Review

A review of polymeric geosynthetics used in hazardous waste facilities

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Abstract

The generation of hazardous wastes from various sources including chemical industries, hospitals, households, etc., is a worldwide problem and is particularly acute in the United States. The petrochemical and refinery industries produce about 70% of this waste. Geographically, the greatest production of hazardous wastes is known to occur along the United State Gulf coast. Presently, it is estimated that about 80% of the total waste remains toxic for years or even centuries. Inappropriate disposal of these wastes on land creates the risk of contaminating ground water and vegetation causing adverse health effects. This review addresses the geotechnical aspects of the problems related to the management of hazardous waste by the use of polymeric materials as 'barriers'. Important findings of research efforts on this topic from 1980 through mid-1994 are discussed. The review gives an awareness to the general public and addresses points of interest to field engineers and technologists for the proper handling of wastes by the use of the polymeric geosynthetics acting as membranes or barriers.

1. Introduction

Man has disposed of wastes on or into land since the beginning of recorded history and the form of waste varies depending on location and country. The term 'hazardous waste' has crept into our vocabulary during the past decade and it denotes waste that presents risk to human life and health. Every year, the United States alone generates about 320 billion pounds of municipal solid waste. About 85% of this is currently

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disposed of in landfills. EPA estimates that it will reach 380 billion pounds by 2000 A.D. and a third of the landfills are expected to close in the next five years. Many are concerned that efforts to deal with the growing quantity of garbage are not moving fast enough to keep up with waste generation.

Both organics and inorganic chemicals are found in waste dumps. The organics are the most feared and complex substances that pose a threat to human health and the environment. According to a recent survey [1], industrial organics are the highest class in hazardous waste volume. The technology has been developed to deal with part of the organic wastes by way of incineration which eventually achieves their complete destruction. Since much of the waste organic chemicals have been dumped into landfills, dilution with dirt is such that incineration is often not practicable. Field experience and research activities have indicated that biodegradation plays an important role. For example, hazardous aromatic hydrocarbons are found in many waste dumps and also in leakage from gasoline tanks. These hydrocarbons along with other chemicals can be oxidized in situ to give CO_2 and H_2O by microorganisms. Among the individual organic chemicals most prevalent at Superfund dumps are trichloroethylene, chloroform, tetrachloroethylene and 1,1,1-trichloroethane. However, no organisms have been found that can grow using these substances as the sole energy and carbon sources. In such situations, multi-disciplinary applications of science, engineering and polymer chemistry can be effective.

In practice, the hazards presented by the wastes may be classified as radiological, biological and chemical. The term chemical waste refers to industrial or laboratory chemicals having corrosive, toxic, flammable or explosive properties. Among all the developments in hazardous waste regulation, the restriction on land disposal exerts the most profound and widespread impact on waste management practices. Many industrial wastes are currently disposed off in unregulated landfills and this will continue to grow despite reduction efforts [2] (see Table 1). These landfills have an average useful life of 20 yr. During this time and often for many years (up to 200 yr or so), the chemicals from the wastes may leach into the aquifer below the landfill and be transported away from the landfill site. The same aquifers may serve as a source of drinking water for people living within a few miles of the landfill site. If the concentrations of toxic chemicals in water are below their taste–odor threshold, then people are likely to suffer prolonged exposure to the chemicals by drinking such water [3, 4].

Corrosive chemicals are quite harmful to animal and plant tissue; they dissolve metals and affect plastic materials and ceramics. Once within the landfill, they may react vigorously with other materials producing leachates and gases which may be highly toxic. Toxic chemicals can enter into the human body in four ways: (i) ingestion, (ii) injection, (iii) skin absorption and (iv) inhalation. Of these, the possibility of absorption by skin contact is a potential hazard to those who work on landfills. Safety precautions in the form of protective clothing to the operator are needed in such situations and this hazard can be minimized by a judicious choice of polymeric protective clothing material [5]. A recent survey showed that about 80 organic chemicals may be present in the atmosphere near a landfill [6].

Chemical reactions can also occur when the wastes are mixed haphazardly. Toxic hydrogen sulfide may be produced further increasing the dangers on a landfill.

Table 1
Growth in waste volume from 1977 to 1993 despite reduction efforts [2]

Type of waste	Average annual growth (millions of tons)				% Increase during	
	1977	1988	1993	2000	1977–88	1988–93
Heavy metals	51	114	149	196	7.6	5.5
Organic chemicals	42	100	132	180	8.2	5.7
Petroleum derived	16	33	44	60	6.8	5.9
Inorganic chemicals	17	35	43	55	6.8	4.2
Other hazardous waste	5	9	13	19	5.5	7.6
Total	131	291	380	510	7.5%	5.5%
By method of disposal						
Landfill/surface impound	12	200	225	165	29.1	2.4
Treatment/stabilization	2	13	50	150	18.5	30.9
Incineration	a	15	35	95	—	18.5
Resource recovery	2	12	30	75	17.7	20.1
Deep-well injection	5	14	15	10	9.8	1.4
Illegal disposal	110	35	20	5	− 9.9	− 10.6
Other methods	a	2	5	10	—	20.1

a – negligible

However, these can be minimized by proper management or handling. Some chemicals are reactive with air or water and these should not be land-filled because they are highly flammable. The alkali metals, magnesium, zirconium and titanium can react with water and dilute acids to produce hydrogen. The carbides, sulfides, phosphides, arsenides and selenides are known to react under certain circumstances to form explosive flammable and toxic gases and phosphorus is flammable when exposed to air. Gases and vapors are potential explosives, especially methane.

Polychlorinated biphenyls (PCBs) are another class of hazardous compounds that are widely studied [7]. These compounds are responsible for harmful effects on wildlife even at low concentrations. They are an extremely complex and diverse group of chemicals and it is difficult to determine their potential effects due to low level exposure. Theoretically, over 200 different PCBs exist, which differ in the number and position of chlorine atoms on the basic biphenyl unit. Several possible arrangements of chlorine atoms give rise to a range of chlorinated biphenyls. Different types of PCBs and their typical concentrations in the environment are given in Table 2.

Landfills and surface impoundments will be a fact of life for many years and polymers in various forms and shapes have been developed. Geosynthetics made from polymers have proven to be resistant to environmental and chemical degradation reactions while maintaining their physical, mechanical and chemical properties [8]. The last decade has witnessed a tremendous growth in the development of newer geosynthetic polymers that provide the desired functions necessary for the construction of hazardous waste storage facilities at a lower cost compared to the previously

Table 2
Distribution of PCBs by level of chlorination [7]

Homologue	Molecular formulae	Number of isomers
Monochlorobiphenyl	$C_{12}H_9Cl$	3
Dichlorobiphenyl	$C_{12}H_8Cl_2$	12
Trichlorobiphenyl	$C_{12}H_7Cl_3$	24
Tetrachlorobiphenyl	$C_{12}H_6Cl_4$	42
Pentachlorobiphenyl	$C_{12}H_5Cl_5$	46
Hexachlorobiphenyl	$C_{12}H_4Cl_6$	42
Heptachlorobiphenyl	$C_{12}H_3Cl_7$	24
Octachlorobiphenyl	$C_{12}H_2Cl_8$	12
Nonachlorobiphenyl	$C_{12}HCl_9$	3
Decachlorobiphenyl	$C_{12}Cl_{10}$	1

Medium	Typical concentrations of PCBs in the environment
Air (rural)	$5 \times 10^{-5}\ \mu g\,m^{-3}$
(urban)	$1-5 \times 10^{-3}\ \mu g\,m^{-3}$
Surface soil	$2-50\ \mu g\,kg^{-1}$
Vegetation	$10\ \mu g\,kg^{-1}$
Water	$2 \times 10^{-3}\ \mu g\,l^{-1}$
Man (adipose tissue)	$1\ mg\,kg^{-1}$ (wet weight)
(breast milk)	$10\ \mu g\,l^{-1}$ (wet weight)
Marine mammals (blubber)	$5-50\ mg\,kg^{-1}$ (wet weight)

used natural construction materials [9]. Because of problems with natural liner materials like clays, recent governmental regulations require the use of man-made polymeric geomembrane liners for containment of hazardous waste. Polymers have been selected based on laboratory test data and confirmed by testing under simulated conditions of use. Chemical resistance of a polymeric material is its ability to withstand chemical attack with a minimum change in appearance, dimensional stability, mechanical properties and weight over a period of time.

This review discusses different types of geosynthetic materials that are used as barriers in various underground applications. These include geomembranes, geonets, geogrids, geotextiles and their various combinations. The available representative and important contributions are collected from 1980 through mid-1994. It is beyond the scope of any authoritative review to cover all the published papers giving full details. However, emphasis will be placed on the use of polymeric geosynthetic materials in hazardous waste containment facilities. For more details, the reader is advised to consult the original papers. Results are discussed in relation to their transport characteristics, degradability, serviceability, etc., in the presence of hazardous chemicals. Experimental results from different sources are collected and critically reviewed to clarify the current state-of-the-art development in the use of these materials in hazardous waste containment facilities.

2. Potential geosynthetic materials

Geosynthetics is a generic term which collectively describes geotextiles, geomembranes, geonets, geogrids and geocomposites. The growth and development of geosynthetics has been phenomenal for two major reasons. First, geosynthetics are an economically viable alternative which can perform a wider range of tasks than the conventional construction materials. Secondly, they can be tailored to suit to any application. In some cases, geosynthetics can remedy a situation which would otherwise be impossible to solve by conventional means. The number of geosynthetic materials available today is very large [10]. The choice of a particular geotextile or geomembrane depends upon the chemistry of the hazardous material that is to be retained.

Various types of geosynthetics prepared from thermosetting and thermoplastic polymers have also been used [11]. Among these, thermosetting polymers such as phenol-formaldehyde, melamine-formaldehyde and urea-formaldehyde are resistant to nonpolar solvents, but not to strong oxidants and alkalis. Thermosetting silicone resins have good solvent resistance, but are attacked by strong acids and alkalis. Epoxy resins resist weak acids, alkalis and hydrocarbons, but are attacked by strong acids and nonpolar solvents. Thermosetting elastomers resist aqueous salt solutions, alkalis, moisture and nonoxidizing acids. They are resistant to mineral and vegetable oils, jet fuel and gasoline. Good chemical resistance is shown by polychloroprene, chlorosulfonated polyethylene and polysulfide rubber [12]. Of the widely used thermosetting elastomers, nitrile rubbers have the best chemical resistance to oils, solvents, alkalis and aqueous salt solutions [13]. Chloroelastomers like chlorofluoroethylene, vinylidene chloride, polyvinylidene fluoride, etc., exhibit excellent resistance to strong acids, alkalis, aqueous salt solutions, dilute mineral acids, etc. [13]. Permeability of these membranes to various gases, water vapor, salt solutions and chemical species has also been studied.

For many applications polypropylene has been the material of choice; however, it will degrade when exposed to direct sunlight. Efforts have been made to get around the UV-exposure problems [14]. One approach has been to use blends of carbon black and UV stabilizers to make the polymer highly resistant. Thermoplastic polymers like polyvinyl alcohol, polycarbonate, polyacrylonitrile, polybutadiene, polystyrene, etc., have also been used [15]. Nylons have good solvent resistance, but are attacked by strong mineral acids, oxidizing agents and some salts. Unplasticized polyvinyl chloride (PVC), the second largest volume of thermoplastics, exhibits a good chemical resistance and is widely used in chemical processing equipment. However, PVC which resists alkalis, salt solutions, oxidizing acids and mineral acids, is attacked by organic acids like acetic acid. Polyvinylidene fluoride (PVDF) (Kynar) is used for chemical equipment linings. It resists most acids, but not fuming sulfuric and chlorosulfonic acids. Its resistance to inorganic bases is excellent up to 120 °C. It is also resistant to halogens, oxidizing acids and inorganic salts. The general chemical resistance data of some widely used geomembranes collected from different sources are given in Table 3.

Table 3
Some typical chemical resistivity data of geomembranes [12, 15]

Chemical	Geomembrane							
	IIR	CPE	CSM	ECO	EPDM	CR	PE	PVC
Aliphatic hydrocarbons	p	g	p	g	p	g	g	p
Aromatic hydrocarbons	p	p	p	g	p	g	g	p
Chlorinated solvents	g	p	p	g	g	g	g	p
Oxygenated solvents	g	p	p	g	g	g	g	p
Crude petroleum solvents	p	g	p	g	p	g	g	p
Alcohols	g	g	p	g	g	g	g	g
Organic acids	g	g	g	g	g	g	g	p
Inorganic acids	g	g	g	g	g	g	g	g
Organic bases	g	g	g	g	g	g	g	g
Inorganic bases	g	g	g	g	g	g	g	g
Heavy metals	g	g	g	g	g	g	g	g
Salts	g	g	g	g	g	g	g	g

p – poor, g – generally good resistance. IIR – Butyl rubber, CPE – Chlorinated polyethylene, CSM – Chlorosulfonated polyethylene (Hypalon), ECO – Epichlorohydrin, EPDM – Ethylene propylene diene monomer, CR – Polychloroprene (neoprene), PE – Polyethylene, PVC – Polyvinyl chloride.

3. Classification of geosynthetic materials

3.1. Geotextiles

Geotextiles comprise the largest group of geosynthetics and their use in the past decade has been growing rapidly. These are textile materials in a traditional sense, but consist of synthetic polymer fibers rather than natural materials like cotton, wool and silk. Thus, biodegradation is not a problem. The fibers are made into a flexible porous fabric by standard weighing machinery or are matted together in a random or nonwoven manner; some are also knit. They are porous to water flow across their manufactured plane and also with their plane, but to a widely varying degree. There are at least 80 specific application areas of geotextiles and the fabric performs at least one of five functions: (i) moisture barrier (when impregnated), (ii) separation, (iii) filtration, (iv) drainage and (v) reinforcement.

Fibers used in geotextiles are made predominantly from polyethylene, polypropylene, polyethylene terephthalate and polyamide. Some typical properties of these polymer fibers used in the construction of geotextiles [16, 17] are given in Table 4. The polymers are formed into fibers by a melt spinning process. The resulting filaments are solidified by cooling and the fibers are stretched or drawn. The drawing increases the fiber strength as the polymer segments in the fiber align themselves in a more orderly fashion and subsequently crystallize. The fiber bundles are formed into mono-filament yarn and then processed. Unlike mono- or multifilament staple, fibers are formed by chopping into continuous lengths of 1–4 in to form a rope-like bundle called a tow. These staple fibers are then twisted or spun into yarns for subsequent fabric

Table 4
Some physical properties of synthetic polymer fibers [16, 17]

Fiber	Breaking tenacity (g/denier)		Specific gravity	Standard moisture uptake (g/g)
	Standard	Wet		
Nylon-66				
Regular tenacity filament	3.0–6.0	2.6–5.4	1.14	4.0–4.5
High tenacity filament	6.0–9.5	5.0–8.0	1.14	4.0–4.5
Staple	3.5–7.2	3.2–6.5	1.14	4.0–4.5
Filament	6.0–9.5	5.0–8.0	1.14	4.5
Nylon-6				
Staple	2.5	2.0	1.14	4.5
Polypropylene				
Filament and staple	4.8–7.0	4.8–7.0	0.91	3.0
Polyester				
Regular tenacity filament	4.0–5.0	4.0–5.0	1.22	0.4
High tenacity filament	6.3–9.5	6.2–9.4	1.22	0.4
Regular tenacity staple	2.5–5.0	2.5–5.0	1.22	0.4
High tenacity staple	5.0–6.5	5.0–6.4	1.22	0.4

manufacture. However, slit film fibers are made from a continuous polymer sheet and then cut. The resulting ribbon-like slit film fibers are then converted into geotextile fabrics [9]. The finished fibers are then made into fabrics that may be woven, nonwoven or knit. Fabrics are woven on conventional weaving machines to produce a wide diversity of fabric weaves [18]. These variations have a major influence on the physical, mechanical and hydraulic properties of the resulting geotextiles. The degree of porosity of the material which may vary widely is used to determine the applications of the specific fabrics.

3.2. Geogrids

Geogrids represent a small and rapidly growing geosynthetics area. These are the plastics formed into a very open net-like configuration. They are often stretched in one or two directions for improved physical properties. Geogrids serve in at least 25 different applications, but they are mainly used in separation and reinforcement studies. Geogrids are produced mainly by two methods: (i) Deformed grids are hardened after extrusion to enhance their physical properties. This type is found in separation and reinforcement applications. (ii) Polymeric strips are joined in a grid-like pattern, bonded and joined at the intersections. This type is also used in reinforcement applications. However, geogrids are commonly used in geocomposite systems [19, 20].

3.3. Geonets

Geonets, unlike geotextiles, are relatively stiff net-like materials with large open space of about 0.9–5.0 cm between the structural ribs and serve primarily in drainage. Geonets are generally extruded and have three-dimensional network structures [19, 20]. Although structural stability is afforded in many applications, geonets may cause considerable instability on side slopes. Nondeformed nets are used as a core material to provide planar flow in drainage systems. Geonets are commonly used as components in geocomposite applications for drainage and reinforcement.

3.4. Geomembranes

Geomembranes represent the second largest group of geosynthetics. The materials themselves are impervious thin sheets of polymer used primarily for lining and covers. The primary function is always as a liquid or vapor barrier. The range of applications is quite large and at least 30 individual applications in civil engineering have been developed. The geomembrane materials come from the category of both thermosetting and thermoplastic polymers. Some synthetic rubbers other than natural rubber are also used as geomembranes. The original geomembrane used as a pond liner was butyl rubber which is a copolymer of isobutylene with approximately 2% isoprene.

For seepage containment liners the competing material is often bentonite clay having a permeability of about 10^{-8} cm^2 s^{-1}. By contrast, the permeability of a rubber geomembrane is approximately 10^{-11}–10^{-13} cm^2 s^{-1}. Thus, it is impermeable. Geomembranes are used in a variety of areas as a liner for: (i) potable water and reserve water, (ii) waste liquids (acidic and basic), (iii) low level radioactive wastes, (iv) solar ponds and (v) brine solutions in addition to primary, secondary and/or tertiary hazardous waste landfills. They are also used as floating reservoirs for seepage control and floating reservoir covers to prevent pollution in addition to controlling odors in landfills, etc.

The three tests that are commonly performed on geomembranes used in landfill liner applications are: (i) conformance testing, which demonstrates the specifications of the material to be met for a solid waste facility; (ii) chemical compatibility testing, which determines whether the geomembrane is compatible with the leachate generated and (iii) quality assurance/quality control testing, which assures that the installation of the liner meets all the specifications and regulatory requirements. Table 5 summarizes the major types of polymers used in geomembranes applications [21]. The major properties of these geomembranes are summarized [22] in Table 6. Of these, polypropylene (PP) is highly resistant to most organic chemicals and hence, about 80% of the geosynthetics are made from polypropylene.

3.5. Geocomposites

Geocomposites consist of a combinations of geotextiles and geogrids, or geogrids and geomembranes, or geotextile–geogrids and geomembranes, or any one of the three materials with other supporting material such as soil, styrofoam, deformed

Table 5
Major types of geomembranes used currently [21]

Thermoplastic polymers
Polyvinyl chloride (PVC), Polyethylenes (PE), Chlorinated polyethylene (CPE), Elasticized polyolefin (3110), Polyamides (nylons)

Thermoset polymers
Isoprene-isobutylene (butyl), Epichlorohydrin rubber, Ethylene propylene diene monomer (EPDM), Poly-chloroprene (neoprene), Ethylene propylene terpolymer (EPT), Ethylene vinyl acetate (EVA)

Combinations
PVC-nitrile rubber, PE-EPDM, PVC-ethyl vinyl acetate, Cross linked CPE, Chlorosulfonated polyethy-lene (CSM), also called "Hypalon"

Table 6
Some major properties of geomembranes and their typical values [22]

Category and property	Approximate range of values
Physical	
Thickness	0.25–2.5 mm
Specific gravity	0.9–1.5
Weight (mass per unit area)	600–3000 g/m^2
Water vapour transmission	1–10 g/m^2 24 h
Mechanical	
Tensile strength at yield	
Unreinforced	1.5 kg/cm^2
Reinforced	5–20 kg/cm^2
Tensile strength at break	
Unreinforced	1–5 kg/cm^2
Reinforced	2–6 kg/cm^2
Elongation at break	
Unreinforced	100–500%
Reinforced	71–250%
Modulus of elasticity	
Unreinforced	35.7–204 kg/cm^2
Reinforced	357–1428 kg/cm^2
Tear resistance	
Unreinforced	2–15 kg
Reinforced	10–50 kg
Impact resistance	
Unreinforced	0.05–2 kg m
Reinforced	2–7 kg m
Puncture resistance	
Unreinforced	5–50 kg
Reinforced	25–250 kg
Soil to linear friction (% of soil friction)	50–100%
Seam strength (% of liner strength)	50–100%

plastic sheets, steel cables, steel anchors, etc. The application areas of these materials are numerous and the major ones are in: (i) separation, (ii) filtration, (iii) drainage, (iv) moisture barrier and (v) reinforcement. Geocomposites are better than some of the other individual geosynthetics. Different geocomposites have been developed for a variety of applications and these are discussed below.

3.5.1. Geotextile–geogrid composites

Separation and filtration are greatly improved when a geotextile sandwich is used over and below a geogrid. These sandwich geocomposites function as barriers and drainage interceptors. When placed horizontally, they make excellent barriers to upward moving water in a capillary zone where salt migration is a problem. When water enters the sandwich, it travels horizontally within the geogrid. They are also used in trapping leachates in landfills and in conducting gases from beneath the geomembrane liners.

3.5.2. Geotextile–geomembrane composites

Geotextiles are laminated on one or both sides of a geomembrane. In the reinforced area, geotextiles provide increased resistance to puncture, tear propagation and friction related to sliding as well as tensile strength. These are nonwoven and relatively heavy-weight fabrics. When the geomembrane is in the form of a quasi-rigid plastic sheet, it can be extruded and deformed in such a way as to transport large quantities of water within it. It is, however, protected by geotextile acting as a filter on both sides. Many such systems are available. The rigid geomembrane can be formed in an egg carton shape (usually of polyethylene or polystyrene) and the geotextile on one side makes an excellent drain for basement walls. The geotextile acts as a filter and the deformed geomembrane is the drain. Many such systems are available which are made from stiff nylon filaments.

3.5.3. Geomembrane–geogrid composites

For the reason that some of the geomembranes and geogrids are made from the same material, namely high density polyethylene (HDPE), they can be joined together to form an impervious barrier with improved strength and frictional resistance. A geomembrane–geogrid–geomembrane sandwich can also be made where the interior geogrid acts as a drain in the form of a leak detection system.

3.5.4. Miscellaneous geocomposites

The use of geocomposites is increasing in recent years. Efforts have been made to weave steel strands within a geotextile matrix to give incredible strength. Some open graded styrofoam beads have also been sandwiched between geotextiles as filters in geomembranes, as vapor barriers for drainage materials behind basement walls and as earth sheltered homes. Here, the styrofoam acts as the drain, but has the added advantage of an effective insulator. Geotextiles with prefabricated holes for the insertion of steel rod anchors have also been used. The rods act as anchors, stressing the geotextile against the soil, which is put into compression. The geotextile thus acts as a tensile stressing mechanism and as a filter allowing the pore water to escape while retaining the individual soil particles.

4. Design and test methods for geosynthetics

The designing of specific geosynthetic materials for any particular application should be done by considering at least three aspects: (i) design by cost, (ii) design by specification and (iii) design by function. The design by cost is simple, i.e., one can take the funds available, divide by the area to be covered and calculate the maximum allowable geotextile unit price. The fabric is selected within this price limit. Geosynthetic design by specification is very common and is used almost exclusively in dealing with public agencies. In this method, several categories of use are listed together with critical fabric properties and those geosynthetics available are then checked for their properties vs. the recommended values. If several geosynthetics are adequate, then the choice is usually made on the basis of availability and cost. The design by function consists in assessing the primary function for which the geosynthetic will be used and then to calculate the required numerical value of that particular property. By dividing this value into the candidate geosynthetic's actual property value, a factor of safety will result and a geotextile is acceptable based on the value of the safety factor.

A variety of different test methods are used for the evaluation of geosynthetics and a unified document on geosynthetic test methods is not available. The tests have been subdivided into the following categories of properties: (i) physical, (ii) mechanical, (iii) hydraulic, (iv) endurance, (v) chemical resistance and (vi) environmental. It may be noted that no standard test method exists for analyzing the durability of geosynthetics other than geomembranes, under different chemical exposure conditions. Several methods have been adapted by ASTM for the individual geosynthetics. The stability of geosynthetics has been assessed on the basis of mechanical property test results, but not on the microstructural changes that alter its mechanical properties. To examine the molecular structure of geosynthetics several analytical techniques have been used.

A good coverage on geosynthetic test methods is given elsewhere [9]. Two important physical property tests involve specific gravity and thickness. Mechanical property test methods determining compressibility, tensile strength, fatigue strength, burst strength, tear tests, impact tests, puncture tests and soil-to-fabric friction are highly relevant. The environmental property test methods are used to recognize the potential problems and limitations of using polymeric fabrics. These tests will be covered under separate headings.

4.1. Resistance to chemicals

The ASTM D453 test method, under the title 'resistance of plastics to chemical reagents', includes reporting changes in weight, dimensions, appearance and strength properties. Provisions are also made for various exposure times with different reagents at elevated temperatures. A list of 50 standard reagents is supplied in order to attempt some sort of standardization. For instance, Du Pont has evaluated most of its fibers (dacron, nylon, orlon, rayon, cotton, wool, silk, etc.) with a wide range of chemicals (sulfuric acid, hydrochloric acid, nitric acid, hydrofluoric acid, phosphoric acid, organic acids, sodium hydroxide, bleaching agents, salt solutions, organic and several

other miscellaneous chemicals) at different concentrations and temperatures. After the specified exposure, the samples were rinsed, air dried and conditioned at 70 °F and 65% relative humidity for 16 h. Data on breaking strength, breaking elongation and toughness of the exposed fibers were compared with the control specimens of the fibers that were not exposed to the chemicals. Similar information is available from most raw material suppliers and fabric manufacturers.

4.2. Resistance to temperature

The ASTM D794 method describes high-temperature testing of polymers depending upon the potential end use. In this method, heat is applied using an oven with controlled air flow allowing substantial fresh air. Two types of tests are described: (i) continuous heat and (ii) cyclic heat. In the former method, heat is gradually increased until failure occurs. Failure is usually defined as a change in appearance, weight or dimension so that the material loses its properties. The test time may vary from minutes to weeks depending on the rate at which temperature increases. The cyclic heat test repeatedly applies heat until failure. The method also addresses the effect of cold temperatures on polymers and, in particular, its brittleness and impact strength. At various temperatures, specimens are tested by a specified impact device in a cantilever beam test mode.

4.3. Resistance to light and weather

The ASTM D1435 test method is used to assess the conditions for the exposure of polymers to weather. The method is only a comparative test depending on climate, time of the year, atmospheric conditions, etc., and gives only an indication of a material's long-term durability.

5. Fundamentals of transport phenomenon of liquids into geomembranes

The molecular transport of a liquid into a dense polymeric geomembrane is described in terms of permeability, diffusivity and solubility coefficients. Permeability is the product of diffusion and solubility [23]. Even though polymeric geomembranes are manufactured as solid homogeneous nonporous materials, they contain free volume spaces through which small molecules transport. Molecular transport takes place by an activated diffusion involving three steps: (i) Solubility or sorption of the liquid at the upstream surface of the geomembrane. Here, transport depends upon the solubility of the permeating species in the geomembrane and the relative chemical potential of the liquid on both sides of the interface. (ii) Diffusion of the dissolved species through the geomembrane. Here, diffusion through geomembrane involves factors such as size and shape of the permeating molecules in addition to structural characteristics of the polymer and the geomembrane-solvent interactions. (iii) Evaporation or desorption of the liquid at the downstream surface of the geomembrane. Step (iii) is similar to (i) and depends upon the relative chemical potential of the

permeant on both sides of the interface at the downstream surface. A comparison of various geomembranes to several organics has been made by Haxo [13].

The property that might result in a good gas barrier very often also results in a poor water barrier and is dependent on the polarity of the polymer. Highly polar polymers, e.g., those containing hydroxyl groups such as polyvinyl alcohol or cellophane are excellent gas barriers, but exhibit poor water permeability. In addition, they become poor gas barriers when plasticized by water. Conversely, nonpolar hydrocarbon polymers (e.g., polyethylenes) have excellent water barrier properties, but at the same time exhibit poor gas barrier properties. In order to be a truly good barrier polymer, it should possess: (i) some degree of polarity such as contributed by the nitrile, ester, chlorine, fluorine or acrylic functional groups; (ii) high chain stiffness; (iii) inertness; (iv) close chain-to-chain packing by symmetry, order, crystallinity or orientation; (v) some bonding or attraction between chains and (vi) high glass transition temperature, T_g. Therefore, permeation rate is a function of many parameters.

Additives, such as impact modifiers or plasticizers, usually increase the permeation rates considerably, depending on the polymer type and the amount added. Many polymers, specifically those containing highly polar sites, absorb moisture from the atmosphere quite rapidly. If water swells or plasticizes the polymer chains, the gas barrier properties will be reduced. The equilibrium permeation rates of liquids into polymers follow the Arrhenius relationship with temperature, i.e., $P = P_0 \exp[-E_p/RT]$, where P_0 is a constant for the given permeant–polymer system, E_p is the energy of activation for the process of permeation which normally ranges from 12 to 130 kJ/mol depending on the polymer–liquid system, R is the gas constant and T is the temperature. Generally, gas permeation increases by 30–50% for every increase of 5 °C, whereas, water permeation increases by 10–100% for every 5 °C rise in temperature. Permeation rates are normally given on a per unit thickness basis. Extrapolation and prediction of thicker or thinner films than those measured can be erroneous if permeation vs. thickness slope deviates from a value of unity.

The molecular structure of the permeating gas or liquid is also an important factor. Liquid permeation depends on: (i) molecular size of the liquid, i.e., small molecules like pentane permeate more rapidly than large molecules like decane; (ii) molecular shape, i.e., streamlined shapes such as p-xylene which permeate more rapidly than the bulky shaped molecule like o-xylene and (iii) polarity of the liquid, i.e., nonpolar molecules like toluene permeate more rapidly than the polar aniline in nonpolar polymers. The latter effect is reversed in the case of polar polymers. The permeability of polymers is determined by many structural and morphological properties of both the polymer matrix and the permeating species. Purely theoretical attempts to correlate any or all of these properties with gas or liquid permeation have not been entirely successful.

Organic liquid permeation is usually measured by using a filled molded container made of the test polymer and noting the gravimetric weight loss [24]. Wide variations of this method have been published in the literature [25, 26]. While measuring gas or liquid permeation, it is necessary to allow the time for attainment of an equilibrium, otherwise erroneous values will be obtained. The time involved in reaching the equilibrium conditions will also vary with the test methods, type of polymer, its thickness and experimental temperature.

6. Geomembrane separation processes

In the handling of landfill hazardous wastes, thin semipermeable polymer films have been used to separate the dissolved species from aqueous solutions in addition to production of process and/or drinking water from sea and/or natural brine solutions [27, 28]. Membranes have also been adopted for commercial separations and concentration of products such as catalysts and recyclable intermediates [29, 30]. Hazardous waste water coming from industrial landfill leachates, lagoon wastes, pesticide wastes and synthetic organic manufacturing effluents have been successfully renovated by using a reverse osmosis system [31]. Moderate and high strength industrial landfill leachates, pretreated by physical and chemical methods and treated biologically, were separated and concentrated in semibatch, steady state and unsteady state modes of operations. Physical/chemical pretreatment with lime was found to be necessary to remove the suspended and colloidal solutions containing heavy metals in the raw leachate. These constituents can cause membrane fouling and rapid flux loss. Lagoon sludge extracts resembling industrial landfill leachate were also treated with a reverse osmosis [32] and ultrafiltration [33] techniques.

7. Discussion of literature results

The potential service life of geosynthetics is of importance when municipal solid waste and hazardous waste landfills are lined with these materials. Because the regulatory agencies and design engineers need to know more about the aging characteristics and the potential service life of polymeric products, it is necessary to review the current state of knowledge about the flexible membrane liners (FMLs) and other polymeric materials used in such environments. Published data on geosynthetics is vast and wide-spread. The period between 1985 to 1990 was extremely active. While it is extremely difficult to compare the published results from different laboratories, efforts have been made to give a representative coverage on the type of geosynthetics used in hazardous waste containment facilities for the period 1980 through mid-1994. While many polymers are used as FMLs, the choice is narrowed when harsh liquids or complex leachates are to be contained. Organic solvents, phenols and a host of other chemicals are reactive to most polymers with the possible exception of polyethylene.

Over the last decade, there has been a great swing from rubber to polyethylene for use as a basic raw material for linings used in the hazardous waste industry due to its superior overall chemical resistance, high strength and low cost. There have been continuous developments and improvements in polymer structure. These include linear low-density polyethylene (LLDPE), which has good stress resistance and an improvement in flexibility and welding with a sacrifice of strength and resistance to hydrocarbons when compared to high-density polyethylene (HDPE). Ultra linear low-density polyethylene (ULLDPE), an improvement on LLDPE, is almost a rubber-like flexible product. HDPE copolymers or combinations with the above materials or rubber based materials, which are aimed at maintaining HDPE's overall chemical resistance, offer improved stress crack and flexibility. HDPE is resistant to

a large number of chemicals including most inorganic and organic acids and salts, but is only mildly attacked by some organic solvents. This material also has a greater tensile strength and elongation at break than other lining products.

One of the major reasons polyethylene being widely accepted as a material for manufacturing geomembrane liners for hazardous waste landfills in the United States is that it is envisaged as a ductile material that will readily conform to the subgrade without breaking. Even after 20 years, some of the HDPE liners are still in working conditions. Various aspects of these problems in relation to HDPE production, installation and testing have been performed by Coulson [34]. In the next sections, we shall discuss the available research results under two main headings, viz., geomembranes and geotextiles. Some miscellaneous type geocomposites will also be covered separately.

7.1. Geomembranes

A variety of polymeric geomembranes have been used for different landfill applications. In a study by August [35], a method was developed to determine the residual permeability of geomembrane liners for landfill applications. This method was based on the permeation cell evaluation with dilute aqueous solutions and landfill leachates. Examples of the application of the method were also discussed. The materials for landfill sealers involving chemical ground impoundment by the addition of bentonite and the testing of sealers were described [36]. Of the synthetic sealers, HDPE was found to be suitable for base sealing of the landfills. A combined sealer based on sealer channels on a mineral sealer layer was also suggested. In the proposed sealing system, a small amount of the permeating seal channels were adsorbed on the mineral layer. In a study by Friesecke [37], some specifications for geomembrane landfill liners were described in relation to physical and chemical resistance of the polymeric liners. Schluetter [38] made some useful suggestions about the proper installation of plastic landfill liners under varied weathering conditions. By using suitable polymer liners in landfills, it was possible to install the leachates and water-resistant liners and at the same time, attain the highest possible safety.

Several articles have appeared on the application of geomembranes in waste containment facilities [39–48], but a complete coverage of all types of geomembranes was not given in any of these papers. In these studies, a discussion was made on the development of geotextiles, geomembranes and geogrids from polymers for strengthening and stabilization of ground during construction. A discussion was also made on collection/detection/monitoring systems for use in waste facilities. The properties and test methods for geosynthetics have been covered. The failure of geomembranes due to oxidative photodegradation, biodegradation, radiation, mechanical or chemical degradations has been discussed. Brittle fracture, including various forms of stress cracking, fatigue and slow crack growth in polyethylene (PE) geomembranes have been studied. To minimize brittle cracking failures, factors such as thermal contraction stress, residual stresses in seams, mechanical damage to the geomembrane, synergism of chemicals and stresses need to be evaluated. Chemical additives to retard such degradation have also been discussed. Different test methods to measure liquid

permeation through geomembranes in complex mixtures of waste liquids were presented along with the specific test methods.

Several papers have appeared on liner compatibility and polymer degradation [49–53]. Harrocks and D'Souza [51] studied different types of degradation processes under different environmental conditions for several major geomembranes and geotextiles. Lord and Halse [54] studied the potential degradation processes in polymeric liners during service in the natural gas pipeline area and identified factors which cause polymer degradation. Cadawallader [55] discussed different factors involved in accelerated aging. He also studied the degradation mechanisms of HDPE liners under the influence of heat, UV light, high energy radiation, environmental stress, biological organisms, chemicals and oxygen. Degradation occurred mainly due to the rupture of the primary and secondary chemical bonds in the HDPE chains.

In a recent study by Dudzik et al. [56], the chemical compatibility testing of HDPE geomembranes and PVC piping materials showed no material degradation caused by exposure to leachate, thereby making it suitable for use as landfill liners and leachate collection pipes. In another study by Dudzik and Tisinger [57], the chemical compatibility of HDPE geomembranes exposed to industrial waste leachates for up to one year has been evaluated using EPA test method 9090. The leachates tested were dissolved metals and salts. The infrared results indicated that organic constituents of the leachates were not significantly absorbed into the geomembrane and no degradation of the geomembrane occurred. Various mechanical, physical and microstructural properties were monitored after 30, 60, 90, 120 and 365 days of exposure in the laboratory and after 120 and 365 days in the sump. Comparison of the tensile property data among the laboratory and sump exposed samples showed considerable similarity. Variability in the geomembranes tested was evident.

Fundamental aspects on chemical degradation of geomembranes have been covered by Lord and Koerner [58]. Degradation was tested by water vapor transmission, radioactive tracer transmission, water and water vapor sorption studies. Diffusion parameters were evaluated and discussed in terms of the possible degradation reactions. The UV-stabilized polyethylene membranes to be used as liners for landfills were studied by Schmidt et al. [59]. Membranes collected from old installation sites did not show significant degradation in physical properties. The effects of film thickness, UV light, ambient temperature and microbial attack on flexible PVC films have been studied [60]. Solutions were suggested for embrittlement problems in terms of the plasticizer choice and plasticizer stabilization. A rationale was developed for the use of plasticized PVC as an exposed geomembrane. Doyle and Baker [61] conducted weathering exposure tests on five geomembranes for waste impoundments and secondary containment of storage tanks. The five membranes tested were: HDPE, Du Pont's Hytrel (a polyester elastomer), a urethane coated polyester, an oil-resistant chlorinated polyethylene and an oil-resistant grade PVC. After two years, HDPE and Du Pont Hytrel were unaffected, but a polyurethane coated polyester showed signs of moderate degradation and chlorinated HDPE and oil-resistant PVC was severely degraded.

Bellen and Corry [62] immersed six geomembrane types in 20 chemical solutions for up to two years. Physical and mechanical properties were measured after exposure

and compared to as-received values to determine any degradative effects. Lord et al. [63, 64], in order to determine the degradation effects by comparing as-received with the exposed property values, exposed (on one side) a number of geomembranes to various chemicals and measured the mass transfer properties (permeability and diffusion coefficients) for exposure time up to 15 months. No stress was applied during the chemical exposure. A study concerning the effect of chemical exposure on seams was also performed [65]. Smith and Parker [66] studied the geochemical testing under different small stresses and found no significant effects with regard to stress/chemical synergism. Other aspects on the development of geosynthetics for landfill applications have been addressed by a number of authors [67–71].

Geomembranes have been used in uranium mill ponds [72]. The technology for uranium mill ponds using HDPE and PVC geomembranes has been developed [73] and the liner performance was analyzed for impoundments containing leachate at active uranium mills. No cases of contaminated groundwater from uranium mill ponds lined with polyethylene geomembrane were reported. In another study [74], HDPE and PVC geomembranes were aged under conditions closely approximating those of uranium mill tailing ponds with acidic leachates. No degradation reactions were detected for HDPE, but PVC geomembranes showed some chemical reactions. The percentage elongation of geomembranes declined at higher temperatures, while other physical properties did not change.

The selection criteria based on the chemical compatibility of geomembranes to be used in ponds at uranium mill operations have been discussed by Mitchell and Cuello [75]. The principal criteria of a geomembrane for this application were specified service life and low permeability. Chemical compatibility with the wastes was also essential in meeting these criteria. In two different types of aging tests using the simulated acidic uranium mill waste, chemical degradation was examined for HDPE, PVC and chlorosulfonated polyethylene geomembranes. Small differences in any of the geomembrane formulation or the waste composition resulted in large differences in their performance characteristics.

In a recent study, the regulatory licensing requirements for the disposal of the radioactive low-level wastes and the uranium mill tailings and the need for long-term stability have been discussed [76]. Examples are given for the use of geosynthetics in waste cover systems and as liners for typical radioactive waste disposal facilities that include a tumulus design, leachate collection system, below-ground vaults and disposal sites. The use of HDPE for the radioactive waste container was also discussed. The regulatory considerations for assessing the use of geosynthetics in waste cover system as liners and as waste containers have been studied with reference to meeting the long-term stability requirements. In recognition of the limited database available on the in-service performance record of geosynthetics, suggestions have been made to address the important design and construction considerations.

In an attempt to investigate the strength and durability of the presently available seaming systems, 37 combinations of reinforced and nonreinforced polymeric sheets joined by various seaming methods were subjected to chemical solutions, brine and water immersion, freeze/thaw cycling, wet/drying cycling, heat aging and accelerated outdoor aging [77]. Polymer sheets used in this study included HDPE, LLDPE,

EPDM, PVC, CPE and Hypalon. The chemicals were chosen to represent a wide range of groups including organic and inorganic acids and bases, halogenated hydrocarbons, ketones and aldehydes. Evaluation was done before and after mechanical testing of the seams (dynamic load in shear and peel, and static dead load) using gas chromatography. The results presented were recommended for use by the field engineers, geomembrane fabricators and other regulatory agencies. The regulations governing the disposal of phosphogypsum, the properties of geomembranes and the case histories in which phosphogypsum was deposited either in a neutralized state or on geomembrane liners have been discussed with reference to groundwater pollution prevention [78]. Polymers used in this study were: LDPE, HDPE, elastomeric polyolefin blend, PVC and butyl rubber.

Ethylene–vinyl acetate (40%)–vinyl chloride graft copolymeric geomembranes were prepared by the suspension polymerization technique [79]. These membranes showed the desired physical properties and weatherability with good chemical resistivity for strong acids and alkalis. These are also resistant to biological attack. The membranes were processed using conventional thermoplastic processing equipment. In situ construction of seamless geomembranes by spraying the elastomeric materials over a suitable geotextile has been the subject of a study by Meader [80]. Typical applications included pond liners for holding fresh or salt water, treated sewage, boiler wash, municipal and industrial wastes and mine tailings.

A double HDPE lining system was designed, installed and put into operation by Giroud and Stone [81]. The double liner concept and the associated drainage systems were discussed in detail. Theoretical analyses were performed to anticipate the mechanical behavior of the liner. Laboratory tests, which simulated the expected stresses on the liner complemented the results of the theoretical analyses. Leakage monitoring systems including underwater inspections and repairs of the HDPE geomembrane liners have been described [82]. The stress concentrations at the geomembrane thickness discontinuities were primary causes of the observed failures. Although the reservoir continues successful operation, long-term leakage monitoring and contingency procedures are necessary to avoid damage to the lining system.

Experience with double liners at solid waste landfills in the United States dates back to the late 1970s. Regulatory agencies both at the State and Federal levels are now mandating that landfills must have primary and secondary liner systems designed to prevent migration of the pollutants into adjacent soil and surface water during their active lives. Primary liners should be at least 0.76 mm (30 mil) thick flexible synthetic membranes protected by 30 cm (12 in) minimum sand layers both above and below the liners. The lower sand layer should contain a perforated discharge pipe to serve as a leak detection system. Secondary liners at the bottom of the landfill are preferably two component systems: a flexible polymer membrane 0.76 cm (30 mil) thick over the top of 90 cm (36 in) of a low permeability soil. Table 7 summarizes the ratings of flexible membranes used in such applications [83]. Regulatory action, liner technology, liner selection, quality assurance/quality control and the performance of double liner installations for landfills were also discussed.

The function of FMLs was to contain waste and leachates. The FMLs based on synthetic polymers showed degradation and permeation to contained fluids [84].

Table 7
Flexible membrane liner ratings [83]

Exposure	FML					
	PVC	CPE	Hypalon	EPDM	Neoprene	Butyl
Exposed liner	NR	R	RR	R	R	R
Exposed side slope liner	NR	RR	RR	RR	RR	RR
Buried liners	R	R	RR	R	R	R
Acid resistance (pH = 2–7)	R	R	RR	R	R	R
Alkali resistance (pH > 7)	NR	R	RR	R	R	R
Domestic waste	R	R	RR	R	R	R
Petroleum products	NR	R	NR	NR	R	NR

R – recommended, RR – recomended only with reinforcement, NR – not recommended.

Information on the chemical resistance of FMLs was collected from vendors and technical publications and compiled into a database; criteria for assessing the useful information were developed. On the basis of these criteria, FML ratings were developed for each chemical/geomembrane system for which data were available. Mass spectrometry was used to study the changes in the composition of the PVC and chlorinated polyethylene geomembranes after field exposures [85]. The analytical techniques used in the chemical composition of the plasticizers in PVC were also discussed.

Polyethylenes possess many properties such as chemical resistance and environmental stress crack resistance (ESCR) that make them useful as geomembranes or liners for hazardous waste landfills [86]. The medium-density linear polyethylene (MDLPE) has been the preferred material due to an excellent balance between chemical resistance and ESCR. The chemical resistance and permeability of MDLPE were evaluated. Testing of the HDPE sheets and seams using a modified form of ASTM D2552 method showed that the sheets could resist stress cracking better than the seams [87]. About 40% of the seamed specimens showed cracking, whereas only 1% of the sheet specimens cracked. The cracks which appeared in the seamed specimens were almost always initiated near the overlapping junction of the two geomembrane sheets where the stress concentration was probably highest. The cracks which were preceded by crazes propagated in a direction perpendicular to the applied stress. SEM photographs indicated that the fracture morphology of the surfaces is a function of the applied stress level. Five types of morphologies were identified: short fibrous, long fibrous, flake, hackle and lamellar. These were used for comparing the failures in long-term laboratory tests, large-scale laboratory tests and in the field to study stress cracking and the conditions under which it occurs.

Polyethylene in geomembrane form is generally considered to be a ductile material that will only fail at an elongation of 700% or more after yielding at an elongation of approximately 13%. However, in the natural gas distribution pipe industry [88] polyethylene was found to be susceptible to several forms of basic brittle fracture

stress cracking phenomenon. The characteristics and typical appearance of stress cracking, including environmental stress cracking due to UV radiation in PE liners of surface impoundments, have also been studied by Peggs and Carlson [89]. Cracking occurred predominantly in lining systems that are overstressed from restrained thermal contraction during low-temperature cycles from residual stresses and notch geometries acting as local stress concentrations (i.e., cracking occurs primarily at the seams). In PE geomembranes, some seam geometries were found to be more susceptible to stress cracking than others. The chemical environments and inadequate additive formulations might have resulted in the accelerated stress crack phenomenon.

Six different HDPE geomembrane materials were evaluated by dynamic and isothermal DSC as a function of even aging at 148 °C for up to 96 h [90]. The properties studied were decomposition onset temperature, the maximum heat flow during dynamic experiments and the oxidative induction time at 200 °C (isothermal). The results indicated that each of the three properties was sensitive to oxidative stability. Therefore, a single test was not sufficient to evaluate this complex phenomenon. However, by combining the results of two tests, before and after the accelerated aging, a more complete evaluation of the oxidative stability was achieved.

The behavior of the 24-year old PVC geomembrane installed for the internal waterproofing of a concrete pipe in a hydroelectric project was studied [91]. The PVC geomembrane was directly exposed to water at 4 °C in the winter and at 9 °C in the summer. A first sampling of the PVC was carried out after 10 yr of installation. A second sample was removed after 24 yr. The first sample was stored in a room for 14 yr in a controlled atmosphere. Thermal analysis on both the geomembranes was performed by thermogravimetry (TGA), differential scanning calorimetry (DSC), thermomechanical analyser (TMA) and dynamic mechanical analysis (DMA) at the end of the 24th year to assess its performance. Only small differences between the two samples were recorded by TGA and DSC. However, TMA showed an increase in the softening temperature from 27 °C in 10 yr to 34 °C in 24 yr. DMA showed about a 24% increase in dynamic loss modulus at the installed geomembrane operating temperature of 4–9 °C.

The high crystallinity (i.e., high density) of polyethylene geomembranes offers excellent chemical resistance to harsh chemical leachates, but can be problematic with regard to stress cracking. In a recent study by Halse et al. [92], the fracture-surface morphology of the cracked PE geomembrane specimens was investigated using the modified ASTM D2552 test method. Five different seam types were evaluated, compared and contrasted under different applied stress levels. Qualitatively, the morphological patterns were grouped into long fibrous, short fibrous, flake, hackle and lamellar. These morphologies were related to the magnitude of the applied global stresses. Short fibers occurred at low stress, the long fibers at the moderate stress and the flake at high stress. Hackle often appeared before the plastic failure as the cross-sectional area of the specimen decreased. The less common lamellar structure was caused by a combination of a low-stress cracking with the local plastic failure.

The increasing use of HDPE geomembranes in geotechnical applications, the different welding techniques used to seam geomembrane sheets and the limitation of

welding apparatus have created the need to improve field quality control methods and proper welding guidelines. In this pursuit, a study was conducted to investigate the seam quality of HDPE geomembranes welded by the well-known welding techniques [93]. It was shown that the shear and peel tests used to evaluate the bond strength of the seams did not adequately characterize the molecular structure changes or identify microstress cracks within the bonded sheets. Microstress crack analysis of the seam cross-sections was also done using scanning electron microscopy (SEM). The microscopic abnormalities in the seams were responsible for the failure modes which contributed to brittle fractures during installation or during the projected service life of the installation.

The presence of acid rain has led to an awareness of the importance of knowing the stability of geomembranes in acids. The most abundant acids in acid rain are HCl, HNO_3 or H_2SO_4. Tisinger and Carraher [94] studied the use of analytical techniques to characterize microstructural changes in geomembranes in the presence of such chemical environments. Linear medium density polyethylene (LMDPE) and HDPE geomembranes were exposed to 70% HNO_3 for 2–10 d at 50 °C and the morphological changes were examined by the thermal (DSC and TGA), spectral (IR) and tensile test measurements which indicated that morphological changes occurred with both the geomembranes. The IR spectra also showed a difference in the chemical structure of the surface of materials exposed to HNO_3 with the appearance of a band indicating the presence of carbonyl groups.

Some practical aspects of testing the chemical compatibility of FMLs for hazardous waste containment facilities have been described [95]. The study also included the failure criteria and test variability, stress–strain measurement and modulus of elasticity, volatiles and extractables estimation for HDPE, quality assurance in chemical compatibility testing and recommendations. In order to understand how seaming affects the microstructure, stress cracking resistance and durability of adjacent geomembranes, an effort was made to investigate the stress-crack failure mechanism [96]. Experimental results were presented from a series of constant tensile load tests using the single-edge-notched specimens of PE geomembranes to determine the effects of different types of seams in geomembranes on stress crack growth rates in liners of fluid waste impoundments. These results indicated that the majority of seaming procedures caused a reduction in the stress cracking resistance of adjacent geomembranes to different degrees. This reduction was caused by a combination of microstructural reorientation effects at the edge of the resolidified weld material and secondary crystallization of the geomembrane in the heat affected zone of the adjacent geomembrane. The influence of microstructure on stress cracking was also assessed.

In order to evaluate the feasibility of construction and the adequacy of design of a landfill final cover incorporating a geomembrane, a three-phase investigation was conducted [97]. Both the textured HDPE and the very low-density polyethylene (VLDPE) membranes used have shown better frictional characteristics than the reported values of smooth membranes. The frictional characteristics of a sand–geomembrane interface was determined using a tilt apparatus. Stability of an element of the final cover under simulated rainfall and freeze-thaw conditions was evaluated using a large-size tilt table. Two test plots constructed at 25% slopes and

periodic observations for more than a year provided information on the construction feasibility and the behavior of the final cover system under field conditions. The results of this study concluded that the final covers incorporating geomembranes could be designed and constructed for slopes of 25%.

In a study designed to determine the composition of municipal solid waste (MSW) leachate and its chemical resistance with FMLs, some limited experiments were performed [98, 99] on the absorption of organics by FMLs. The object of the study was to assess how best the EPA test method 9089 can evaluate the resistance of FMLs with the MSW leachate. The applicability of the EPA test method 9090 to obtain the realistic results was discussed. The study also outlined new production technologies and developments leading to corrosion-resistance materials with a high thermal stability. Attention was particularly focused on fiber-reinforced phenolic resins and fluorinated polymers as liners. A liner system is required to prevent escape of leachates to ground or surface water, prevent ingress of groundwater, which would otherwise lead to excessive leachate production, and control the migration of landfill gas.

The paper by Seymour [100] on landfill leachate containment liners covers the role and responsibility of the National Rivers Authority in landfilling need for engineered liners, acceptability of lining, principles of design and liner systems. The relation between different mass transport components and their effects on landfill design was discussed [101]. The general mass transport equation, incorporating parameters for diffusion and sorption was used as a mathematical tool to calculate the emission characteristics of different liner systems under different landfill geometries. In addition, details of a special clay mineral liner material with high retention of contaminants, good physical strength characteristics and easy compaction during placement were presented.

The long-term stability of plastic landfill liners as a function of chemical, mechanical and thermal stresses and application of liners in landfills for groundwater protection were discussed [102–107]. Permeability measurements of plastic landfill liners for concentrated organic solvents, solvents in aqueous solutions and solvent mixtures were made. The HDPE sheets were examined as waterproof linings of large-size dumps [108]. The dimensions and welding of HDPE sheets, mechanical, chemical, and biological properties, heat and light stability, resistance to rodents and cost of sheets were also considered. Another study [109] covered a discussion on the governmental inspection measures required for landfill liners. These were discussed in terms of materials choice, inspection for production supply and installation. Knipschild [110] discussed the selection of plastic landfill liners for groundwater protection by considering only mechanical stresses which included pressure by loads on the bottom and slope regions, shearing stress by settlement of the load on slope regions and pull stress by its own weight and by various settlement on slopes.

Methods to calculate the stress–strain relationships for plastic sheets under single- and double-axial stresses were described [111]. The stress–strain relationships of plastic sheets were important in designing the landfill linings. In a laboratory test of the permeability of plastic sheets to be used in landfill lining, a double-sealing mode showed better results than a single-sealing mode [112]. In the single-sealing mode, a 2 mm polyethylene sheet showed saturation with organic chemicals in the test

medium for $\leqslant 1500$ h, whereas in the double-sealing mode, a sorption equilibrium in the sheet was not reached even after 3000 h of testing.

Construction of a waste treatment plant was described by Nagel [113] which included a waste landfill and leachate clarified ponds. The landfill base was covered with 2–5 mm thick plastic lining to prevent leachate from reaching the groundwater. The leachate was treated in four successively connected ponds which included two aeration, one equalization and one polishing pond. They were covered with plastic sheets before discharge. Applications of HDPE liners in refinery installations containing groundwater-polluting fluids and in landfills of sludges from natural gas and petroleum operations were studied [114]. In another study [115], HDPE linings were discussed in relation to protection of groundwater near waste disposal sites when they are used as base-liners in closed waste deposit facilities. Requirements for the linings were the minimum thickness and the adequate resistance to chemical, mechanical and biological loading. Hot gas and extrusion welding was discussed with respect to joining HDPE linings. Quality control in the manufacture and installation of the linings was also discussed. Requirements for the HDPE linings in dumps were studied [116]. Stress deformation of HDPE linings was determined from long-term tensile and relaxation tests. Tests of welded seams in the HDPE linings showed that short-term tests could not be used to predict the long-term behavior of the weld.

A gas chromatographic analysis of the plasticizer components from a number of PVC films commonly used as liners for drinking water reservoirs, which were previously soxhlet extracted into n-C_6H_{14} over a 12 h period, revealed predominantly dialkyl phthalic acid esters, in addition to esters of adipic and azelaic acid [117]. Approximately 20–30% by weight of the plasticizer-containing films were extracted compared to only 0.7–2.2% for the two flexible PVC copolymer films without the plasticizers. Parallel studies of total microbiological growth on these foils in a three-month test according to a standard German method, revealed growth in all cases with the exception of the copolymers. Growth correlated with the samples' contents of phthalic acid ester plasticizer. However, frequently observed microbiological growth on the PVC-lined drinking water containers resulted from a migration of the poorly soluble plasticizer to the liner surface and the microorganisms ability to utilize it as a carbon source. In another study [118], information was presented on procedures for installation of fluoropolymer sheet lining systems and fluoropolymer backed linings for transportation of corrosive chemical wastes. Material selection, inspection of the installed system and the repair procedures were also discussed.

Linings for concrete vessels for waste storage prepared from polyesters, epoxy resins and vinyl ester polymers were found to be useful monolithic linings for chemical waste disposal [119]. Physical and chemical properties, methods of joining pieces of the polymeric lining materials, surface time and membrane selection were the subject of a study by Schmidt and Barker [120]. Estimated installed costs for liner materials like butyl rubber, HDPE, Hypalon, CPE and PVC has also been discussed. The use of fluoropolymer (e.g. poly(vinylidene fluoride)) linings for the corrosion protection of transport containers was discussed [121].

A study was conducted to determine the performance of a buried 10 mil thick PVC plastic liner for use in seepage control in Bureau Irrigation canals [122]. Samples from

different canal installations ranging in service life from 1 to 19 years were evaluated. The study indicated that buried membrane linings provided satisfactory service for seepage control. These linings were viable alternatives in areas not suitable for concrete or compacted earth linings. Laboratory studies and field observations indicated that some stiffening or aging of the PVC lining might have occurred with time due to the loss of plasticizer. A reduction in elongation, an increase in modulus at 100% elongation and a decrease in resistance to impact damage at low temperature were observed with aging. The rate of this aging varied as: (i) the linings originally manufactured with a high plasticizer content exhibited less aging; (ii) samples obtained from within the water prism exhibited less aging than those obtained outside the prism and (iii) samples obtained from areas where the lining had been placed over a fairly smooth subgrade exhibited less aging than those installed over a coarser base. Design criteria, construction procedure, upgraded construction and material specifications for PVC liners were also studied.

A discussion was made on the basic requirements for the containment liner for hazardous waste [123]. The study included the compatibility of the liner with the loading conditions, compatibility of the wastes, or leachate with the liner material, or its seams and selection of a liner seaming method that produce seams that are chemically compatible with the impoundment constituents having the strength of liner material itself. Haxo et al. [124] discussed the permeability of polymeric membrane liners for waste management facilities. Different types of liner materials used in waste management were discussed. The experimental permeability results were presented for butyl rubber, chlorinated polyethylene, Hypalon, elasticized polyolefin, elasticized PVC, epichlorohydrin rubber, ethylene propylene rubber, neoprene, nitrile rubber, polybutylene, polyester elastomer and polyethylenes, to gases, water vapor and various solvents. Due to their low permeability, these films were useful for lining facilities in waste storage, treatment and disposal, in order to prevent groundwater contamination.

The permeabilities to carbon dioxide, methane, nitrogen, water vapor, methyl alcohol, acetone, cyclohexane, xylene and chloroform were reported for a broad range of polymer membranes [125]. The membranes used were epichlorohydrin (ECO), ethylene propylene diene terpolymer (EPDM), neoprene (CR), butyl rubber (BR), nitrile rubber (NBR), chloropolyethylene (CPE), polybutylene, Hypalon, polyester elastomer, LDPE, HDPE, PVC and some geocomposites. The gas and water vapor transmission (WVT) data were obtained by the standard ASTM methods. Permeability characteristics of the thermoplastic and partially crystalline membranes were also assessed in pouch-type tests with salt solutions, actual wastes, acetone, xylene, water-soluble and organic soluble dyes. All the membranes were permeable to some extent. The magnitude and direction of the fluid transport varied with the membrane composition and its thickness, temperature, the permeant fluid and the driving force which in turn, depended upon the concentration or the vapor pressure gradient across the membrane.

August and Tatzky [126] presented a method to determine the permeation rates of liquid organics, their mixtures and dilute aqueous solutions when in contact with polymeric liners. Results of permeation rates of different organic chemicals and

municipal leachates permeating through common liner materials (HDPE, ethylene copolymer with bitumen, chlorinated polyethylene, PVC and EPDM with thicknesses ranging from 0.8 to 2.7 mm) were presented. The HDPE liner materials with only small differences in crystallinity have shown large differences in the permeation rates. Haxo and Nelson [127] studied the factors contributing to durability of the polymeric membranes under different exposure conditions to select the membranes and the design impoundments. The inherent ability of the membrane to resist aggressive agents was determined by polymer type, construction and manufacture. Experimental data for butyl rubber, CPE, Hypalon, elasticized PE, elasticized PVC, ECO, EPDM, CR, NBR, PVC, LDPE and HDPE with solvents and wastes indicated the importance of the characteristics of the liquids and potential adverse effects of minor amounts of organisms in waste streams.

A method to evaluate pond-lining materials for waste disposal was based on exposing the elastomer of known composition to a hydrocarbon liquid and then measuring the resulting weight or volume change of the elastomer after a specified time [128]. The effects of many organic pollutants on elastomeric liners were tested and classified for the easy evaluation of liners. In another study [129], the test methods for chemical resistance of membrane liners were examined and compared. Two tests used were NSF standard number-54 and EPA test method 9090. Several other tests developed by the liner manufacturers and researchers were also used. Although details of the tests vary, all were laboratory tests in which the selected physical properties of the geomembrane were compared and evaluated after contact with the liquid for specified periods of time. All these methods were tedious, time-consuming and costly. Useful data for product specification and application were derived from these tests, but none adequately addressed all the issues and questions with regard to liner lifetime prediction.

The use of a HDPE geomembrane to contain dioxin contaminated soil marked the first major application in Italy during 1984 [130]. The PVC, CPE, HDPE, EPDM and butyl rubber geomembranes were tested for immersion in the leachates at 21°, 37° and 65 °C for 180 d. The material thickness ranged from 1.2 to 2.5 mm. HDPE membranes were less affected whereas others showed slight swelling. The variations in physical properties were correlated with the extent of swelling.

A study was undertaken by Haxo et al. [131] to assess the relative effectiveness and durability of a wide variety of liner materials when exposed to hazardous wastes under conditions simulating various aspects of service in waste storage and disposal facilities. The materials studied included compacted soil, admixes, sprayed-on asphalt and 32 other geomembrane liners. Four partially crystalline sheets of butyl rubber, neoprene, polyester elastomer and elasticized polyolefin, though not compounded for use as liners, were included in the study. This was done because of their known chemical aging resistance. The lining materials were exposed to 10 hazardous wastes (two acidic, two alkaline, three oil, a mixture of lead, a pesticide and a brine containing industrial waste and other waste chemicals) under a variety of conditions. These data were tabulated in Ref. [131]. Results from the testing of liner materials to toxic and hazardous wastes indicated that oily wastes generally caused the greatest swelling and loss in the properties of the polymeric and asphaltic lining materials. Acidic and

Table 8
Effect of aging on water transmission rate of Hypalon geomembranes using ASTM F372 method [134]

Experimental condition	Transmission rate $(g\,m^{-2}\,d^{-1})$ for grades from		
	Industrial (30 mil)	Potable water (30 mil)	Industrial (18 mil)
Original	2.1	3.0	3.2
100 h at 80 °C in xenon arc weather-o-meter	2.1	3.7	3.4
200 h at 80 °C in xenon arc weather-o-meter	2.1	3.0	3.3
20 yr in direct sunlight (Florida)	2.6	5.5	—

alkaline wastes caused significant losses of the plasticizer and softening of the PVC specimens. A bentonite–sand mixture type lining was not found to be useful for oil wastes. However, cadmium, chromium, lead, mercury and nickel did not migrate more than 2 cm into the soil liners. Sprayed-on asphalt liner softened considerably when the waste containing lead compounds and other gasoline additives was used; it absorbed water in all cases. Since waste combination could be highly specific, compatibility testing was needed to select a liner for a given waste.

The leaking rate of hazardous liquid wastes through flaws in flexible membrane liners of retention facilities was evaluated in terms of flaw size and shape, liner type and thickness, effect of geotextile between the liner and the sub-base and the liquid head [132]. The test permeates were filled with gravel and overlaid with the liner having a flaw to be evaluated. The measured flow rates were lower than those calculated for hole, slit or seam flaws. Chlorosulfonated polyethylene and PVC liners showed slower flow rate than HDPE and EPDM membranes. The presence or absence of an underlying geotextile made no difference in the leakage rates. A table of established maximum leakage volume was given for use in drainage systems below the FMLs. Results were presented for the testing of a PVC liner to be used in landfill applications [133]. For more than 5 yr of exposure to landfill gas and other environmental stresses, the PVC top cap maintained its integrity. The property changes observed in the sample were consistent with those attributed to plasticizer loss, and to those published for PVC used as canal lining, although other factors in the landfill environment were responsible for the observed changes.

Geomembranes based on thermoplastic chlorosulfonated polyethylene (Hypalon) showed long-term weathering resistance equivalent to vulcanized Hypalon [134]. Geomembranes covered with soil provided very long service life of more than 400 yr. The Hypalon geomembranes showed low permeability to water and this characteristic was not significantly changed by long-term soil burial or outdoor exposure. Seams of the geomembranes maintained high strength even after long-term direct sunlight exposure. Table 8 demonstrates the effect of aging on water transmission rate of cured Hypalon membranes. The potable water grade Hypalon membrane has a slightly higher transmission rate than the industrial grade and both showed a small increase after long-term aging in direct sunlight. The selection and installation of a Hypalon FML to reduce leakage in an underground reservoir were described by

Tomes et al. [135]. The geomembrane adopted well to the complex and tedious installation requirements and provided a successful solution to the leakage problem.

A vast majority of haloalkanes are used for cleaning fabricated metal parts in industries such as aerospace, electronics and automobiles, in addition to their use as chemical intermediates in making adhesives and paints. Similarly, health and environmental effects of aromatic solvents are quite diverse. In many areas even esters have shown harmful effects. Recently, Aminabhavi et al. [136–139] evaluated the solvent resistivity for chlorosulfonated polyethylene (Hypalon) geomembranes manufactured by Utex Industries, Weimen, TX with a variety of hazardous organic solvents like haloalkanes, aromatics and esters. The sorption, diffusion and permeation properties for this system given in Table 9, indicated that dichloromethane, trichloromethane, chlorobenzene, toluene and benzene showed aggressive effects on Hypalon geomembranes as evidenced by large values of diffusion coefficients.

7.2. Geotextiles

Information on the behavior, durability, selection criteria and regulatory restrictions of a large group of geotextiles to be used in hostile environments was published [140–142]. Several papers were presented in a recently held workshop dealing with the engineering aspects of geotextiles used in soil reinforcements, bridges, highway systems, dams, chemical ponds, etc., [143]. A special geotechnical publication [144] discussed the use of geosynthetics for soil improvement. The mathematical modeling studies and other theoretical aspects of geosynthetic materials have been elegantly discussed in a book by Darve [145]. Koerners' recent book [9] on designing with geosynthetics deals with the fundamental aspects of geotextile materials including their applications.

There have been several useful and extensive contributions in the general area of geotextiles; however, only representative data will be discussed. Rankilor [146] provided a technological base for determining the chemical resistance and long-term durability of geotextiles, geonets and pipes with waste solutions representative of those which might be exposed in a waste-containment facility. Experiments were performed to evaluate the proposed testing procedures based on EPA test method 9090 with modifications to accommodate geotextiles, geonets and pipes. Standard analytical techniques were employed to study their chemical degradations and the results were compared with the physical property data. For polyethylene terephthalate (PET) geotextiles, grab strength and permitivity yielded useful data. However, elongation at the break point was found to be an acceptable index test for the HDPE geonet.

Short reviews on various aspects of geotextiles have been published in non-English periodicals [147–150]. Of these, the review by Sakaguchi [147] covers the potential problems of using geotextiles and their applications in drainage, reinforcement, waterproofing, etc. Other reviews [148, 149] were concerned about the mechanical and hydraulic properties and test methods of geotextiles. The development of geotextiles, geomembrane drainage prefabricates and geogrids for strengthening and stabilization of ground during construction was reviewed by Strunga and Bostenaru [150].

Table 9
Sorption (*S*), diffusion (*D*) and permeation (*P*) coefficients of CSM geomembrane for different solvents at 25 °C [136–139]

Solvent	S (mol%)	D ($\times 10^7$) (cm^2/s)	P ($\times 10^7$) (cm^2/s)
Aromatics			
Benzene	1.06	5.28	4.36
Toluene	0.95	5.17	4.53
p-Xylene	0.79	3.79	3.18
1,3,5-Trimethylbenzene	0.65	1.72	1.35
Methoxybenzene	0.82	2.82	2.48
Chlorobenzene	1.15	5.56	7.17
Nitrobenzene	0.89	1.12	1.22
Bromobenzene	1.12	4.05	7.13
o-Dichlorobenzene	1.05	2.80	4.33
Chloroalkanes			
Dichloromethane	1.58	11.95	16.01
1,2-Dichloroethane	1.12	4.00	4.45
Trichloromethane	1.45	6.76	11.69
Tetrahydrofuran	0.91	2.84	1.86
1,4-Dioxane	0.57	1.03	0.52
Tetrachloromethane	0.83	1.09	1.38
1,1,2,2-Tetrachloroethane	1.16	1.65	3.23
Cyclohexane	0.43	0.52	0.19
Esters			
Methyl acetate	0.29	2.50	0.53
Ethyl acetate	0.43	2.79	1.06
Methyl acetoacetate	0.06	0.26	0.02
Ethyl acetoacetate	0.06	0.23	0.02
n-Butyl acetate	0.51	1.63	0.96
Diethyl oxalate	0.09	0.22	0.03
iso-Amyl acetate	0.44	1.74	1.00
Diethyl malonate	0.10	0.17	0.03
Diethyl succinate	0.17	0.14	0.04
Methyl benzoate	0.61	0.74	0.61
Phenyl acetate	0.34	0.24	0.11
Methyl salicylate	0.60	0.38	0.34
Ethyl benzoate	0.55	0.75	0.62
iso-Butyl salicylate	0.53	0.11	0.11
Diethyl phthalate	0.17	0.02	0.01

Many authors have reviewed the test methods for geotextiles and geomembranes [151–155]. Some short reviews [156–159] covered the brief accounts of chemical compatibility testing of geotextiles, geonets and pipes. Of these, the review by Fluet et al. [156] presents the general aspects of geosynthetic liner systems and emphasizes the fundamental differences between a liner system and a liner. It also discusses the types of liner systems that are effective in landfill applications and how the components of

a liner system vary depending on the type of application, regulatory requirements, site hydrogeologic and climatic conditions and availability of materials. The two aspects of chemical compatibility – retention and resistance to chemical attack – are discussed and a generalized approach to designing geosynthetic liner systems was presented. Leachate constituent data from a typical sanitary landfill have been tabulated. The review by Menoff et al. [160] covered the minimum requirements of plastic liners, welding methods for joining plastic liners and packaging/sealing systems with the plastic liners at the landfill sites and construction considerations for the use of geotextiles in waste containment facilities.

In a study by Gan and Friesen [161], four different lining systems were proposed and evaluated to determine their effectiveness in controlling the leachate flow under various degrees of flow in FMLs. A computer model was used to predict the performance of leachate collection systems and to evaluate the lining systems namely, a single FML or liner, a single FML with a clay composite, a single FML with a geotextile and a double FML. Based on the climatic conditions and the lining construction cost, the study showed that a single FML or liner was the most economical and the least effective in controlling the leachate flow. However, the third design, a single FML with a geotextile, reduced the leakage of leachate by several orders of magnitude. The second design was also effective, but the cost incurred in constructing a 3 ft thick clay sub-base was prohibitive. Therefore, to effectively and economically minimize the hazards of potential ground water contamination by leachate, the third design was recommended as the composite lining system for future landfill sites.

The mechanical behavior of woven geotextiles under uniform load at various boundary conditions was studied by Ki and Kim [162]. The deflection of geotextiles under uniform load for three different boundary conditions was obtained by adopting the plate elasticity theory for a small deformation range, i.e., under the mode of crimp interchange deformation of woven geotextiles. The validity of the equations was examined with the measured values of the deflection of geotextiles under uniform load. A landfill liner system comprising a support layer of HDPE, a low-fiber mineral liner of two layers of geotextile with bentonite and a cover layer of polypropylene was developed [163]. This liner system was demonstrated for domestic waste landfills. The properties of various geotextiles (nonwoven or woven, synthetic or natural) in applications involving hydrotechnical construction, such as filters, drainage and erosion control systems have been described [164]. In another study [165], research results on the filtration properties of soils and geotextiles (used for strengthening of soils and waste dumps) were evaluated. The experimental results were analyzed by using the theoretical equations to calculate the filtration characteristics of hydraulic permeability of soils and geotextiles.

A geotextile consisting of drawn and textured polyester wool fibers and textile dust was developed for the reinforcement of concrete in hydraulic engineering [166]. The use of these materials in reinforcing river banks or shores was discussed including the technology and economic advantages. A study was made on geotextiles emphasizing the classification, properties and applications in areas including road construction and surfacing, waste disposal sites, ground drainage and erosion control, slope and

embankment reinforcement [167]. In another study [168], the preparation and evaluation of jute–polypropylene nonwoven fiber blends for geotextiles were described. Test methods for evaluating the chemical resistance of geotextiles, geonets, geogrids and plastic pipes used as liners in industrial waste landfill leachate were presented and the immersion procedures for these tests were described [169] along with wet testing and fingerprinting.

The preliminary results of a study on biological growth in geotextile fillers used in landfill leachate collection systems were presented [170]. First-year findings have shown that the clogging of the geotextile filler and leachate buildup occurred in long-term drainage of the leakage collection system. From the second generation, the flow devices were described wherein it was found that most of the clogging occurred due to biological activity rather than to the particulate. The times for severe clogging (a flow decrease of 95%) for different soils of geotextiles were relatively short. Geotextiles showed a significant decrease in flow soon after the biological activity initiated, whereas in geotextile/soil systems, the flow decrease was gradual, thus indicating that the soil afforded a buffering effect not available to the geotextile by itself. Potential remediation measures were discussed.

Geotextiles for landfill applications are generally used as an integral part of the leachate collection system. Compatibility with the chemical environment to which the geotextile will be exposed must be demonstrated for long-term exposure to the chemical environment. The geotextile must be capable of retaining its design function throughout the lifetime of the landfill. To meet the need of having information regarding the chemical compatibility of a nonwoven polypropylene and polyester geotextile, test programs were conducted using EPA test method 9090, in which geotextile is exposed to the chemical environment collected from the landfill areas [171]. During exposure, various properties of geotextile were monitored for 120 d at 23 °C and 50 °C. Chemical compatibility testing involved only the bulk mechanical and physical properties. The mechanical properties showed much variability upon exposure to leachates. The chemical resistance of geotextiles to leachates were also measured in terms of dimensional changes which did not vary appreciably.

7.3. Geocomposites

Geocomposite liner systems have been in use for sometime in the United States and other countries. However, the published results on these systems are not as extensive when compared to geomembrane liners. The advantages of composite pipes prepared from glass fiber-reinforced unsaturated polyesters and polyolefin liners were discussed and compared to rubber lined steel pipes and polyolefin pipes [172]. In this study, the adhesion of the polyolefin liner to the pipe was also discussed. PE and polypropylene liners for glass fabric reinforced pipes and their resistance to corrosive media were discussed. Another paper covers a discussion on HDPE liner materials for waste disposal sites, including their chemical resistance, production, installation and testing [173].

The lining sheets useful in preventing underwater metal corrosion were prepared by laminating plastic films on UV-curable resin layers comprising porous materials [34].

The lining sheet had a peel strength of 4.2 and 6.6 kg/25 mm of foam and the film respectively. A new geocomposite manufactured by laminating 25 mil (0.65 mm) Hypalon having various design thickness of needle-punched nonwoven geotextiles was developed to cap waste cells and piles with steep slopes [174]. The product manufactured in 7–6 m width was available with fabric on one or both sides weighing around 270–670 g/m², exhibited superior tensile, tear and puncture resistance properties, while retaining the same seaming characteristics of Hypalon. Laboratory test results used in the Hypalon/geotextile geocomposite development were presented along with the description of the test methods. Methods for evaluating the chemical resistance of linings and factors determining lining durability were also discussed [175].

The upper temperature limit for using glass fiber-reinforced polyester lining layers in water was 20 °C lower than the glass transition temperature of the binder. In selecting a mechanical property for evaluating the durability of the sample, tensile strength was more sensitive to a change in the chemical stability of the sample than the flexible strength. Modifications were proposed for the sorption method in determining the chemical stability of the reinforced plastic linings [176]. The PVC-lined metal pipes, with improved layer bond strength, were prepared by using a mixture containing a solvent or swelling agent for PVC and a polyethylene adhesive composite containing a blowing agent for binding the PVC to the metal pipe [177]. Thus, a polyol, a silicone foaming regulator, dibutyltindilaurate, Freon, 4,4'-diphenyl methane diisocyanite and cyclohexanone were mixed. The PVC pipe was coated (0.5 mm) with the resulting mixture, inserted in a metal pipe and heat-treated at 100 °C to give a lined metal pipe with the layer bond strength of 25 kg/cm², compared with 8 kg/cm² for the pipes joined with a similar composition without the coating.

Yabumota published a review [178] on various aspects of corrosion-resistant thermosetting resin linings to be used in chemical plants. In another review by Kanning [179], testing regulations and applications of plastic liners used in storage of liquid substances that are potential water pollutants, were addressed. Other short reviews were also published [180–183] on the use of plastic films and textile reinforced plastic films as liners in waste ponds and landfills. Of these, Semonelli [183] discussed the secondary containment of underground storage tanks using FML in waste-containment facilities. He summarized the secondary containment and release-detection requirements for hazardous wastes. The performance standards for new and existing petroleum and hazardous substances were also covered. Factors like material compatibility with the service environment, permeability to the liquid to be contained and membrane construction, were studied.

Acid resistance of lining material was increased and the accumulation of relative residual compression deformation was decreased during an operation with the lining materials in a nickel sulfate/chloride electrolyte solution at 80–90 °C in the electrolysis of nickel, 1,3-butadiene-α-methylstyrene copolymer containing stearic acid, vulcanization accelerator, ZnO, carbon black and sulfur [184]. Domange [185] showed that linings greater than 1 000 000 m² of lagoons, canals and other water bodies with an air-tight bituminous membrane prevented the pollution of groundwater by discharges. The membranes consisted of a nonwoven polyester fabric and oxidized bitumen binder modified by mineral additives.

A polymeric material used for acid-resistant linings contained 70–80% thermal power station ash and 20–30% of the binder [186]. The binder was obtained by blending terephthalic or biphenolic resin containing 60–70% styrene or epoxy resin, vinyl monomer, acrylic or methacrylic esters or their mixtures, 20% solution of Co–naphthenate in toulene as an accelerator, polysulfide polymer accelerator and a mixture of 95% methyl ethyl ketone peroxide and 5% cyclohexanone peroxide as a hardener with 1–3 parts by weight. The advantages of composite pipes prepared from glass-fiber reinforced unsaturated polyesters and polyolefin liners were discussed and compared with the rubber-lined steel pipes and polyolefin pipes [173]. Adhesion of the polyolefin liner to the pipe was also studied. In a study by Sckikawa et al. [187] sheets prepared by coating adhesives on one side of plastic films (e.g., polyethylene, ethyl vinyl acetate, polypropylene, polyesters, polyurethanes or polyamides) have shown good rust preventing and liquid insulating properties and were useful in lining nuclear reactor containers, tanks, etc.

Water-impermeable and gas-permeable barriers for hazardous waste ponds, lagoons and landfills were studied [188]. In another study [189], a landfill liner consisting of a series of V-shaped elements constructed from an impervious membrane, a boxed soil water saturated with clean water and a gravel layer was proposed. Certain idealized boundary conditions were stipulated and an analytical solution was given for the diffusional mass transport of leachate through the saturated layer. This was used to assess the maximum value and time of occurrence of the leachate concentration at the impervious membrane. A method was formulated to estimate diffusion coefficients for the type of containment, the effect of the porous medium and the possibility of contaminant adsorption onto the soil matrix. This procedure was useful in establishing the potential for destruction of the impervious membrane from the chemicals contained in the leachate.

8. Conclusions

The area of geosynthetics is an exciting, useful and rapidly growing field within polymer chemistry, civil and environmental engineering. Several new uses have been developed almost on a daily basis. The two principal Federal laws that regulate hazardous wastes are the Resource Conservation and Recovery Act (RCRA) and the Comprehensive Environmental Response, Compensation and Liability Act (Superfund). Both are administered by the EPA. RCRA is designed to ensure that hazardous chemicals are not discarded in such a way as to cause harmful effects on human health and the environment. The RCRA requires specific permits for treatment, storage or disposal of hazardous wastes and provides for a manifest tracking system to ensure proper handling of the wastes. Superfund, on the other hand, provides for the cleanup of old waste sites (landfills, waste lagoons, ponds and warehouses) where hazardous chemicals have been abandoned while still potentially dangerous.

Currently, EPA has a list of more than 1000 abandoned sites on its national priority list. Either the government or the companies pay for cleaning these sites. A variety of physical, chemical and biological processes are available for the waste treatment. For

example, wastes in solution can be evaporated to separate harmful components. Toxic metals can be chemically precipitated from solution. Basic and acidic wastes can be neutralized, whereas some organics can be destroyed by bacteria via bio-remediation.

A wide variety of FMLs are available for applications to landfills. Weathering resistance, soil compatibility and resistance to biological and chemical attack must be considered in membrane selection, yet limited data are available in the open literature. Though several standard ASTM test methods are available to test the physical strength characteristics of a membrane, more than one procedure is often used to measure the same property, making it difficult to compare data from different laboratories. More data on waste/membrane compatibility are needed and correlation with field performance data is yet to be demonstrated. Though design and installation procedures are well documented in the literature by membrane suppliers, design and installation deficiencies remain the key reasons for liner failures.

In summary, this survey has revealed that certain aspects of the membrane liner technology are well developed including membrane manufacturing processes, laboratory test methods, liner design and installation. Although an extensive effort was made to examine the available database, it is clear that several key issues remain unresolved. Particularly, there is a lack of data on the physical stresses that an FML can withstand and the correlation of laboratory test data with actual field operations. More research efforts in these directions are necessary for a successful use of geosynthetics. There exists a great future for the development of new geosynthetics and their practical applications.

9. Future directions

The purpose of this review is to identify areas which require further research in efforts to improve our present understanding of the geosynthetic materials and their reinforcement with soil. Better understanding should lead to an establishment of safe, economic design methods and further improvements in construction technology for such structures.

There are distinct levels of needed research which include the following.

(i) Development of additional laboratory test methods to study failure and crack mechanisms of polymers used as liners in contact with radioactive wastes. Also, efforts are needed to develop uniform and simple test methods for different types of pollutants and geocomposites. However, the most urgent need is the development of comprehensive durability test methods. These should assess the potential changes in strength properties caused by effects from chemical, biological, UV aging, construction damage and temperature.

(ii) Further efforts in developing/improving the chemical structures of polymers to be used in different chemical environments (especially while in contact with strong acids and bases).

(iii) Availability of comprehensive background information on field failures of geosynthetic-hazardous systems under different soil burial conditions.

(iv) In testing methodology, an urgent need to define the environmental working conditions for geosynthetics in the field. Another aspect is the temperature regime which will set representative temperature ranges to be considered in the design of polymers and their testing.

(v) The need to establish stress–strain relationship characteristics with the chemical compatibility data of geosynthetics.

(vi) Encourage cooperative research efforts with polymer chemists, textile specialists and field engineers for a comprehensive approach.

(vii) The success of polymer-reinforced soil systems perhaps attributed in part to the synthesis of a variety of polymer backbones. Although a complete understanding of system behaviour has not yet been achieved, developmental work to ensure safe and economical design should be done. Development of more new geocomposites is needed.

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