric geomembranes are determined mainly by their polymer structure (architecture of the chains), molecular weight (i.e. the length of the chains) and the crystallinity (packing density of the chains). Polymer crystallinity is one of the important properties of all polymers. Polymers exist both in crystalline and amorphous forms.

Common geomembranes can be classified into two broad categories depending on whether they are thermoplastics (i.e. can be remelted) or thermoset (i.e. crosslinked or cured and hence cannot be remelted without degradation) (see Table 1.1). Since thermoset geomembranes are crosslinked, they can exhibit excellent long-term durability.

When selecting a geomembrane for a particular application the following aspects need to be considered:

- choice of polymer;
- type of fabric reinforcement;
- colour of upper ply (e.g. white to maintain lower temperatures for sun exposed applications);
- thickness;

A Guide to Polymeric Geomembranes: A Practical Approach J. Scheirs

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Thermoplastic geomembranes	Thermoset geomembranes	Combinations of thermoplastic and thermoset
HDPE, LLDPE fPP PVC EIA TPU, PVDF	CSPE (crosslinks over time) EPDM rubber Nitrile rubber Butyl rubber Polychloroprene (Neoprene)	PE-EPDM PVC-nitrile rubber EPDM/TPE (Trelleborg) Polymer-modified bitumen

Table 1.1 Main plastic classifications for common geomembrane types

- texture (e.g. smooth or textured for improved friction angles);
- product life expectancy;
- mechanical properties;
- chemical resistance;
- ease of installation.

Table 1.2 lists various advantages and disadvantages of common geomembrane types. Firstly, geomembrane quality begins with base polymer resin selection. It is important to select or specify high-grade polymer resins that have been manufactured to meet the specific, unique demands encountered by geomembranes. Polymeric geomembrane properties are a function of the chemical structure of the base polymer resin, the molecular weight, the molecular weight distribution and the polymer morphology (e.g. the crystallinity). Next it is necessary to select the right combination of additives to protect the geomembrane, such as premium carbon black as well as antioxidant additives and stabilizers to ensure long life even in exposed conditions. Finally, it is necessary to select the most appropriate geomembrane manufacturing method.

1.2 VISCOELASTIC BEHAVIOUR

Polymers exhibit both viscous and elastic characteristics when undergoing deformation and hence are termed viscoelastic. Viscous materials (like honey), resist shear flow and strain linearly with time when a stress (e.g. in-service loading) is applied. Elastic materials strain (i.e. elongate) instantaneously when stretched and quickly return to their original state once the stress is removed (e.g. as in the case of EPDM liners). Viscoelastic materials have elements of both of these properties and, as such, exhibit time dependent strain.

Some phenomena in viscoelastic materials are:

- 1. If the strain is held constant, the stress decreases with time (this is called relaxation).
- 2. If the stress is held constant, the strain increases with time (this is called creep, as can be observed with HDPE liners).

Viscoelastic behavior comprised of elastic and viscous components is modelled as linear combinations of springs and dashpots, respectively.

The Maxwell model for viscoelastic behaviour can be represented by a viscous dashpot (a piston in oil) and an elastic spring connected in series, as shown in Figure 1.1(a). In

INTRODUCTION TO POLYMERIC GEOMEMBRANES

Geomembrane	Advantages	Disadvantages
HDPE	Broad chemical resistance	Potential for stress cracking
	Good weld strength	High degree of thermal expansion
	Good low temperature properties	Poor puncture resistance
	Relatively inexpensive	Poor multiaxial strain properties
LLDPE	Better flexibility than HDPE	Inferior UV resistance to HDPE
	Better layflat than HDPE	Inferior chemical resistance to HDPE
	Good multiaxial strain properties	
fPP	Can be factory fabricated and folded so fewer field fabricated seams	Limited resistance to hydrocarbons and chlorinated water
	Excellent multiaxial properties	
	Good conformability	
	Broad seaming temperature window	
PVC	Good workability and layflat behaviour	Poor resistance to UV and ozone unless specially formulated
	Easy to seam	Poor resistance to weathering
	Can be folded so fewer field fabricated seams	Poor performance at high and low temperatures
CSPE	Outstanding resistance to UV and ozone	Cannot be thermally welded after ageing
	Good performance at low temperatures	
	Good resistance to chemicals, acids and oils	
EPDM	Good resistance to UV and ozone	Low resistance to oils, hydrocarbons and solvents
	High strength characteristics	Poor seam quality
	Good low temperature performance	
	Excellent layflat behaviour	
Butyl rubber	Good resistance to UV and weathering	Relatively low mechanical properties
	Good resistance to ozone	Low tear strength
		Low resistance to hydrocarbons
		Difficult to seam
Nitrile rubber	Good resistance to oils and fuels (but not biodiesel)	Poor ozone resistance unless properly formulated
		Poor tear strength

 Table 1.2
 Advantages and disadvantages of commonly used synthetic geomembranes

this model if the polymer is put under a constant strain, the stresses gradually relax. That is, the tension in the spring (the stress) is gradually reduced by movement of the piston in the dashpot after a strong elongation (or displacement). Stress relaxation describes how polymers relieve stress under constant strain.

The Kelvin–Voigt model for viscoelastic behaviour also known as the Voigt model, consists of a viscous dashpot and Hookean elastic spring connected in parallel, as shown in Figure 1.1(b). It is used to explain the creep behaviors of polymers. When subjected



Figure 1.1 Polymers are viscoelastic materials having the properties of both viscous and elastic materials and can be modelled by combining elements that represent these characteristics. One viscoelastic model, called the Maxwell model, predicts behavior akin to a spring (elastic element) being in series with a dashpot (viscous element), while the Kelvin–Voigt model places these elements in parallel. Stress relaxation describes how polymers relieve stress under constant strain. Because they are viscoelastic, polymers behave in a nonlinear, non-Hookean fashion. This nonlinearity is described by both stress relaxation and a phenomenon known as creep, which describes how polymers strain under constant stress

to a constant stress, viscoelastic materials experience a time-dependent increase in strain (i.e. change in length). This phenomenon is known as viscoelastic creep. In this model on the application of a force, the spring gradually expands until the spring force equals the applied stress. Creep describes how polymers strain under constant stress.

The temperature dependence of strain in polymers can also be predicted using this model. An increase in temperature correlates to a logarithmic decrease in the time required to impart equal strain under a constant stress. In other words, it takes less energy to stretch a viscoelastic material an equal distance at a higher temperature than it does at a lower temperature.

1.3 POLYMER STRUCTURE

Polymer structure describes the chemical makeup of the polymer chains. HDPE, for example, is comprised of linear molecules of repeating CH₂ groups as shown in Figure 1.2.

Chemical structures of the main classes of geomembranes are shown in Figure 1.3. Note that HDPE due to its regular, symmetrical structure is crystalline and quite stiff but by substituting one of the hydrogen atoms (shaded) with a bulky methyl group (as in flexible polypropylene) or an even more bulky chlorine atom (as in PVC) the crystallinity of the polymer is disrupted and the material becomes more flexible.



Figure 1.2 Schematic of (a) the chemical structure of ethylene gas and polyethylene, (b) the molecular structure of a single polyethylene chain or 'backbone' and (c) multiple HDPE chains showing the close packing behaviour of polyethylene chains which gives high-density polyethylene a semi-crystalline morphology and its high density.

The degree of incorporation of chlorine in the polymer structure also has a large bearing on the final properties. Chlorinated polyethylene (CPE) for instance contains between 36–42 wt% chlorine while PVC has 57 wt% chlorine. The low crystallinity of CPE allows high plasticizer and filler loadings and gives it rubbery elastomer properties. In the chlorination process the larger diameter chlorine atoms randomly replace the far smaller hydrogen atoms. The random substitution and the size discrepancy effectively disrupts the crystalline structure. Furthermore the incorporation of a polar plasticizer in both CPE and PVC destroys the dipole attraction between the chains and these polymers become very flexible and rubbery. The use of a ketone ethylene ester (KEE) polymeric plasticizer for PVC (in the case of EIA geomembranes) creates a material that is permanently plasticized since the plasticizer cannot be extracted or lost.

The incorporation of chemically active cure sites in the polymer structure such as diene in EPDM and the sulfonyl chloride group in the case of CSPE allows these materials to be crosslinked or cured to give thermoset elastomers. Where the partially (surface) fluorinated HDPE gives it increased chemical resistance, the polymerized polyvinyliene fluoride is a thermoplastic liner material that has outstanding chemical resistance to all those chemicals that can swell or oxidize HDPE (such as aromatic solvents and oxidizing acids).

1.4 MOLECULAR WEIGHT

Molecular weight (Mw) is basically the length of the polymer chains. Polymer chains are very long (made up of thousands of carbon atoms linked in series) and hence are

A GUIDE TO POLYMERIC GEOMEMBRANES



* denotes less than stoiciometric amount of designated atom

Figure 1.3 Chemical structures and repeat units of various geomembrane polymers. Note the most basic repeat unit is that of HDPE. Substitution of a hydrogen atom in the HDPE structure confers properties such as greater flexibility, greater polarity, greater solvent resistance and the ability to undergo crosslinking

also referred to as macromolecules. In general terms, as the polymer molecular weight increases, the geomembrane strength increases.

The molecular weight of the polymer can affect physical properties such as the tensile strength and modulus, impact strength, puncture resistance, flexibility and heat resistance as well as its long-term durability properties.

It is difficult to measure the molecular weight directly so generally a simpler way of expressing molecular weight is by the melt index (MI) (also referred to as melt flow index (MFI) or melt flow rate (MFR)). The melt index is inversely proportional to the polymer's molecular weight. For example, a low melt index value indicates higher molecular weight and stiffer melt flow behavior (i.e. higher melt viscosity) while a high melt index value indicates a lower molecular weight and easier melt flow (i.e. low melt viscosity) (Scheirs, 2000). Note: MFI is not applicable to PVC polymers.

Table 1.3 shows the effect of molecular weight and melt index on polymer properties.

HDPE geomembrane resins are generally high MW resins and therefore have low melt flow index values (see Figure 1.4). For this reason they are referred to as 'fractional melt' and 'HLMI' (high load melt index) resins. The term 'HLMI' HDPE refers to those polyethylene resins that should really be called High Molecular Weight resins with an HLMI of less than 15 g/10 min using ASTM D1238, Condition F (21.6 kg load).

INTRODUCTION TO POLYMERIC GEOMEMBRANES

Property	As Molecular weight increases	As melt index increases
Molecular weight (chain length)	Increases	Decreases
Tensile strength (at yield)	Increases	Decreases
Tensile elongation	Increases	Decreases
Stiffness	Increases	Decreases
Impact strength	Increases	Decreases
Stress crack resistance	Increases	Decreases
Permeability	Decreases	Increases
Chemical resistance	Increases	Decreases
Abrasion resistance	Increases	Decreases
Processability	Decreases	Increases

Table 1.3	Effect of	molecular	weight	and	melt	index	on	polymer	prope	rties
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Figure 1.4 Relationship between melt flow index and % elongation at break for MDPE. Note the typical MI range for HDPE geomembranes (when tested with a 2.16 kg weight at 190 °C.)

The relationship between polymer molecular weight and melt index is summarized in Table 1.4

In addition to the length of the polymer chains (i.e. the molecular weight) the mechanical and physical properties of the plastics are also influenced by the bonds within and between chains, chain branching and the degree of crystallinity.

1.5 MOLECULAR WEIGHT DISTRIBUTION

The molecular weight distribution (MWD) is a fundamental polymer property which determines the processability and the end use properties of the polymer. Since an increase in the molecular weight of a polymer improves the physical properties, there is a strong

Classification	Number of carbon atoms	Molecular (Mw) weight	MI (2.16 kg) standard melt index	MI (21.6 kg) high load melt index
Medium MW	7500–12 000	100 000–180 000	0.6–10	25–50
High MW	18 000–56 000	250 000–750 000	0.06–0.15	7–25

Table 1.4 Molecular weight and melt index relationship

demand for polymers having high molecular weights. However, it is the high molecular weight molecules that render the polymer more difficult to process. A broadening in the molecular weight distribution tends to improve the flow of the polymer when it is being processed at high rates of shear as the low molecular weight tail acts as a "processing aid" for the higher MW chains.

Thus due to the high viscosity of higher molecular weight resins such as low HLMI HDPE used for geomembranes, the molecular weight distribution becomes a very important consideration in the processability of these HDPE resins. Resin manufacturers can tailor the molecular weight distribution (MWD) by catalyst and process selection. Geomembrane resins benefit from a broad to very broad distribution. While narrow distribution resins are tougher than broad distribution resins (at equivalent molecular weights), processability becomes easier as the MWD broadens. Table 1.5 shows the effect of molecular weight distribution on polymer geomembrane properties.

1.6 CRYSTALLINITY

In addition to the chemical structure, the properties of polymers are very dependent on the polymer morphology – particularly crystallinity.

The term crystallinity refers to the presence of crystalline regions where the polymer chains pack efficiently into dense regions that are impervious to both oxygen and chemicals (see Figures 1.5). Hence highly crystalline polyethylene has excellent chemical resistance and oxidative stability.

The ordered and aligned portions of the polymer chain form small regions that are called crystallites. The non-ordered regions are called amorphous. These amorphous regions that

Property	As molecular weight distribution broadens
Stiffness	Decreases
Impact strength	Decreases
Stress crack resistance	Increases
Melt strength	Increases
Processability	Increases

Table 1.5Effect of molecular weight distribution (MWD)on polymer geomembrane properties

INTRODUCTION TO POLYMERIC GEOMEMBRANES



Figure 1.5 Schematic of crystallites in semi-crystalline polymers. The polymer chains fold tightly in densely packed crystallites which are impervious to oxygen and chemicals. The crystallites (or lamellae) are interconnected by tie molecules which span the amorphous regions

are not crystalline contain more random orientation of the polymer chains. The proportion of crystalline (ordered and tightly packed) regions to the amorphous (disordered) regions is expressed as the degree of crystallinity of the polymer.

Polymer chains can fold and pack together to form ordered (crystalline) regions. These regions where parts of the polymer molecules are arranged in regular order are called crystallites. In between these ordered regions molecules are arranged in a random disorganized state and these are called amorphous regions.

Amorphous regions of a polymer are made up of randomly coiled and entangled chains. Amorphous polymers have lower softening points and are penetrated more by solvents than are their crystalline counterparts. PVC represents a typical amorphous polymer.

The role of crystallinity is very important in explaining the behavior of polymeric geomembranes. The amount of crystallinity of geomembrane materials varies from nil in the case of PVC, to as high as 55–65% for HDPE (see Table 1.6).

The degree of crystallinity has a pronounced effect on the performance properties of the geomembrane, especially the mechanical properties and chemical resistance. The tightly packed molecules within the crystallites of HDPE, for example, creates dense regions with high intermolecular cohesion and these areas are resistant to penetration by chemical, gases and vapours. In constrast the complete lack of crystallinity of PVC geomembranes makes them susceptible to permeation and solvation by small solvent molecules.

Polymer	Crystallinity (%) (average values)
HDPE	55
MDPE	40
LLDPE	15
VLDPE	10
FPP	5
CPE	1–2
PVC	0

Table 1.6 Typical % crystallinity values for variousgeomembrane polymers

The highly crystalline nature of HDPE is responsible for its higher density and stiffness, as well as its low permeability and high chemical resistance.

HDPE is semi-crystalline but introducing an alkene comonomer (e.g. butene or hexene) into the polymer backbone gives side chains that reduces the crystallinity. This in turn has a dramatic effect on polymer performance, which improves significantly as the side-chain branch length increases up to hexene, and becomes less significant with octene and longer chains. It is by manipulating this side branching that various grades of polyethylene varying in crystallinity are produced.

The greater number of crystalline regions is what differentiates HDPE from its lower density cousins such as LLDPE, MDPE, LDPE and VLPE. This semi-crystalline microstructure of HDPE imparts excellent chemical resistance and high strength; however it also makes HDPE susceptible to environmental stress cracking (ESC). fPP, CPE and PVC owing to their low crystallinities are more flexible and not susceptible to ESC (see Figure 1.6).

Polymer chains with side branches (e.g. LLDPE) or irregular pendant groups (e.g. PVC, CSPE) cannot pack together regularly enough to form crystallites. This is the reason why LLDPE and VLDPE, which have a controlled number of side branches, have much lower crystallinities than HDPE.

HDPE crystallizes from the melt under typical conditions as densely packed morphological structures known as spherulites. These are small spherical objects (usually from 1 to 10 μ m) in diameter composed of even smaller structural subunits: rod-like fibrils that spread in all directions from the spherulite centres, occupying the spherulite volume. These fibrils, in turn, are made up of the smallest morphological structures distinguishable, small planar crystallites called lamellae. These crystallites contain folded polymer chains that are perpendicular to the lamella plane and tightly bend every 5 to 15 nm (see Figure 1.7).

Lamellae are interconnected by a few polymer chains, which pass from one lamella, through a small amorphous region, to another. These connecting chains, or tie molecules, are ultimately responsible for mechanical integrity and strength of all semi-crystalline polymer materials. Crystalline lamellae offer the spherulites rigidity and account for their high softening temperatures, whereas the amorphous regions between lamellae provide flexibility and high impact strength to HDPE products.



Ire 1.6 Effect that the substitution of a hydrogen atom in HDPE b

Figure 1.6 Effect that the substitution of a hydrogen atom in HDPE by substituents of increasing size (e.g. methyl group, chlorine atom) has on the crystallinity and the flexibility of the polymer

Highly crystalline polymers are rigid, high melting and less affected by solvent penetration. Hence HDPE geomembranes which have some 55–60% crystallinity exhibit excellent solvent resistance. Crystallinity makes polymers strong, but also lowers their impact resistance. For instance, samples of HDPE prepared with crystallinities of 95% are extremely brittle.

An increase in the degree of crystallinity leads to a direct increase in rigidity and tensile strength at yield point, hardness and softening point and to a reduction in diffusion and permeability. However increasing crystallinity also means a reduction in the number of 'tie' molecules in the amorphous regions which are susceptible to chemical attack (e.g. oxidation) and tie chain pullout from the crystallites (i.e. stress cracking) (see Figure 1.8).

Increasing crystallinity results in the following property attributes: increased tensile strength, increased stiffness or hardness, increased chemical resistance, decreased diffusive permeability (or vapour transmission), decreased elongation or strain at failure and decreased stress crack resistance.

In semi-crystalline polymers, the antioxidants reside in the amorphous regions which fortuitously are the same regions where oxygen can diffuse into cause oxidation. In contrast, the crystallites are too dense for either oxygen or antioxidant and diffuse into. The more amorphous polyolefins are more prone to oxidative degradation since oxygen can



Figure 1.7 Schematic of spherulites in semi-crystalline polymers

diffuse more freely throughout their entire structure and there is a greater volume of polymer that must be protected by the antioxidant. In addition, antioxidants can also diffuse more readily through and migrate more easily from amorphous polymers compared to their more crystalline forms (Scheirs, 2000).

Crystalline thermoplastics (also called semi-crystalline) include HDPE, LLDPE and polypropylene. In these materials the polymeric chains are folded in a crystal lattice. The folded chains form lamellae (plate-like crystals).

Whilst the crystallites (i.e. tightly packed crystalline regions) are impervious to both oxygen and chemical ingress, the 'tie' molecules which interconnect the crystallites are susceptible to oxidation and chemical attack. The area in which the tie molecules reside is termed the amorphous region (i.e. disordered region) and these areas have lower density than the crystallites and so oxygen and opportunistic chemical can diffuse into these areas.





Figure 1.8 Schematics of (a) the chain folding and packing behaviour of high-density polyethylene chains to form crystalline regions and (b) the crystalline regions or 'crystallites' in HDPE (which are interconnected by 'tie molecules') which can be pulled apart under the combined action of stress and a chemical agent (referred to as environmental stress cracking). Reprinted with permission from *Polymer*, Importance of tie molecules in preventing polyethylene fracture under long-term loading conditions by A. Lustiger and R. L. Markham, **24**(12), 1647. Copyright (1983) Elsevier

1.7 PROPERTIES OF POLYETHYLENES

Polyethylene is by far the most widely used polymer to manufacture geomembranes. Polyethylene resins are manufactured in very-low-density, low-density, linear low-density, medium-density and high-density varieties. The density range for all polyethylene geomembrane polymers falls within the general limits of 0.85 to 0.960 g/cm³.

Molecular weight, molecular weight distribution and crystallinity (i.e. density) are the three most important characteristics of polyethylene resins and play a major role in determining the durability and end-use performance properties of HDPE and LLDPE geomembranes.

Polyethylene is classified into several categories based on its density and branching. HDPE has little branching, giving it stronger intermolecular forces and higher tensile strength than lower density polyethylene, thereby making it ideal for geomembrane applications. HDPE is defined as having a density of equal to or greater than 0.941 g/cc.

The density of polyethylene is primarily controlled by the frequency and length of the side branches (which in turn are determined by the type and level of comonomer). The side branches prevent the PE chains from packing closely together, so the longer the side branches, the more open the structure and hence the lower the density. Homopolymer HDPE has a density greater than 0.960 g/cc while copolymers have densities less than 0.960 g/cc.

Note that true homopolymer HDPE is not used for geomembranes due to its tendency to undergo environmental stress cracking.

Typical comonomers are butene, hexene and octene which are carbon chains with 4, 6 and 8 carbons respectively. These comonomers are denoted as C4, C6 and C8 for simplicity. They all have a reactive double bond at the end of the chain and are referred to as alpha olefins. The 'olefin' indicates they contain a C=C bond in their structure while alpha indicates the double bond is between the first and second carbon atoms.

The type of comonomer used determines the end-use performance characteristics of the resin. Hexene and octene copolymers are tougher and more flexible; however butene copolymers are typically less expensive.

It is important to emphasize that HDPE geomembranes are actually manufactured using a polyethylene resin with a density 0.932–0.940 g/cm³ which falls into the MDPE category as defined in ASTM D-883. It is the addition of carbon black that pushes the final density of the geomembrane up into the density range between 0.941 and 0.950 g/cm³ which corresponds to a HDPE as defined in ASTM D-883. For this reason the 'HDPE' nomenclature is used to describe most black polyethylene geomembranes.

Note that 'HDPE' geomembrane resins are in fact MDPE base polymer with the addition of 2% carbon black, which raises its density into the classification range of HDPE.

The effect of increasing density on various PE geomembrane properties is shown in Table 1.7.

Table 1.8 lists the density classifications for polyethylene resins.

Property	As density increases
Crystallinity	Increases
Tensile strength (at yield)	Increases
Stiffness	Increases
Impact strength	Decreases
Stress crack resistance	Decreases
Permeability	Decreases
Chemical resistance	Increases
Abrasion resistance	Increases
Processability	Decreases

Table 1.7 Effect of density on PE geomembraneproperties

Table 1.8 Density classifications for polyethylene resins

Polyethylene type	Defined density range (g/cc)
HDPE	0.941-0.965
MDPE	0.926-0.940
LLDPE	0.915-0.925
LDPE	0.910-0.915
VLDPE	0.880-0.910

HDPE is the most common field-fabricated geomembrane material primarily due to its low material cost, broad chemical resistance and excellent mechanical properties.

MDPE is a substantially linear polymer, with high levels of short-chain branches, commonly made by copolymerization of ethylene with short-chain alpha-olefins (e.g. 1-butene, 1-hexene and 1-octene).

LLDPE is a substantially linear polymer, with significant numbers of short branches, commonly made by copolymerization of ethylene with short-chain alpha-olefins (e.g. 1-butene, 1-hexene and 1-octene). As its name implies, Linear Low Density Polyethylene is a lower density polymer (<0.939 g/cm³), with increased material flexibility. LLDPE is mainly used for liners where large settlements are anticipated for long term consolidation, such as for landfill covers. Capping contaminants with LLDPE geomembranes, not only makes it possible to control the release of carbon dioxide and methane (by-products of the decomposition of organic matter), but allows their capture and reuse. The flexibility of the LLDPE is also useful for geomembrane liners that are installed on subgrades prone to differential settlement.

LLDPE has a higher tensile strength and higher impact and puncture resistance than LDPE. It is very flexible and elongates under stress. It can be used to make thinner sheets, with better environmental stress cracking resistance. It has good resistance to chemicals and to ultraviolet radiation (if properly stabilized). However it is not as easy to process as LDPE, has lower gloss and a narrower operating range for heat sealing. Hence it finds application in plastic sheets (where it permits use of lower thickness profile than comparable LDPE), coverings of cables, geomembranes and flexible tubing.

LLDPE geomembranes are available in a smooth, textured or single textured finish. The comonomers used to produce the resin can include hexene or octene.

Low-density polyethylene (LDPE) has very poor environmental stress crack resistance and rather poor mechanical properties and so it does not find application as a geomembrane. LDPE has a high degree of short- and long-chain branching, which means that the chains do not pack to form a dense crystal structure as well. It has therefore less strong intermolecular forces, as the instantaneous-dipole induced-dipole attraction is less. This results in a lower tensile strength and increased ductility.

VLDPE is most commonly produced using metallocene catalysts and is a highly flexible and ductile material.

1.8 STRESS–STRAIN BEHAVIOUR OF POLYMERS

The stress-strain behaviour of polymers used to manufacture geomembranes is largely determined by the properties discussed above, namely the molecular weight, molecular weight distribution and crystallinity or density.

Figure 1.9 shows a typical stress-strain curve for HDPE which identifies the following:

- the linear elastic region (where it obeys Hooke's Law);
- the plastic region where the polymer draws and extends;
- the yield stress;
- the ultimate strength (or tensile strength at break);
- the modulus of elasticity (i.e. the gradient of the initial linear slope).



STRESS-STRAIN CURVE FOR A TYPICAL VISCOELASTIC POLYMER



Figure 1.9 Stress-strain curve showing elastic and plastic regions



Figure 1.10 Stress-strain curve for HDPE showing main tensile test value parameters

Figure 1.10 is a similar stress–strain curve which also identifies the elongation at yield (also know as the yield strain) and the elongation at break (also known as the breaking strain).

Figure 1.11 shows the stress-strain curves for various polymer types. If the load rises linearly to fracture with no plastic deformation then the material is said to be brittle as is the case for PVC liners where the plasticizers have been extracted or, for HDPE geomembranes after extensive oxidation. More commonly though the behaviour of geomembranes is ductile but may exhibit brittle behaviour depending on the temperature. The brittle transition occurs at sub-zero temperatures for common geomembranes (see section on low temperature properties) (Scheirs, 2000). For geomembranes applications either hard and tough (e.g. HDPE) or soft and tough (e.g. CSPE, fPP, EIA) polymers are the most suitable.

1.8.1 YIELD BEHAVIOUR

'Yield' is defined as the onset of plastic deformation in a polymer under an applied load. This is an important parameter because it represents the practical limit of use more than does ultimate break or rupture. The yield properties depend on the polymer crystallinity and the polymer morphology. The yield behaviour also depends on the test conditions used. The yield properties vary with both the test temperature and the speed of the test. For this reason it is very important that tensile testing of polymer geomembranes be conducted at 23 $^{\circ}$ C where possible. This may therefore cast doubt on field tensiometer measurements where higher or lower temperatures might be encountered. Since the speed of the testile test is also critical, the tensile test speed (also known as the *crosshead speed* and determined by the strain rate) must be standardized and defined (Scheirs, 2000).



Figure 1.11 Stress-strain curves for various polymer types

1.8.2 PLASTIC DEFORMATION

'Plastic deformation' is the deformation that remains after a load is removed from a polymer sample. It is also called permanent deformation or non-recoverable deformation. Under small enough loads less than the yield stress the deformation is elastic and is recovered after the load is removed (i.e. the specimen returns to its original length). Yielding thus represents the transition from elastic to plastic behaviour. Consider a HDPE geomembrane sample under an applied tensile load. The length of the specimen will increase (as measured by the elongation). As the elongation increases, the load at first increases linearly but then increases more slowly and eventually passes through a maximum where the elongation increases without any increase in load (as in Figure 1.10). This peak in the stress–strain curve (i.e. the load–elongation curve) is the point at which plastic flow (permanent deformation) becomes dominant and is defined as the yield point. Not all polymers exhibit a defined yield point such as that exhibited by HDPE. PVC, for example, shows no obvious yield point in the stress–strain curve.

1.8.3 STRESS

The shape and magnitude of the load–elongation curve depends on the particular polymeric geomembrane being tested. Rather than load, the properly normalized variable is stress which is defined as the load per unit cross-sectional area of the test specimen. Stress therefore has units of pressure (1 MPa = 1 MN/m² = 145 psi).

INTRODUCTION TO POLYMERIC GEOMEMBRANES

1.8.4 STRAIN

Rather than quoting elongation, the proper normalized variable is strain which is the extension divided by the initial length. Strain is therefore dimensionless whereas elongation is expressed as a percentage.

1.8.5 TYPES OF LOADING

The most common type of loading used for testing polymeric geomembranes is *uniaxial tension* but other types of loading are arguably more important such as compression, hydrostatic compression and uniaxial (i.e. multiaxial tensile) loading. The simplest variation of the tensile test is the uniaxial compression test which should not be confused with hydrostatic compression in which the load is applied from all sides. It has been found that compressive stresses are higher than tensile stresses for a given strain value.

1.8.6 TEMPERATURE EFFECTS

The shape and magnitude of the stress-strain curve is very dependent on temperature. As the temperature increases, the yield stress, elastic modulus (i.e. stiffness) and yield energy all decrease while the yield strain (elongation at yield) increases (see Figure 1.12).

1.8.7 STRAIN RATE EFFECTS

Strain rate determines to the speed of the application of force on the material being tested. High strain rates (i.e. high testing speed) have the effect of making the polymer behave in a more brittle fashion - in the same way that reducing the temperature makes the polymer stiffer and more brittle (Figure 1.13).



Figure 1.12 Effect of swelling and increased temperature on the stress strain properties of HDPE geomembranes. The material becomes softer and more rubbery but loses its tensile strength



Figure 1.13 Effect of increasing density or increasing testing rate (i.e. strain rate) or decreasing temperature on the stress–strain properties of HDPE geomembranes. The material becomes stiffer and stronger as the density or testing speed increase or as temperature is decreased

Polymer	Melting point (°C)
Poly(ethylene vinyl acetate) (EVA)	85
Metallocene polyethylene (mPE)	90-100
Low-density polyethylene (LDPE)	108
Linear low-density polyethylene (LLDPE)	125
High-density polyethylene (HDPE)	130
Flexible polypropylene (fPP)	150

 Table 1.9
 Melting points of various polymer resins

1.9 MELTING POINTS

Polymer geomembrane resins have very different melting points as shown in Table 1.9. The polymer melting point (or more correctly the melting range) is of importance during thermal welding; particularly when welding different geomembrane materials to each other.

REFERENCES

Scheirs, J., Compositional and Failure Analysis of Polymers: A Practical Approach, John Wiley & Sons, Ltd, Chichester, UK, 2000, 766 pp.

Geomembrane Manufacturing Methods

Polymeric geomembranes can be manufactured by a number of different techniques and the nature of the specific manufacturing methods can impart various characteristics to the final product. The two main manufacturing methods are the extrusion and the calendering operations (see Table 2.1). Extrusion can further be divided into three sub-methods namely, blown extrusion, cast extrusion and extrusion coating.

Polyolefin geomembranes (i.e. HDPE, LLDPE and fPP) are all manufactured by an extrusion method where the polymer resin in pelletized form is mixed with a pelletized concentrate called a masterbatch. The masterbatch comprises the additive formulants such as carbon black (or titanium dioxide in the case of white membranes), antioxidants and stabilizers. The mixture is then fed to an extruder where the materials are heated, intimately mixed and sheared using a special tapered flighted screw. The melt is both distributively mixed and dispersively mixed to ensure homogeneous distribution and dispersion of the additives (see Figure 2.1). The melt is then forced through a die – either a flat die (in the cast sheet extrusion method) or an annular die (in the blown film method).

The cast extrusion is alternatively called 'Flat die', 'Flat bed' or 'Slot die' extrusion. Flat-die geomembrane manufacturing delivers greater thickness and gauge control than round die blown-film. Blown film on the other hand provides certain advantages of polymer orientation not present in flat-die produced material. For instance, the vertical bubble provides biaxial orientation of the film to give it improved tear resistance that would not be possible on cast-film liners.

On account of the weight of the vertical bubble of film, the blown film process tends to introduce a degree of balanced orientation to the liner. Polymer orientation can improve the mechanical properties of the liner. Therefore for the same starting resin, a blown film geomembrane has the potential to produce a higher performance geomembrane than a flat-die manufactured liner.

A Guide to Polymeric Geomembranes: A Practical Approach J. Scheirs

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Table 2.1 Some of the geomembrane types manufactured by extrusion and calendering methods respectively

Extrusion (by blown film or flat die)	Calendering (counter-rotating rollers)
HDPE	FPP and fPP-R
LLDPE	PVC
fPP	CSPE-R
VLDPE	EPDM and EPDM-R



Figure 2.1 Schematic showing the importance of both distributive and dispersive mixing on the dispersion of an additive (e.g. carbon black) in the polymer geomembrane. Reproduced by permission of NAUE

2.1 BLOWN FILM (ROUND DIE)

In the blown film method the molten plastic is extruded through a vertical orientated annular die to produce an inflated bubble (see Figure 2.2) that is hauled off vertically and slit to produce a flat sheet.

Blown film lines can produce geomembranes 7.0 m wide in thicknesses of 0.5 to 2.5 mm at rates of more than 1200 kg per hour. Blown film lines use complex three-layer dies to optimize melt flow, eliminate dead spots and prevent overheating of the resin. Typically three extruders feed the die. The B extruder is used for the core of the sheet while the A and C extruders supply the polymer to the inner and outer skins of the geomembrane. The multilayer can be textured for greater friction and traction by pumping nitrogen gas into the A and C extruders. When the nitrogen gas exits the die in the outer and inner layers, it disrupts the flow of resin and creates a controlled texturing of the skins. The largest roll





that can be wound is 900 mm in diameter, although the geomembrane is generally wound into rolls 400 to 500 mm in diameter. According to Battenfeld Gloucester the blown film method is the process of choice for geomembranes, with about 80% of products extruded in this way (Battenfeld Gloucester, 2006).

The blown film manufacturing method is less costly than the cast method. Geomembranes made by the blown film method can contain fold lines from collapsing of the bubble and these can give the final geomembrane sheet different strength characteristics (Figure 2.3). Figures 2.4 to 2.6 show these fold lines.

Geomembrane made by the blown film method can also have tears and pin holes due to various defects known as unmelts, gels and die build-up. These are areas of poorly fused and/or crosslinked polymer that have smeared along the polymer surface when the bubble exits the annular die, creating small holes or tears (see Figure 2.7).

2.2 FLAT SHEET EXTRUSION (FLAT DIE)

In the flat sheet extrusion method the molten plastic is forced through a flat die and then between polished chill rollers to produce the flat geomembrane sheet (see Figure 2.8). The role of the flat die is to uniformly distribute the molten plastic along the width of the die and to develop uniform flow patterns. Flat die extrusion of geomembranes has greater thickness control than the blown film method; however advances in gauge control for the blown film method is closing this gap.

Table 2.2 summarizes some of the advantages of the flat sheet extrusion method for manufacturing HDPE geomembranes.

Table 2.3 summarizes the differences in the properties of blown and flat sheet extruded HDPE geomembrane.



Figure 2.3 Photograph (taken looking upwards) of an HDPE geomembrane made by the blown film method. Note that the bubble narrows at the top of the tower due to the converging collapsing frame assembly. Reproduced by permission of Battenfeld Gloucester



Figure 2.4 Schematic of the blown film geomembrane manufacturing method. Reproduced by permission of NAUE

Schematic of Blown Film Manufacturing of Geomembranes



Figure 2.5 Schematic showing that a geomembrane produced by the blown film method has foldlines in its cross-section after slitting



Figure 2.6 Photograph of fold lines in a deployed HDPE geomembrane. The fold lines are a legacy of the blown film manufacturing process where the blown tube or bubble is collapsed at the top of the blown film tower. Reproduced by permission of NAUE

2.3 COEXTRUSION

Coextrusion uses two or more extruders to feed one die to give a product composed of various layers (see Figure 2.9). In coextrusion the layers of molten polymer simultaneously exit the die so that they form molecular entanglements with each other. This interpenetration gives a monolithic structure if the same polymer formulation is used for all three layers. Coextrusion is fundamentally different from lamination since no plane of weakness exists with coextrusion.

Coextrusion provides for novel combinations and structures by simply changing one or more of the polymer types in the A:B:A or A:B:C construction. For example, in order to



Figure 2.7 Photograph of a typical manufacturing defect in a HDPE geomembrane sheet made by the blown film process. The hole defect is caused by a cold slug of extrudate in the melt forming an annular slit as it passes through the die lips. Reproduced by permission of NAUE



Figure 2.8 Photograph of a flat sheet extrusion die. The extruded sheet exits the gap in the die block on the left and then passes between the polished nip rollers. Reproduced by permission of NAUE

GEOMEMBRANE MANUFACTURING METHODS

Attribute	Stated advantages
Higher MFI resins can be used for flat sheet extrusion	This translates to higher sheet flexibility and less energy to weld (due to the higher MFI)
Greater welding speed	Typically 2.4 m/min for 1 mm HDPE
No fold lines	Homogeneous sheets
Good thickness control	Thickness variation <5%
No blown film defects	Defects such as 'cold slugs' and 'gels' which can lead to holes in the blown geomembrane do not occur in cast liners
Good dimensional stability Shiny/glossy surface finish	Shrinkage <1% at 100 °C for 1 h Easy damage recognition

Table 2.2 Summary of advantages of the flat sheet extrusion method for manufacturing HDPEgeomembranes. Reproduced by permission of NAUE

Table 2.3 Comparison of blown and flat sheet extruded HDPE geomembranes. Reproduced by permission of NAUE

Property	Blown film	Flat sheet (cast)			
Stiffness	Low melt index 0.6 g/10 min (190°C/5 kg) and therefore higher stiffness	Melt index >2.0 g/10 min (190 °C/5 kg) and therefore lower stiffness			
Fold lines	Fold lines present can give variations in modulus	No fold lines			
Thickness variation	7–15%	<5% (therefore better weld quality)			
Dimensional stability	<2% (100 °C for 1 h) and therefore more folds in sunlight	<1% (100 °C for 1 h) and therefore less folds in sunlight			
Welding speed	1.9 m/min for 1 mm sheet	2.4 m/min for 1 mm sheet			

combine the flexibility and out-of-plane elongational properties of VLDPE with the chemical resistance of HDPE, a coextruded HDPE/VLDPE/HDPE three-layer (20%:60%:20%) geomembrane can be manufactured (see Figure 2.10).

For textured geomembranes a blowing agent can be added to one or both of the outer layers to give either singly or doubly textured sheet. The purpose of such texturing being to give improved friction angles.

Other coextrusion variations that are employed are:

- The top layer may be white-surfaced to reduce heat build-up and therefore extend the geomembrane lifetime and reduce desiccation (i.e. drying out) of the underlying clay.
- The middle layer could have high levels of electrically conductive carbon to facilitate spark testing.
- The top layers can be heavily UV stabilized for long-term UV exposure applications.

A point that is little discussed is that, three-layer coextrusion capability also provides the geomembrane manufacturer the option of introducing regrind or recyclate into the geomembrane. A lower quality/off spec/recycled material can be used in the middle layer



Figure 2.9 Photograph of a top view of a flat sheet (cast) extrusion line for manufacturing HDPE geomembranes. Note that the two extruder barrels on the left feed the slot die right of middle. The two extruders are required to produce a multilayer sheet. Reproduced by permission of NAUE

accounting for 75% of the structure; these materials may be purchased for two-thirds of the cost of virgin geomembrane resins.

2.4 CALENDERING

PVC, CSPE and scrim-reinforced geomembranes including CSPE-R and fPP-R are not produced by conventional extrusion methods and are manufactured instead by calendering. In this process the polymer resin, carbon black, fillers and various additive are mixed either in a heated batch mixer (such as a Banbury) or a heated continuous mixer (such as a Farrel FCM). The mixture is then masticated using mixing units customary in the rubber processing industry such as a roll mill where it is homogenized. The mixed mass is then passed through a set of calender counter-rotating rollers to form the final sheet. Most scrim-reinforced geomembranes (SRG) are highly flexible liners manufactured by this type of calendering method.

Typical SRG base polymers are PVC, CSPE and fPP. In the calendering process the polymer formulation is intensively mixed in a special Banbury mixer and then passed through a two-roll mill where it is flattened. The dough-like material is then passed through a set of counter-rotating rollers which comprise the calender to produce the final sheet. The sheet is made up of polymer plies laminated to the scrim support (which is an



Figure 2.10 Some possible three-layer coextruded geomembrane structures possible with modern coextrusion equipment

open weave fabric generally made from polyester). The adhesion of the plies is due to 'strike-through' through the open weave fabric. The openings in the scrim (i.e. the apertures) need to be large enough to enable good adhesion between the plies. Inadequate ply adhesion can lead to delamination which is one of the potential shortcomings of scrim-reinforced geomembranes. The scrim-reinforced geomembranes can either have one central scrim and two outer plies (hence are three-ply geomembranes) or, comprise two scrim layers on each side of a central polymer layer and with two polymer plies on each outer face (hence are five-ply geomembranes).

It is important that the apertures (i.e. the openings) in the scrim are sufficiently large to enable the polymer plies to adhere to one another. This gives 'key and lock' bonding that is necessary to achieve the required ply adhesion and prevent delamination failure. These reinforced geomembranes are generally slightly thicker than the unit dimensions due to the additional thickness of the scrim. For instance, a 1.21 mm fPP-R geomembranes are often only available in limited widths (e.g. 2–3 m) owning to width limitations of the calendering equipment.

2.5 SPREAD COATING

Spread coating (or solvent coating) is a process by which the polymer is dissolved in a solvent which is then spread onto the textile and heated to evaporate the solvent and leave the coating.

Reinforced ethylene interpolymer alloy (EIA-R) type geomembranes (e.g. XR-5) are generally produced by this manufacturing process. In the spread coating process the molten polymer is spread in a relatively thin coating over a dense fabric substrate (i.e. tightly woven fabric or non-woven fabric) using a spreading knife. The coating knife runs parallel to the weft.

Penetration of the viscous polymer to the opposite side of the fabric is limited due to the dense weave of the fabric and so the material is turned over and the process repeated on the other side of the fabric. Since the polymer coating intimately encapsulates the fabric there is no tendency for delamination.

2.6 EXTRUSION COATED GEOMEMBRANES

Extrusion coated geomembranes are made by a specialized technology where fabrics or scrims are coated with polymer. It is a process by which the molten polymer is extruded as a flat sheet film and pressed into the fabric surface, adhering to and coating the surface (e.g. EIA-R geomembranes from Cooley).

The extrusion coating provides a number of purported advantages over spread coating, solvent coating and lamination such as:

- Extrusion coated fabric achieves all material properties immediately upon cooling. Non-extrusion coatings may undergo changes post-production as the adhesives and solvent-borne coatings continue to cure.
- Extrusion coating provides intimate contact between membrane and fabric resulting in a stronger bond than the abrupt glue line that separates coating and fabric in the lamination process.
- Extrusion coating does not involve volatile organic constituents (VOCs) typical in solvent coating processes. Therefore, off-gassing and unpleasant odours are not an issue with extrusion coating.
- Extrusion coated fabrics have high wear and abrasion resistance unlike laminated products in which the adhesive provides a failure plane for delamination.
- Extrusion coating is monolithic with none of the micropores typically found in solvent coated fabrics as a result of the solvent evaporating during processing (Cooley, 2006).

2.7 PIN-HOLE DETECTION

The geomembrane production line should be fitted with an in-line pin-hole detection system. This normally comprises a spark testing bar fitted to the geomembrane production line. This works by holding a charge in the bar at the location where the geomembrane passes over a metal roller. If there are any pin-holes in the geomembrane, then the charge passes through the hole and makes contact with the metal roller to complete a circuit, which sets off an alarm. The spark tester is generally capable of detecting defects or pin-holes less than 0.25 mm in diameter.

2.8 TEXTURING

Texturing is a randomized surface roughness technique intended to enhance friction to prevent geomembrane liners from sliding down slopes. Textured geomembranes have roughened surfaces in order to increase the friction angle in contact with soil or geosynthetic layers. They can also be patterned or embossed with structured profiles to give engineered liners that physically interact and engage with various mating surfaces. The surface of a textured geomembrane significantly increases the interfacial friction with adjacent materials as compared to the same geomembrane with smooth surfaces.

Textured surfaces give increased friction and shear stability for applications on steep slopes.

GEOMEMBRANE MANUFACTURING METHODS

Sliding failures or slope failures with geosynthetic interfaces have been well documented over recent years. Usually these failures have occurred at the geomembrane/geotextile interface or the geomembrane/soil interface. The advent of textured and/or structured geomembranes however have significantly reduced the likelihood of sliding failures.

Textured geomembranes are thus much less prone to sliding on steeper slopes. Moreover, in the case where the textured side faces upward, nor will the material (for example MSW in a landfill) slip on top of the textured geomembrane surface. This however may lead to failure due to high shear forces and high tensile forces being applied to the membrane. In such cases it is important to use a geomembrane with a smooth top surface and so any material on top slides on the liner rather than inducing damaging stresses into the liner.

The friction angle between a textured geomembrane and the soil layer (or a geotextile) is measured by short-term friction tests in the laboratory. Since these tests are relatively short term they only reflect the friction properties of the new sheet. The long-term friction angle (and hence the slope stability) however is dependent on the ability of the texturing particles to sustain shear stress. Accordingly, in order to ensure the friction is maintained at a constant level, the particles at the sheet surface must not yield under the applied shear stress. Slow but steady loss of adhesion of sheet surface particles (ultimately leading to catastrophic loss of stability and slope failure) may occur due to creep, stress cracking and oxidative ageing.

Textured or structured sheet made by flat-die extrusion and embossed calendars have been touted as premium products over the texturing produced by blown film coextrusion processes (see Table 2.4). The latter technique has limitations with respect to variable quality and lower-than-expected asperity height and cross-roll friction values. This has led to some documented slope failures (Sieracke, 2005).

The texturing processes for HDPE differs between manufacturers.

The flat-die extrusion method enables the formation of a textured or embossed surface that does not affect the core thickness. This overcomes some of the limitations associated with blown film coextrusion texturing such as non-uniformity, variable peak height, variable area coverage and reduced mechanical properties. The reduction in

Texturing method	Process description	Comments			
Blown film coextrusion with blowing agent	In-line with primary bonding	Used extensively in North America			
Hot particle impingement	Secondary process with secondary bonding	Resembles small thread-like nodules			
Hot foam laminated	Secondary process with secondary bonding	Not widely used			
Patterned (or structured) roller	In-line with primary bonding	Used extensively in Europe			

Table 2.4	Techniques	used to	produce	textured	geomembranes	to	enhance	their	frictional
properties									

mechanical properties associated with blown film coextrusion texturing is of particular concern in long-term applications where differential settlement (e.g. due to localized settlement) can cause damaging multiaxial (i.e. out-of-plane) stresses to develop.

Geomembrane liners can be textured on either one side or on both sides. In order to prevent soil and other cover materials from slipping along the top of smooth geomembrane sheet, the upper layer can also be textured or structured.

It should be noted however that the interface shear strength of the upper interface should not be higher than that of the lower interface otherwise potentially damaging tensile stresses can be induced in the geomembrane. Such tensile stresses can be particularly detrimental for HDPE liners if residing over the long term, due to likelihood for stress rupture and brittle cracking.

It is very difficult to remove dust from the edges of textured geomembranes. For this reason it is necessary to specify that the geomembrane has a non-textured flat edge for convenient welding.

2.8.1 COEXTRUSION TEXTURING

The blown textured surface is produced using coextrusion processing equipment. The texture can be applied to one or two sides of the liner and is an integral component of a three-layer coextruded geomembrane. Texturing combines the durability of HDPE liners with a roughened surface that provides very good frictional characteristics against a variety of soils and geosynthetic surfaces. This increase in friction helps keep cover soil in place and improves the overall liner stability on slopes.

In the blown film coextrusion texturing method nitrogen gas is injected into the polymer melt and when the extruded polymer exits the die the nitrogen bubbles rupture (see Figures 2.11 and 2.12). As the bubbles of nitrogen gas expand they give a burst bubble effect, producing a roughened textured surface (see Figure 2.13). This method of texturing is however highly variable within a single roll or across the roll width. In addition, it is difficult to standardize this method of texturing as it is highly variable from one manufacturer to another.

Since nitrogen blown texturing occurs in a relatively uncontrolled fashion it is difficult to produce a consistent asperity height across the roll width of the geomembrane. Individual asperity height readings can vary from 0.225 to 0.8 mm (Ivy, 2003).

Blown-film textured geomembranes which have smooth edges are covered by US Patent Nos 5 763 047 and 5 804 112. The blown-film texturing provides increased friction angles for higher stability on steep slope applications while the smooth edges result in easier, more cost-effective, more consistent and better welding.

2.8.2 IMPINGEMENT TEXTURING (ALSO KNOWN AS SPRAY-ON TEXTURING)

Impingement texturing involves a secondary process where granulated LDPE (which has a lower melting point) is dropped (or sprayed) onto the hot surface of an extruded geomembrane. The lower melting point particles fuse to the surface of the HDPE geomembrane as



Figure 2.11 Schematic showing the method for double texturing of polyolefin geomembranes by the nitrogen gas blown film method



Figure 2.12 Schematic showing the mechanism for texturing of blown geomembranes by injecting nitrogen gas into the melt



Figure 2.13 Photograph of a HDPE geomembrane with *nitrogen blown* texturing where a blowing agent (based on nitrogen gas) is injected into the melt during coextrusion manufacture of the GM sheet. The limitations of this type of texturing over other forms of texturing are variable core thickness, non-uniform area coverage, inconsistent asperity heights on the surface and generally reduced tensile, elongational and stress crack resistance

small nodules (Figure 2.14). It is important to note that the minimum thickness of these impingement textured geomembranes remains the same as if the material were smooth sheets.

The polymer used for the textured particles that are deposited on the geomembrane surface should of the same type (i.e. compatible) as the parent geomembrane so that good adhesion is achieved and the texturing is not the weak link.

With impingement texturing care needs to be taken with the distribution of the threadlike particles and the homogeneity of the coverage (see Figure 2.15). The uniformity of the impingement texturing can vary across (and along) the geomembrane roll and this can lead to differences in the frictional properties of the geomembrane.

The surface texturing on geomembranes can vary to the extent that the surface roughness can vary from one location to the next. Significant surface agglomeration of texturing is present if it can be seen as obvious shade variation from a distance of 15 m from the surface being inspected and if the patches are larger than 20 mm in diameter.

The other important factor to consider with impingement texturing is the level of adhesion between the particle and the sheet. Clearly the level of adhesion between the particles and the base sheet needs to exceed the shear forces applied in a shear box test or else the texturing will simply scrape off in service.

It is possible that if the sprayed-on texturing is removed it can leave depressions/nicks on the geomembrane sheet that may be defect sites due to localized reductions in the geomembrane strength and thickness. The angular nature of texturing can cause notches, which are stress concentrators and precursors to cracks.