LINER SYSTEMS
An Annotated Bibliography

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ANNOTATED BIBLIOGRAPHY OF LINER SYSTEMS

1. Albrecht, K.A., and Cartwright, K., "Infiltration and Hydraulic Conductivity of a Compacted Earthen Liner", Ground Water, Vol 27, No 1, Jan/Feb 1989, pp. 14-19.

Specific study on a clay liner made of illitic gray loam glacial till which was constructed to perform with a hydraulic conductivity of 10^{-8} and a wetting front transit time of 3 years. The liner was 3 feet thick and made using 6 lifts (23 cm loose, 15 cm compacted; padfoot compactor with 50,000 lbs force in vibratory mode). Seepage flux was calculated using the Green-Ampt equation which states that the time required for the wetting front to reach a depth, L, during ponding is a function of changes in moisture content (estimated using a density ratio), the matric potential at the wetting front, the hydraulic gradient, and the saturated hydraulic conductivity. A tracer dye study revealed that flow through the liner could be approximated with plug flow relationships.

2. Anderson, D., Brown, K.W., and Green, J., "Effect of Organic Fluids on the Permeability of Clay Soil Liners", Texas Ag Experiment Station, PB82-173154, pp 179-190.

Four soils (noncalcareous smectite, calcareous smectite, mixed cation kaolinite, and mixed cation illite) was tested using organic liquids (acetic acid, aniline, methanol, acetone, ethylene glycol, heptane, and xylene). The clays varied from very high to moderate shrink/swell potential. The acid may have caused some dissolution of material and an initial decrease in permeability. The migrating particles later lodge in pore throats and reduce permeability.

The organic base, aniline, increased all four clay permeabilities without dissolution of clay particles. Inspection showed that the clay became aggregated and platy with visible cracks and openings. The predominant mechanism was then the change in the structural arrangement of the clay particles.

Ethylene glycol alters the soil fabric to increase the permeability after an initial decrease after several pore volumes.

The explanation for acetone was: the higher dipole moment of acetone caused initial increase in interlayer spacing betwen adjacent clay particles as compared to water. As more acetone passed through the soil, more water layers were removed from clay surfaces resulting in gaps not completely filled by adsorbed acetone layers and therefore, more pore space available for fluid to flow.

Permeability also increased with methanol although no signs of particle mobilization was noted in the effluent. Examination of the soil after flow revealed that the soil had developed large pores and cracks. Author suggests that the lower dielectric constant of methanol will cause the d-spacing to decrease which means structural changes occur.

Xylene also caused a structural change in the clay soils and an increase in permeability. Heptane caused an increase of 10,000% which plateaued out just like xylene. The calcareous smectite showed a much lower permeability to heptane that to xylene.

Neutral nonpolar fluids caused increases in permeability but they generally plateau. This may be caused by the inability to penetrate the interstitial layers. Neutral polar liquids showed a continuous increase. The permeability changes were not fully explained by the ratio of viscosity and density used in other media. The calcareous smectite showed the best resistance to changes in permeability by organic liquids. The noncalcareous smectite showed the least resistance. The kaolinite allowed more pore volumes of organic liquids before showing in the effluent. The illitic clay allowed the least pore volumes of organic liquid before showing in the effluent. All clays ended up with permeabilities greater than 1×10^{-7}.

Anderson, D., et al, "Review and Evaluation of the Influence of Chemicals on the Conductivity of Soil Clays", Texas Ag Experiment Station, PB88-170600, EPA Cincinatti, OH.

Review of on-going research reported above. Clays that are dispersed in water will flocculate in the presence of organics and salts and the degree of flocculation increases with concentration. The dielectric concentration range of 30 to 50 for water miscible organic liquids causes flocculation. Salt concentrations between 0.1 and 0.5 N also caused flocculation in the three soils tested.

The effect of hydraulic gradient on the results of the permeability test was pronounced when water was the permeant but less so when the organic liquids were used in kaolinite and mica soils.

Field conductivity tests confirmed the permeability trends measured in the laboratory. Authors state that the data indicates that a dielectric constant less than 30 will cause clay to flocculate, desiccate, crack, and increase permeability.

This report includes figures of basal spacing versus dielectric constants for all organic liquids, percent swelling versus dielectric constants, and zeta potentials.

3. Auvinet, G., and Espinsoa, J., "Impermeabilization of a 300 Hectare Cooling Pond", ASTM Symposium, eds. Wheeler, J.B., Hoersch, H.M., Mahy, H.P., and Kleinberg, A.S., Philadelphia, PA June 17-23, pp 151-167.

Thermoelectric power plant located in Mexico with an above ground cooling pond was designed to minimize the loss of makeup water. The investigation included a soil profile; physical properties of the native soil; permeability tests using adsorption tests, E-19 tests, Nasberg and Lefranc tests; and a review of other local pond retention behaviors. An allowable seepage rate of 0.3 m^3/sec was set as the maximum acceptable to maintain blowdown water salt concentrations. Their geotechnical investigation of subsoil and permeability tests led to the liner solution: use native soil as a clay liner compacted wet of Proctor optimum with kneading action. Initial construction used sheepfoot roller (3-tonne) and a rubber-tired roller (8 tonne), 87% compaction, 12% water content (well below optimum of 18%). Result was excessive seepage. Final construction technique used 0.5 m layer of soil homogenized and cured wet of optimum using a nonstandard compaction procedure. The authors recommend using crawler type tractor for several passes and follow with a 12 tonne farm tractor (8 passes). Soil was periodically sprayed to maintain good wetness. Also tested FML (8 mil PE) which failed miserably due to pinholes.

Bagley, J.R., and Wilkes, E., "Asphalt-Rubber Geomembrane at Palo Verde Nuclear Generating Station", Land Disposal of Hazardous Waste, Proceedings of the 11th Annual Research Symposium, Cincinatti OH, May 1985, pp 385-387.

The asphalt rubber spray used was made with ground tire rubber made by Arm-R-Shield. It was applied to a thickness of 200 mil on the bottom of the impoundment and paried with a PE membrane on the side-slopes. Asphalt-rubber was prepared on site and used to line evaporation ponds for cooling tower blowdown.

Barden, L and Sides, G.R., "Engineering Behaviour and Structure of Compacted Clay", Journal of the Soil Mechanics and Foundations Division, in Proceedings of the American Society of Civil Engineers, Vol 96, No SM4, July, 1970, pp 1171-1192.

The main focus of the paper is to determine effects of moisture content on the physical properties of clays as they relate to dam construction. Includes detailed descriptions of triaxial and Rowe consolidation apparatus, air and water permeability tests, suction tests, pore pressure tests, applied stress tests, electron microscopic structure analysis of clays, and broad literature review.Experimental results indicated that: compaction moisture content has considerable effect on soil structure; time effects due to viscous creep of the soil skeleton and Henry's Law or the compression of water with time due to air going into solution; air and water permeabilities are a function of soil structure and degree of saturation; water permeability drops several orders of magnitude when compacted near optimum water content; soil collapse occurs when a loose structure is subjected to stress then wetted; high magnification of structures compacted wet and dry of optimum did not show marked differences; low magnification, however, revealed a macroped structure in the dry but not in the wet; the effects of macrostructural differences outweighs the microstructural differences; soil that is compacted dry of optimum exhibits a flocculated structure; and permeability is controlled by flow through interpacket channels rather than through the channels themselves.

Bass, J.M. and Little, A.D., "Assessment of Synthetic Membrane Successes and Failures at Waste Storage and Disposal Sites", EPA/600/2-85/100, Aug 1985.

27 lined facilities were analyzed to determine the factors that contributed to success/failure of liner systems. Failure - reasons or mechanisms:

1. Failure to control operations that safeguard the liner.
2. Poor or inadequate design work, in general.
3. Failure to use an independent qualified design engineer.
4. Poor or inadequate installation work.
5 Poor or inadequate communication and cooperation between companies working on installation.
6. The use of untrained/poorly supervised installers.
7. Failure to adequately conduct waste/liner compatability tests.
8. Adverse weather conditions during installation.
9. Use of old dump site (with contaminated soil)
10. Did not choose an installer with good materials and workmanship.
11. Liner material chosen by design engineer, not the manufacturer.
12. Age of facility.

<u>Success - reasons or mechanisms:</u>

1. Overdesigned the system.
2. Knowledgeable customer
3. Bidding to specifications of job, not by low bid.
4. Selection of qualified installation companies.
5. Cooperation between companies during installation.
6. Good weather conditions.
7. Liner properties were appropriate and high quality.
8. Conducted waste/liner compatability tests.
9. Simplicity of the design.

<u>Other failure mechanisms:</u>

1. Difficulty placing liner over geotextile fabric.
2. Difficult to test degree of soil compaction in the field.
3. Facility was used other than what was designed for.
4. Gas generation between limestone and effluent.
5. Used "cheap solution" when corrected mistakes.
6. Asphalt cracking due to freeze/thaw.
7. Subgrade had differentially settled which cracked the clay liner.
8. Earthwork contractor did a poor job.
9. Mud and water at site interfered with seaming job.
10. Difficult to repair aged liner.
11. Used unskilled, low cost construction workers. Lowest bid usually got the job.
12. When too many independent contracors are used, communication becomes a problem with regard to who is responsible for quality control.
13. Poorly selected and placed gravel drains.
14. Inadequate quality assurance on seams.

Bonaparte, R., Beech, J.F., Giroud, J.P., "Background Document on Bottom Liner Performance in Double-Lined Landfills and Surface Impoundments", EPA/530/SW-87/013, Gaithersburg, MD, PB87-182291, April 1987.

Introduces the concepts of waste management units; ground pollution mechanisms; types and materials used in liner systems; leakage detection, management, and collection; and regulation regarding double-liners. The perfomance of soil liners was studied with regard to leakage and breakthrough time (one and two dimensional partially saturated flow conditions) as a function of hydraulic head, liner thickness, and hydraulic conductivity. The performance of composite or geomembrane liners was studied with regard to leakage through "intact" FML and FMLs with holes or pinholes along with a two-dimensional transient flow analysis with regard to leak detection and collection efficiencies. Both studies were compared to each other looking at leak detection sensitivity, collection efficiency, and waste management. An EPA survey is also discussed.

In one-dimensional, steady-state, saturated flow through a soil liner, leakage out of the unit (gallons per acre day) is directly proportional to hydraulic head (if > 1 ft) and hydraulic conductivity, but is not affected by liner thickness. The breakthrough time is directly proportional to liner thickness and hydraulic conductivity, but is not affected by hydraulic head. In one-dimensional, steady-state, partially saturated flow through a soil liner, leakage out of the unit is ...

Bouwer, H., "Design Considerations for Earth Linings for Seepage Control", Ground Water, Vol 20, No 5, Sept/Oct 1982, pp 531-537.

Two types of seepage rate prediction methods are in terms of volume rate per unit area of wetted perimeter (infiltration rate) and volume rate per unit are of water surface (rate of pond depth change). Seepage rates are calculated using hydraulic properties of the liner material, the support material, and the system geometry. Assume that the liner is saturated but the subliner soil is unsaturated - flow is steady state and governed by gravity. Calculate flow through the liner (saturated) using Darcy's Law. Assume unsaturated permeability of subsoil to be equal to the infilitration rate (Darcy's Law). The relationship between permeability, pond height and moisture content exhibits hysteris with changes in water content. Arid regions will follow the low to high moisture curve, whereas humid regions may follow a high to low moisture curve.

Author states hydraulic conductivity of soil depends on the dispersion-flocculation conditions of the clay particles, the sodium adsorption ratio, and the total salt content. K decreases with increasing SAR. Dispersion can occur if cation adsorption sites contain at least 15% sodium ions. The hydrophobic/hydrophillic nature of solvents dominates any effects viscosity or density may have on transport. Using a particle size ratio of 15 (mixing clays with sand and gravel) is shown to reduce permeability and could reduce clay requirements by 50%. The seepage rate divided by the water content yields the actual downward velocity of water during dynamic equilibrium. Anions follow convective transport, cations tend to adsorb. Therefore, seepage rates of water do not necessarily reflect the seepage rate of the contaminant. High seepage rates and low aquifer transmissivities can cause ground water mounding.

Bowders, J.J., Jr., Daniel, D.E., "Hydraulic Conductivity of Compacted Clay to Dilute Organic Chemicals", Journal of Geotechnical Engineering, Vol 113, No 12, Dec, 1987, pp 1432-1448.

Kaolinite and illite based clay soils were tested using four organic chemical solutions: methanol, acetic acid, heptane, trichloroethylene, and water. These chemicals represent neutral polar, neutral nonpolar, acidic, and chlorinated compounds. Permeability was measured using rigid-wall and flexible-wall permeameters. Methanol did not affect k until concentration of 80%, due to shrinkage of double layer on clay particle, macropores, and cracks. Pure heptane and trichloroethylene increased k significantly but at solubility limits (lower concentration) did not affect k. Pure acetic acid caused an increase in k. Dilute solutions did not affect k due to precipitation and dissolution caused by flow of acid.

Boynton, S.S., and Daniel, D.E., "Hydraulic Conductivity Tests on Compacted Clay", Journal of Geotechnical Engineering, Vol 111, No 4, April, 1985, pp 465-478.

Compares permeameter results between rigid-wall and flexible-wall permeameters, tested for anisotrophy, effects of dessication, using distilled water. No differences in permeability was seen with the different permeameters. Permeability acted isotrophic.

Bramlett, J.A., Repa, E.W., and Mashni, C.I., "Leachate Characterization and Synthetic Leachate Formulation for Liner Testing", EPA/600/D-87/016, EPA Cincinatti OH, PB87-145983, Jan 1987.

The purpose of the study was to develop a synthetic leachate for testing purposes. Thirteen hazardous waste sites were used to determine leachate components of interest. The priority pollutant metals were easier to characterize than the organics. Geared more towards RCRA sites.

Bryant, J.L. and Bodocsi, A., "Precision and Reliability of Laboratory Permeability Measurements", Land Disposal of Hazardous Waste Proceedings of 11th Annual Research Symposium, Cincinatti OH, May 1985, p. 225.

The purpose of the study was to collect data on permeability measurements and procedures, to analyze the variability of data, and to recommend future permeability testing protocol. Data was retreived from EPA research labs, government labs, private consulting firms, and universities.

Information on the clay liner that was requested included: clay type, clay source, Atterberg limits, soil classification, Proctor density, optimum water content, pH, ion exchange capacity, and specific gravity.

Permeability data requested included clay type, initial density, water content, void ratio, degree of saturation, type of pemeameter used, type of permeability testing apparatus, and the types of permeants used.

Variation in permeability was discussed as it was related to many parameters. Moisture content was presented as having a larger role in the variation of permeability. They used data from Brown and Anderson (Brown, J.M., and Anderson, D.C., "Effects of Organic Solvents on the Permeability of Clay Soils", EPA Grant R806825010, Cinci OH, 1983) which showed a change in permeability equivalent to three orders of magnitude (OOM) when moisture content ranged from 15.9% to 23.5%. This equals 0.4 OOM for each 1% change in water content.

An example was given using an estimated error associated with the moisture content calculation to be 0.5%. If the slope of the permeability versus moisture content graph is -0.46 OOM per 1% water content, then a 0.5% error in moistening the soil would equate to 0.23 OOM or $10^{.23}$ or a 70% error associated with permeability. Large differences between laboratory permeability values for soils that were "independently" moistened could be explained by looking at the additional source of error in estimating moisture content and how it affects the estimation of permeability.

Brown, K.W., Thomas, J.C., and Green, J.W., "Permeability of Compacted Soils to Solvents Mixtures and Petroleum Products", Proceedings of 10th Annual Research Symposium, PB84-177799, pp 124-137.

Three soil types (sand mixed with kaolinite, mica, and bentonite) and organic liquids (polar, gasoline, kerosene, diesel oil, and paraffin oil) were used to study permeability changes with respect to elevated hydraulic gradients, dilution with water, and mixtures of polar and nonpolar. Permeability was measured using backpressures of 5, 15, and 30 psi (author equates to HD of 31, 91, and 181). Dilution was tested using an unsaturated micaceous soil and acetone:water dilutions from 0:100 to 100:0 with a HD of 91 (15 psi). X-ray diffraction was used to analyze the d-spacing of the interstitial layer when clay was exposed to acetone, xylene, and dilutions thereof.

As the hydraulic conductivity increased for each soil, only slight increases in permeability was observed when water was used as the permeant. For acetone:water combinations greater than 75%, the permeability increased for all hydraulic gradients. The author proposes that at low concentrations of acetone, the soil is dispersed and swells, but at high concentrations the soil flocculates and shrinks.

On a microscopic level, this means that at low concentrations, the acetone attaches so that the carbonyl group is adsorbed on the mineral surface. The methyl (hydrophobic) group faces the pore wall away from the water layers on the mineral which causes a decrease in pore throat volume. Other studies discuss this in more detail.

Increases and decreases in permeability were coupled with d-spacing changes by X-ray diffraction. An increase in d-spacing was observed with a decrease in permeability. D-spacing for water in bentonite is 34 Angstroms as compared to 18 for glycerol, 12.6 for acetone, and 18.4 for xylene. The nonexpansive mica has a constant d-spacing of 10 angstroms for water, acetone, and xylene. Kaolinite d-spacing is 7.12.

Results of water versus kerosene showed an increase in permeability of 3 orders of magnitude. With paraffin oil, an increase of 1 to 2 OOM, which may be affected by the increased viscosity. Diesel fuel affected the permeability of mica by 1 to 2 OOM. Gasoline increased permeability of mica by 2 OOM. Motor oil also increased the permeability by 1 OOM.

Similar tests were performed using commercial clays. Water caused a steady decrease in permeability. When xylene was used, the permeability increased rapidly by 4.5 OOM but acetone only increased it by 3 OOM.

Cope, F., Karpinski, G., Pacey, J., and Steiner, L., "Use of Liners for Containment at Hazardous Waste Landfills", Pollution Engineering, March 1984, pp 22-32.

Summarizes Subtitle C of RCRA mandates for liner design requirements. Mainly all sites will use liners to prevent migration of wastes out of the unit to the subsurface soil, ground water or surface water. Liners should be constructed with chemically compatable materials that can withstand failure due to pressure gradients, physical contact with waste, adverse climatic conditions, and stress of installation, operation, and maintenance. Liners must be supported by a foundation that will not settle, compress, or uplift. Liner systems should be monitored and inspected. Specifically, FMLs should be inspected for uniformity, imperfections, or physical damage. Soil liners should be inspected for cracks, channels, foreign objects, root holes, etc. Liner systems are required to have leachate collection and removal systems.

Types of FMLs used in RCRA sites are: Butyl rubber, chlorinated polyethylene (CPE), chlorosulfonated polyethylene (CSPE), epichlorohydrin rubber (ECO), ethylene propylene rubber (EDPM), ethylene propylene terpolymer (EPT), high density polyethylene (HDPE), neoprene (chloroprene rubber), polyvinyl chloride (PVC), and thermoplastic elastomers.

Selection criteria for liner systems should include anticipated performance levels (regulatory standards, design life), waste/liner compatability, site conditions (subsoil properties, geophysical, hydrogeological), and environmental factors (wind, heat, humidity). Geotechnical info includes Atterberg limits, compaction tests, unconfined compressive strength tests, triaxial compression tests, direct shear test, permeability tests.

Minimum requirements: FML's should be > 30 mils. Soil liners > 3 feet with permeability $< 10^{-7}$.

Daniel, D.E., "Predicting Hydraulic Conductivity of Clay Liners", Journal of Geotchnical Engineering, Vol 110, No 2, Feb, 1984, pp 285-300.

Reviews four case histories of earth liners that failed due to field permeability larger than predicted by laboratory. Case histories include fresh water holding ponds, brine holding ponds, and blowdown water evaporation ponds (all ponds had thin liners, dessication cracking, poorly predicted permeability, and poor construction documentation). Also discusses the sources of error in laboratory tests.

Daniel, D.E., "Earthen Liners for Land Disposal Facilities", Geotechnical Practice for Waste Disposal '87, In Proceedings of a Specialty Conference, ASCE, University of Michigan, Ann Arbor, MI, June 1987, pp 21-39.

Discusses the proper construction of earth liners. Two most important variables are moisture content and roller weight. Compares water content, compaction effort, and in-situ hydraulic conductivity.

When discussing Lambe (1958) and Olsen (1962) theories regarding dependence of permeability on moisture content, the author pulls from both sides to support the contention that the macropore or inter-clod pore structure dominates k. Low k can be achieved using "small, soft, weak clods of clay" because they can be remolded and compacted into a more cohesive, non-macro pore structure.

Construction equipment suggested is a heavy roller with medium length feet which should be tested on the soil to be used. Fully penetrating feet would be better if the vehicle can keep from bogging down. The weight of the roller is very important to insure the complete destruction of the macropore structure.

EPA, "Minimum Technology Guidance on Single Liner Systems for Landfills, Surface Impoundments, and Waste Piles - Design, Construction, and Operation", EPA/530/SW-85/013, EPA Washington DC, PB87-173159, May 1985, 62 pgs.

Federle, T.W. and Pastwa, G.M., "Biodegradation of Surfactants in Saturated Subsurface Sediments: A Field Study", Ground Water, Vol 26, No 6, Nov/Dec 1988, pp 761-770.

Laundromat scenerio (26 year old Wisconsin laundromat discharge pond) where it was shown that biodegradation and adsorption were primary mechanisms of removal of surfactants from subsurface environments. Lists nonionic, anionic, and cationic surfactants studied as: linear alkylbenzene sulfonate (LAS), linear alcohol ethoxylate (LAE), benzylamine, and both monoalkyl and dialkyl quaternary ammonium compounds. The pond was naturally made with a wetland area on one side and 15 cm of clay in the middle with a communication to aquifer via the wetland. LAS surfactant concentration was greatest at surface (200 micrograms/gram) and reached 3 to 4 meter depths. Microbiological community maintained a concentration of 10^6 to 10^8 cells/gram of sediment for 2 meters in pond. When compared to a control pond, the biological community was 10 times greater in laundromat pond. Biological activity comparisons were similar with activity 5 to 15 times greater in laundromat pond than in control. Microbes utilize the carbon and nutrient source of the surfactant. LAS rapidly mineralized in laundromat pond subsurface but required a lag time in control pond suggesting assimilation of biological community to LAS as energy source. Rates for LAE were faster than for LAS with shorter time required to mineralize in laundromat pond and longer lag time in control. The benzylamine rapidly degraded in both ponds. Author suggests the acclimation due to microbe exposure to aromatic compounds existent in humic substances and sediment kerogen.

Folkes, D. J., "Control of Contaminant Migration by the Use of Liners", Fifth Canadian Geotechnical Colloquim, 1982, pp 320-344.

Reviews liner material seepage properties: fluid transport, solute transport, and attenuation. Primary mechanisms of mitigation effects of liners are dilution, time delay, and retardation. Dilution occurs by restricting the rate at which the contaminant enters the ground water so that small volumes are mixed with large aquifer volumes. Low permeability is used to create a time delay between exposure and seepage. Physical and chemical reactions are used to retard the movement of contaminants by attenuation. Total containment is accomplished by using several liners and drainage systems. States that permeability of compacted clay soils is dependent on soil structure (aggregates or single clusters; macropores), grain and pore size distribution (micropores), particle and aggregate orientation (soil fabric), bonding forces, and cementing agents. The clay fabric and pore size are dependent on clay mineralogy, compaction water content, compaction method, chemistry of water in pores. Permeability in Na-saturated water (dispersion) ranges from montmorillonite < illite < kaolinite. Permeability in Ca-saturated water (flocculated) is more a function of macropores than clay mineralogy. Compaction at or above optimum water content causes the soil to weaken and shear deformation occurs.

Briefly reviews admixes, polymeric membranes, and spray ons. Discusses compatability of wastes with liners. Acids dissolve Al, Fe, alkali metals and earths from clays. Bases dissolve silica. Cations in solution will reduce the clay particle diffuse double layer causing a decrease in repulsive forces (shrinkage, fissuring). Less cations cause dispersion and decreases in k. Total dissolved salts that contain >60% sodium are more likely to cause dispersion. Clay minerals react differently to SAR and TDS. Montmorillonite has curvilinear relationship, whereas illite is 2:1.

Compacted soil showed seepage of alkaline waste but low permeability with aromatic oil; clays show good compatability with pesticides and oil refinery sludge. Modified bentonite showed seepage of alkaline, low lead gas, and aromatic oil and complete failure with oil. Hydraulic asphalt concrete failed with acidic waste, maintained well with alkaline waste and pesticides, and turned mushy with low lead gas. Spray on asphalt maintained well with alkaline waste and pesticide. Smectite clays show dramatic increase in permeability when exposed to aniline, acetone, ethylene glycol, heptane, and xylene. High CEC fluids cause repulsive forces of clays to be reduced which results in shrinkage and increased permeability.

Reviews adsorption of waste by FMLs, gas flotation of liners, detailed case history of brine pond liner design, construction, monitoring, and performance; detailed case history of sanitary landfill liner.

Fong, M.A., and Haxo, H.E.,Jr., "Assessment of Liner Materials for Municipal Solid Waste Landfills", In Proceedings of the Seventh Annual Reasearch Symposium: Land Disposal: Municipal Solid Waste, EPA 600/9-81-002a, Cincinatti, OH, March 1981, pp 138-162.

Study looks at four admix liners, two asphaltic, and six flexible membrane liners to test the effects of landfill leachate on the physical properties of the liner materials. An exposure of 56 months revealed no increases in permeability but did show a decrease in compressive strength, swelling, and softening of the admix, FMLs, and asphalts, respectively. A water absorption test was run for 186 weeks which showed the largest absorption by FMLs made using neoprene (CSPE and CPE). The PVC FML swelled the least but did lose plasticizer.

The leachate contained 4500 mg/l COD, 24,330 mg/l total volative acids, and a pH of 5. The asphalt liner absorbed the leachate which caused large decreases in compressive strength, developed a cheesy texture, and lost elongation. The soil cement specimen used was small and did not realistically represent field conditions because these materials brittle and tend to crack. Unreinforced, vulcanized butyl rubber at 63 mils showed minor water absorption and little changes in physical property. Thermoplastic, non-crosslinked CPE showed large changes in peel and shear strength. Crosslinked CSPE showed largest absorption, 14% volatiles, and large seal strength losses. LDPE showed little to no changes after 56 month exposure. PVC at 21 mils showed slight decreases in properties.

Gibb, J.P., Barcelona, M.J., Ritchey, F.D., and LaFarver, M.H., (Illinois State Water Survey) Land Disposal of Hazardous Waste, Proceedings of 11th Annual Research Symposium, EPA/600/9-85/013, PB85-196376, p. 190.

The effective porosity of a soil sample is that void space to rock matrix ratio that allows fluid flow. pore channels that are blocked or dead end are not included in the effective porosity. When considering flow of complex molecules, surface tension and molecular configuration may also restrict fluid flow and therefore, effective porosity. It is apparent that effective porosity of the same soil would be different using different fluids.

Initial studies used Ottawa sand and glass beads which did not illustrate the difference in porosities due to a lack of dead end pore spaces. The second phase will use soils with high fractions of clay.

Gibbons, R. D., "A General Statistical Procedure for Ground Water Detection Monitoring at Waste Disposal Facilities", Ground Water, vol 28, No 2, Mar/Apr 1990, pp 235-243.

Utilizes nonparametric statistical procedures to determine the number of ground water monitoring wells.

Giddings, M. T., "The Lycoming County, PA, Sanitary Landfill: State of the Art in Ground Water Protection", Ground Water, Vol 15, No 1, Jan/Feb 1977, pp 5-14.

PVC liner with drainage and monitoring used to provide data for concerned public that ground water is protected.

Giroud, J.P., and Beech, J.F., "Stability of Soil Layers On Geosynthetic Lining Systems", Geosynthetics '89 Conference, San Diego, CA , Volume I, pp 35-46.

This paper describes a method of evaluating the stability of soil layers on geosynthetic lining systems as they occur on the side slopes of solid waste impoundments. Slope angles generally range from 4HL:1V to 2.5H:1V. The interfacial friction angle between the soil and geosynthetic liners range from 10 to 25 degrees. If the friction angle is less than the slope angle, a slip plane will develop causing liner instability. An infinite slope model is used to determine the slip plane which is conservative because the real slope is finite. The anchorage at the trench and buttress at the toe act to delineate the slope. In addition, shear resistance at the top of the slope adds to the stability of the liner system.

The maximum height of a nonreinforced soil cover over the geosynthetic can be calculated using the equations provided in the text where the polygon is divided into two wedges. A free body diagram shows the forces are weight, force between the wedges, interfacial friction, and tension. The liner is described as polygons of force per unit width, W1* and W2*. The geosynthetic tension, " , is calculated as a function of W1*, W2*, P, Tc, the sideslope angle, ß, and interfacial friction angle, ". If " equals zero or negative, then no reinforcement is needed. If it is a positive value then tension exists and the liner system must be reinforced. The maximum height of the soil is a function of Tc which is the thickness of the soil cover, ", and ß. Trade-offs between reinforcement and soil cover thickness can be compared using the geosynthetic tension and maximum cover thickness equations. The tension for each soil cover thickness is compared to the support a geonet or geogrid could provide.

Goldman, L.J., "Design, Construction, and Evaluation of Clay Liners for Waste Management Facilities", EPA/530/SW-86/007F, EPA Cincinatti OH, PB89-181937, Nov 1988, 566 pg

A technical resource document that provides detailed background on clay liners based on literature surveys and interviews. Clay soils are discussed with regard to mineral structure, chemistry of clays, soil fabric, and hydraulic conductivity. Soil properties are discussed with regard to the interactive relationships between water content, porosity, degree of saturation, Atterberg limits, and grain size distribution. Laboratory and field tests are presented for permeability, density, and moisture content. Clay/chemical interactions as they affect permeability is presented along with an annotated bibliography of 23 studies. Current practices of clay liner design and installation looks at foundation deisgn and control of failure mechanisms. Construction methodology includes equipment choices and quality control. Failure mechanisms are discussed and include desiccation cracking, slope

instability, settlement, piping, penetration, and erosion among others. Seventeen case studies are reviewed with regard to physical description, geo/hydrology, waste, liner, installation, and performance.

Griffin, R.A., "Movement and Attenuation of Chemical Constituents in Groundwater Attenuation of Chemical Constituents in Ground Water", personal notes for University of Texas - Austin Waste Disposal Projects, Illinois State Geological Survey - Geochemistry Section, Champaign IL, October 7-10, 1985.

Physical attenuation mechanisms include dilution and dispersion. Dilution is a function of the release rate of the consituent into the ground water and the volume of the receiving water. Dispersion is a function of pore geometry and concentration.

Attenuation can also occur by soil fitration or clogging which can be caused by physical, chemical, or biological activities. Physical activities are mechanical filtration of the solute by the pore throat. Chemical clogging occurs because of colloidal dispersion or chemical precipitation. Colloidal dispersion occurs when ion exchange on the colloidal surface change the electrostatic properties. Chemical precipitation is a function of concentration and pH. Biological clogging occurs when microbial growth collects in pore openings.

The soil properties that affect attentuation are soil fabric, pore size distribution, clay composition, and chemical composition. The pH and redox potential along with the ionic and organic composition of the leachate are important in determining what attenuation mechanisms will dominate.

Hartley, R.P., "Assessing the Reliability of Flexible Membrane Liners", EPA/600/D-88/029, EPA Cincinatti OH, PB88-170055 AS, Feb 1988.

Document discusses the methodology the EPA is using to assess the reliability of FMLs as they are used for hazardous waste sites. Research of FML assessment has focused on: resistance to degradation by waste chemicals, punctures, and tearing; the seamability; weathering characteristics; repairability; construction inspection and testing; and long-term field performance.

Design methodology discussed is based on the principle that the reliability equals the probability of a system leak will be less than a failure value. The magnitude of the leak is equal to the amount of liquid imposed on the system minus the system's capacity to reject that liquid. The text goes on to explain the 14 components of flow with regards to the liner, collection and removal, and the cap along with the design factors that affect each flow and how to minimize the flow.

Hauser, V.L., "Seepage Control by Particle Size Selection", Transactions of the American Society of Agricultural Engineering, ASAE Paper No. 77-2016, 1978, pp 691-695.

Experiments using particle size ratios to test the effects on hydraulic conductivity resulted in the conclusion that using two-component systems using aggregate 15 times larger than the weighted particle size of the treated soil can reduce the hydraulic conductivity and the amount of clay needed. The tests were geared more towards water conservation and structure stability. Kaolinite and bentonite were compared. The permeable soil must have particle sizes small enough to trap the clay particles in the pores. Bentonite forms a sticky consistency when wet which is easier to trap than kaolinite.

It would be helpful if similar experiments were geared to reduce the permeability down to the levels required by regulatory agencies to see if the aggregate would reduce the clay requirements and still maintain low hydraulic conductivities when in contact with leachate. This approach may be applicable to farm ponds and innocuous water surface impoundments as an economic alternative.

Haxo, H.E., Haxo, R.S., et al, "Liner Materials Exposed to Toxic and Hazardous Wastes", Waste Management and Research, Vol 4, 1986, pp 247-264.

Study started in 1975, ended in 1985 - studied one compacted clay, three admixes, on asphalt spray-on, and 32 FMLs. Wastes used include 2 acidics, 2 alkalines, brine, aqueous lead oil, 3 oily wastes, and a pesticide; also studied deionized water, 5% salt solution, 0.1% tributyl phosphate. Discusses compatability of wastes with liners. Tested FMLs using one-sided exposure, two-sided immersion, outdoor exposure, and pouch test. Soil liner was also tested with heavy metals: copper, cadmium, chromium, lead, mercury, and nickel which were present in oil. Deionized water affected only FMLs with chlorine based polymers. Oily wastes caused the most swelling and loss of properties in polymers and asphalts as did the aqueous lead waste (it contained low concentrations of gasoline).

Results indicated that soil liner withstood low alkaline, lead, oily, and pesticide wastes (was not tested against acidic waste). Soil used had high ratio of nonclays in the fraction < #200 sieve and had a high salt content.

Asphalt concrete cannot be used with oily wastes. Leaks occured when exposed to strong acids, spent caustics, and oily lead wastes. Water seeped through a 2.5 inch thick liner. Bentonite and sand mixtures do not work with acid or strong alkaline wastes. Fingering of waste through liner occured when exposed to oily wastes.

Soil cement is highly resistant to spent caustics, oil lead wastes, oily wastes, and pesticide wastes but not to acidic waste. Used small test specimens.

Asphalt spray-on worked well with spent caustic, pesticide, and water. Leak occured when exposed to brine. Should not be used with oily or acidic wastes. Softened when exposed to oil lead and absorbed water.

FMLs tested included cross-linked polymers, thermoplastic polymers, semi-crystalline polymers and fabric-reinforced membranes. Author states that cross-linking causes the FML to swell less and resist changes in liquids. All cross-linked FMLs that failed did so at the adhesive system along the seam. Thermoplastics maintained good seam seals. Study included FMLs based on CPE, CSPE, PVC, and EDPM which all reacted to each waste differently. Semi-crystalline FMLs used were ELPO, HDPE, LDPE, polybutylene, and polyester elastomer. They showed the least adsorption of waste and better retained physical properties. ELPO swells considerably in oily wastes (also lowest crystallinity).

Tables include % volatiles, % extractables, % elongation retention, % stress retention, for each group of FMLs. Text includes more results than listed above.

Haxo, H.E., Jr., Nelson, N.A., and Miedema, J.A, (Matrecon), :Solubility Parameters for Predicting Membrane/Waste Liquid Compatability", Land Disposal of Hazardous Waste in Proceedings of 11th Annual REsearch Symposium, Cincinatti OH, April 1985, p. 198.

FML property losses atttributed to absorption of waste liquids and subsequent swelling which is affected by the solubility, crossslinking and crystallinity of the polymer. the filler, plasticizer, and soluble components of the FML will also affect swelling. The authors suggest that the solubility of the FML in the waste liquid is the most significant factor and can be described using a solubility parameter. The solubility parameter is equal to the square root of the ratio between the energy required to vaporize one mole of material and the molar volume. It is a measure of potential energy of any material with respect to its energy in an entirely disassociated form free of intermolecular interactions like solute/solute or solute/solvent (units are in $(cal/cm^3)^{1/2}$). The potential energy may be due to dipole-dipole interactions, London dispersion forces, hydrogen bonding, or repulsive forces.

Waste/liner compatability will depend on an appropriate separation betweeen the solubility parameters of the liner and the waste. Careful selection criteria must be given because the range of solubility parameter values for both liners and wastes lies between 8 and 10.

Analysis should begin with comparing solubility parameters. Then the FML should be tested with the waste liquid for changes in properties, such as tensile strength, elongation at failure, tear resistance, moduli, hardness, and permeability. Semi-crystalline materials are subject to environmental stress-cracking and rupture which should be tested.

Matrecon intended to develop a prediction method that would estimate service life under different conditions and determine whether a solubility index will be a good predictor. The experiment looked at swelling of FMLs in nine solvents where the solubility parameter ranged from 6.8 to 14.5. Each material swelled but reached a "swelling maximum". Other conclusions from the research are as follows:

The organics of the waste affect the FML more than inorganics because of their insolubility in aqueous solutions and their solubility in FML material. Organics collect at the liner/water interface, absorb into the liner, travel through the liner by molecular diffusion, and if volatile, will evaporate into the soil pore spaces beneath the liner.

If the specific gravity of the waste is greater than water it will settle in the impoundment and come into direct contact with the FML. This condition allows for a higher concentration of organics in contact with the FML due to settling of high molecular weight hydrocarbons and interfacial accumulation.

Swelling decreases with increasing crosslinking. Crystallinity acts much like crosslinking in that it decreases swelling. In fact, highly crystalline materials like HDPE will not even dissolve. The filler material (carbon black, silica, clays, or plasticizers) act in increase swelling.

FML	Elastomers	Cross-Link	Swelling
Rubbers	elastomers	crosslinked	dec swelling
Thermoplastic	elastomers	not crosslinked	inc swelling
Highly crystalline thermoplastics			dec swelling

Low molecular weight components of flexible membrane liner can be lost after prolonged immersion. Plasticizers and oils may be extracted or biodegraded. Antidegradants can also be extracted.

Haxo, H.E., and Waller, M.J., "Laboratory Testing of Geosynthetics and Plastic Pipe for Double-Liner Systems", EPA/600/D-87/059, EPA Cincinatti OH, PB87-167029, March 1987.

A review of the basic characteristics of FMLs and how they relate to field perfomance and laboratory testing. The four types of FMLs are thermoplastics (PVC and EVA), cross-linked elastomers (EDPN and neoprene), semicrystalline plastics (PE), and highly crystalline (polypropylene and polyester fibers).

Potential failure of geomembranes: puncture due to settlement, environmental stress-cracking, bridging, sloughing of soil cover, tensile stresses, thermal cycling, and waste incompatability. Potential failure of geotextiles: waste incompatability, clogging by waste particles, and tensile stresses. Potential failure of drainage nets: membrane intrusion and clogging, property losses, and collapse under load. Potential failure of plastic pipe: collapse under load.

Polymers vary in modulus and elongation at break; are sensitive to organic liquids and vapors; are viscoelastic and sensitive to temperature and rate deformation; tend to creep and relax in stress; have high coefficients of thermal expansion; contains residual strain or "strain history"; will elongate under biaxial strain; will have broad range of permeability; are subject to stress-cracking and static fatigue; have amorphous and crystalline phases; usually highly resistant to degradation if protected properly; can have properties modified by compounding.

Laboratory tests performed on FMLs include: permeability, frictional properties, strength and elongation, transmissivity, permittivity, and filter properties. Analytical tests for compositional changes over time include: volitalies, ash content, trace metals, extractables, gas chromatography, semicrystalline composition, thermogravimetric, and specific gravity (collectively called "finger printing" a polymeric material). A listing of the appropriate test methods is given for FMLs, geonets, geotextiles, and plastic pipes.

Herrmann, J.G., and Elsbury, B.R., "Influential Factors in Soil Liner Construction for Waste Disposal Facilities", Geotechnical Practice for Waste Disposal '87, In Proceedings of a Specialty Conference, ASCE, University of Michigan, Ann Arbor, MI, June 1987, pp 522-537.

Discusses the impact that destruction of soil clods and bonding between lifts has on the hydraulic conductivity. Secondary effects are roller type and weight, coverages,lift thickness, and water content.

Ho, Y.A., and Pufahl, D.E., "The Effects of Brine Contamination on the Properties of Fine Grained Soils", Geotechnical Practice for Waste Disposal '87, In Proceedings of a Specialty Conference, ASCE, University of Michigan, Ann Arbor, MI, June 1987, pp 547-561.

Brine contamination affects the liquid limit, dispersivity, and clay mineral double layer. Brine changed soils from non-dispersive to dispersive. Brine caused double layer shrinkage which means larger pore openings, and increase in hydraulic conductivity.

Hodge, V., DeSalvo, N., et al., "Guidance Manual on Overtopping Control Techniques for Hazardous Waste Impoundments", EPA/600/2-86/012, EPA Cincinnati, PB86-154168, Jan 1986.

Discusses the use of FMLs as floating covers, otherwise not helpful with reference to topic.

Horton, R., Thompson, M.L., McBride, J.F., "Method of Estimating the Travel Time of Noninteracting Solutes through Compacted Soil Material", Soil Science Society of America Journal, Vol 51, 1987, pp 48-53.

Pollutant travel time as a function of effective porosity, hydraulic conductivity, and thickness of compacted layer.

Johnson, R.L., Palmer, C.D., and Fish, W., "Subsurface Chemical Processes: Field Examples", EPA Seminar Publication: Transport and Fate of Contaminants in the Subsurface, Robert S. Kerr Environmental Research Laboratory, Ada OK, EPA/625/4-89/019, Sept 1989, pp 57-66.

Several examples of the chemical processes that occur in the subsurface that affect the transport and fate of contam-inants. Biodegradation of hydrocarbons, organic transport, indicator compounds, leachate production, clay liner failure, plume sniffing, chromium migration, and leaded gasoline are topics presented. The discussion on clay liner failure attacks permeability research results that use high hydraulic gradients to determine whether or not solvents increase the permeability by entering the clay mineral and displacing water molecules. The authors state that HG's equal to dozens of meters are being used to force solvents into clay intersticial areas. Without a large hydraulic gradient, the solvent transport would follow Fickian diffusion principles which is dependent on the solubilities of the solvent in the aqueous phase. Fickian diffusion states that diffusivity is a function of the change in concentration with time, the initial concentration, and the distance the chemical is to diffuse. The authors suggest that nonpolar, immiscible solutes would not diffuse into the interstitial areas. Polar, miscible solutes, on the other hand, would diffuse rapidly into the interstitial areas and alter the electrostatic repulsive forces in the electrical double layer.

Knipschild, F.W., "Selected Aspects of Dimensioning Geomembranes for Groundwater Protection Applications", Intn'l Conference on Geomembranes, Volume II, Denver, CO, pp 439-443.

The dimensioning of geomembranes is an attempt to apply short and long term loading effects on various membrane materials to assist the design engineer in the proper selection for each site. Discusses design changes (loading rates) and liner thickness as they apply to reducing stresses on the membrane. Three loading tests are tear resistance, penetration resistance, and puncture resistance. All are a function of liner thickness. Absolute minimum liner thickness is 20 mils.

Short term loading occurs during construction and is difficult to model. Some times of loads include construction equipment, pulling the membrane across the facility, climate, improper seam techniques, and carelessness. Long term loading can be designed for and includes: compressive, shearing, and tensile stresses.

Compressive forces dominate the bottom and embankment and are considered evenly distributed. Local concentrations of stress can be reduced by carefully selected grain shape, grain size, and grain curve for the submaterial.

Shearing forces in solid waste impoundments occur when the waste settles and desifies. Can also occur during the cycling of fluids through an impoundment. To avoid excess tension, use an interfacial friction between geomembrane and submaterial greater than that between the membrane and the fluid. The friction will hold the material to the subgrade and prevent shear. As the angle increases, the cosine goes to zero, leaving the value T also at zero. Most shear values of membranes lied between 5 and 75% of the acceptable tensile stress of the material

Tensile forces occur because of differential settling of the subgrade or dead weight settling on the embankment and can be uniaxial or biaxial. Dead weight on embankments causes forces according to: F = W*(sin" - μ*cos") where the interfacial friction determines the force (also μ=tan" when under equilibrium) and the force increases with increasing angle, ". Differential settling can be assumed uniform also if the membrane has a high modulus of elasticity and is thick enough.

The text goes on to show examples of how the loading of the system changes with liner thickness, inclusion of drainage pipe, and deformation. All references are in German. The author is from Schlegel Lining Technology of West Germany,

Koerner, G.R., and Bove, J.A., "Inspection of HDPE Geomembrane Installations", Geosynthetics '89 Conference, San Diego, CA, pp 70-83.

HDPE is used in hazardous and nonhazardous applications. Regardless, there are precautionary procedures that should be followed to reduce the number of problems. HDPE has a permeability of 1 x 10^{-14} cm/sec, contains additives like carbon black, antidegradants, and solids, and has a density less than water.

There are three ways HDPE is manufactured: flat mouth extruder, calendered, and bubble extruded. The paper provides illustration of the equipment used.

CQC - Those actions which provide a means to measure and regulate the characteristics of an item or service to contractual and regulatory requirements.

CQA - A planned and systematic pattern of all means and actions designed to provide adequate confidence that items or services meet contractual end requirements and will perform satisfactorily in service.

The difference is that CQC is provided by the manufacturer and CQA is enforced in the field during installation. According to the authors, a CQA program should "cover every component or operation during construction", especially "qualification and cretification of the companies and their employees, certification and testing, and final documentation and warranty.

Certification and testing of HDPE resin focus on density, crystallinity, and the melt index. Testing of the HDPE geomembrane includes shear tests and additive delineation. A table of ASTM tests and min/max values is given. Field seams are also tested where nondestructive tests are done on 100% of the seams and destructive tests are not. Nondestructive seam tests include: air lance, mechanical point stress, vacuum chamber, dual seam, ultrasonic pulse echo, ultrasonic impedance, and ultrasonic shadow. Costs, speed of test, and results are given in table. Destructive seam tests are usually done at start-up each day and every 150 to 300 meters of seam. Two mechanical tests are performed: shear and peel tests.

Briefly discusses potential problems in the field as: rough subgrade during the pulling of the liner, shingling used to counteract any rainfall during installation, membrane will either stretch or trampoline due to temperature flunctuation, environmental stress cracking, inexperienced labor, sand bags filled with gravel, and membrane folded and not rolled.

Koerner, R.M., Lord, A.E., Jr., and Lucian, "A Detection and Monitoring Technique for Location of Geomembrane Leaks", International Conference on Geomembranes, Denver, Co, June 1984, pp. 379-387.

The three aspects of monitoring liner systems for leaks are detection, location, and magnitude. Mthods in use include monitoring wells, double liner with leachate collection, electrical resistivity, time domain reflectometry and acoustic emission monitoring. This paper discusses acoustic emissions which are the sounds generated by a leak. The acoustic emissions are picked up on piezoelectric sensors and the transducer produces an electrical pulse proportional to the amplitude of sound.

Koerner, R.M., and Richardson, G.N., "Design of Geosynthetic Systems for Waste Disposal", Geotechnical Practice for Waste Disposal '87, In Proceedings of a Specialty Conference, ASCE, University of Michigan, Ann Arbor, MI, June 1987, pp 65-81.

Geosynthetic systems include geotextiles, geomembranes, geogrids, and geocomposites which are used in liner systems to provide a man-made region of higher permeability through which leachate can be collected. Selection of geosynthetic depends on regulatory requirements (thickness of drainage soil and permeability) and minimum head requirements. Important design factors include: core strength to support load of impoundment material; transmissivity and core flow rate capabilities measured at maximum applied pressure and minimum hydraulic head; creep sensitivity of drainage core flow; elastic deformation of soil around geosynthetic, intrusion, and subsequent reduced flow; creep deformation of geosynthetics. Elastic intrusion poses the most severe problem.

Common failure mechanisms are: frictional downdrag of waste on liner; object impact on unprotected geosynthetic; puncture; anchorage of geomembrane; differential settling of subbase material. Seams are made using hot air, electrically heated blade, extrusion welding, flat welking, fillet welking, and solvents and adhesive bonding methods. Appurtenances are the most difficult to seam around.

Korfiatis, G.P., Rabah, N., and Lekmine, D., "Permeability of Compacted Clay Liners in Laboratory Scale Models", Geotechnical Practice for Waste Disposal '87, In Proceedings of a Specialty Conference, ASCE, University of Michigan, Ann Arbor, MI, June 1987, pp 611-624.

Study focused on the spatial variability of density and hydraulic conductivity in laboratory samples. Discusses microscopic and macroscopic variations in clay samples. As sample density increases, the effect of hydraulic gradient on the hydraulic conductivity decreases. Increased head may cause migration of fines and clogging/unclogging of pore spaces. Showed that k decreased with height of sample core (cut core into quarters) as a logarithmic, linear relationship. Explained these effects as due to either sample density variation or scale effects. "Close to two orders of magnitude decrease of k is observed for an increase of the modified Proctor density from 90% to 100%. Scale effects include the loss of cracks and fissures in the lab sample that occur in the field. Hydraulic conductivity shows a hysteris when compared to changes in surcharge pressure. Increases in pressure logically cause decreases in k, however, as pressure is released the value of k increases more rapidly. Author suggests the random spatial distribution of heterogeneity of the sample means that flow through liners is a stochastic process.

Lahti, L.R., King, S.K., Reades, D.W., and Bacopoulos, A., "Quality Assurance Monitoring of a Large Clay Liner", Geotechnical Practice for Waste Disposal '87, In Proceedings of a Specialty Conference, ASCE, University of Michigan, Ann Arbor, MI, June 1987, pp 640-654.

Discusses the clay liner beneath a landfill in Ontario, Canada located in a former sand and gravel pit. Ground water table is between 2 and 3 meters below landfill bottom. Hydraulic conductivity requirements were 1×10^{-8} at 1.2 meters thick. Trial sections were constructed. First section used 8 variations of water content and number of passes with 15,000 kg Caterpillar. Second section used 30,000 kg. Third section used a second soil type with 30,000 kg compactor. All soils were compacted at 95% Proctor density, in 150 mm lifts, first soil at > 20% clay, second soil at 10 to 16% clay, and total thickness 1.2 m for 1 and 3 and .6 m for 2. Heavy tractor had longer feet than smaller tractor and was more effective.

Liner was constructed using subbase at 95% Proctor, side-slopes of 2:1, leachate collection system to keep head below 3 m, clay at > 95% Proctor, > 20% clay content, 2-3% wet of optimum moisture, 1.2 meters thick, 150 mm lifts (200-300 mm uncompacted), using four padfoot compactors (39,000 lb on slopes, 76,200 to 69,500 lbs for base).

Quality Control: Boreholes and tests of soil borrow pit to establish variablity of properties; periodic testing of clay and water content; removal of rocks; periodic watering of clay due to heat of the day and watering before and after shift; continual visual inspection of soil for suitability; nuclear density tests; field and lab conductivity tests using a lightly oiled Shelby tube.

Monitoring: vibrating wire piezometers (monitor ground water level changes), areal collection lysimeters (seepage rates), conductivity sensors, and sub-liner water samplers (detect significant leakages).

Landreth, R.E., "Durability of Geosynthetics in Waste Management Facilities: Needed Research", EPA/600/D-86/268, EPA Cincinatti OH, PB89-132682 AS, Dec 1988.

Discussion of research needed with regards to the short-term and long-term performance of geosynthetics. Early uses of geosynthetics occured in the west and were mainly for containing water. Use extended to containing wastes from the food industries and municipal solid waste landfills. Initial questions posed included selection of FML, testing, and installation. Research began to test FMLs against waste constituents so a short-term testing procedure, Method 9090, was established. Installation research included soil bedding, site conditions, seaming, and construction quality control. Guidance documents were published that provided design criteria for stresses and a "design ratio".

The author states that the highest research priority is the longevity of FMLs used to contain wastes. Longevity of FMLs is a function of the environmental stresses imposed: chemical, biological, and mechanical. In summation, service life concerns are: combination stresses; swelling and softening; extraction, volitalization, and biodegradation; sedimentation and biological growth; and seams.

Landreth, R.E., "EPA Testing Program for Components of Treatment, Storage, and Disposal Facilities", EPA/600/D-87/058, EPA Cincinatti OH, PB87-167011.

Discusses EPA Method 9090 that was developed to test FMLs under environmental conditions similar to the field; uses an elevated temperature to hasten failure mechanisms, such as chemical attack and fatigue.

Landreth, R.E., "Lining of Waste Impoundment and Disposal Facilities", EPA SW-870, EPA Washington D.C., PB86-192796, Mar 1983, 480 pp.

Guidance document for the selection of liner systems given the type of impoundment and type of waste. Provides discussion on the types of hazardous waste components; types of liners (soil, admix, FML, spray-ons, soil sealants); failure mechanisms of each type of liner (lab studies and field data); design and construction of liner systems; leachate collection and management; operation and maintenance of lined facilities; costs of liner systems; selection criteria for choosing a liner type; ASTM construction specifications; listing of liner producers; liner test methods (appendiced); FML installation procedures; among others.

Landreth, R.E., "Locating and Repairing Leaks In Landfill/Impound-ment Flexible Membrane Liners", Geosynthetics '89 Conference, San Diego, CA, pp 467-477.

Includes a brief discussion of the techniques available to locate and repair leaks. Generally, the acoustic emission monitoring was abandoned because of the difficulty in establishing background data at each site. The principle is that fluids have specific sound levels as they travel, and the flow through a leak will be turbulent and more noisy. Field tests did not live up to the laboratory results. Sound attenuation was listed as the greatest problem.

Time-domain reflectometry was also studied. It uses parallel wires to detect moisture changes. The field results were as good as the laboratory but the projecte was still abandoned. Reasons include that the system has to be installed before the FML, the long-term durability of the wires was questionable, and the results from yet a third type of locater was better.

Electrical leak locators use the high electrical resistivity of the FML material such that the flow of current travels through the waste, the liner, and the leaks to return to the current electrode in the soil sayer. When no leaks are present this current has little voltage produced. The leak however, shows a larger voltage response because the leak is a conductive flowpath and allows a current density to build up. Discusses using ELL in double liner systems, locating leaks in covers (without water), differences in di-pole/pole, AC/DC, and other parameters. Field demonstrations through RSKLab indicate a 3/100 inch hole was detected within 5 ft.

Author discusses a computer model to help interpret the electrical signals into more useful graphs for the user.

Lindstrom, F.T., and Boersma, L. "A Theory on the Mass Transport of Previously Distributed Chemicals in a Water Saturated Sorbing Porous Medium", Soil Science, 1971, pp 192-199.

Numerical model of transport.

Lord, A.E., et al, "The Hydraulic Conductivity of Silicate Grouted Sands with Various Chemicals", National Conference on Management of Uncontrolled Hazardous Waste Sites (Barriers), 1983, Washington, DC pp175-178.

Cement grout curtains (not applicable)

Lundell, C.M., and Menoff, S.D., "The Use of Geosynthetics as Drainage Media at Solid Waste Sandfills", Geosynthetics '89 Conference, San Diego, CA, Volume I, pp 10-17.

In landfill applications, more attention is placed on the available "air space". Membranes are being used in the collection and detection of leachate in an effort to reduce the air space dedicated to this aspect. Geonets have the highest transmissivity of the membranes available.

Primary leachate collection (bottom to top): geomembrane, geonet, geotextile, protective soil as drainage. Or use: clay liner, geotextile, geonet, geotextile, protective soils layer or refuse.
Secondary leachate collection (bottome to top): geomembrane, geonet, geomembrane. Or use: geomembrane, geonet, geomembrane, bentonite matting, geomembrane. Or use: geomembrane, geonet, geotextile, drainage material, geotextile, and clay liner. Or use: clay liner, geotextile, geonet, geotextile, and clay liner.

Geonet design considerations are transmissivity (ASTM D4716), directional drainage characteristics (anisotrophy problems), leachate compatability, frictional characteristics (especially during installation; friction angles), and economics. Typical values of transmissivity are listed for geonets and geotextiles ($.30 to 1.00/yd depending on layers and material).

Construction guidelines include: only use membranes that have good quality control and match those listed in the design, have a quality assurance monitor on site at all times, have a quality assurance plan before construction begins, careful attention to the placement, orientation, and joining techniques used on the geomembranes, cleanliness of site during seaming, and careful storage of membranes.

Matrecon (Haxo), Inc., Lining of Waste Containment and Other Impoundment Facilities, EPA 600/2-88/052, Cincinatti, OH September 1988, pp 6-9 to 12-20.

A comprehensive review and discussion of liner systems written by Haxo and Matrecon, Inc., which covers soil, soil cement, admixes, asphalts, and flexible membrane liners. Discusses experiments, results, case histories, laboratory and field scale models. Lists factors to consider in the design, construction, and operation of liner systems. Site-specific factors related to failure mechanisms.

Metry, A.A., "Predictive Tools for Contaminant Transport in Ground Water", Permeability and Groundwater Contaminant Transport, ASTM STP 746, 1981, pp 197-208.

Good discussion of the available models and comparative tools available and in use for transport prediction. Describes attenuation potential of soil as physical, chemical, and biological processes. Pollution prediction techniques include criteria listing, criteria ranking, matrix, classification or decision trees, mathematical models, and column studies or laboratory experiments.

Mitchell, J.K., and Madsen, F.T., "Chemical Effects on Clay Hydraulic Conductivity", Geotechnical Practice for Waste Disposal '87, In Proceedings of a Specialty Conference, ASCE, University of Michigan, Ann Arbor, MI, June 1987, pp 87-116.

Good waste/liner compatability study looking at clay soils exposed to inorganic salts, acids, bases, hydrocarbons, other organics, alcohols and phenols, ethers, etc. Matrices.

Montalvo, J.R., "Evaluation of the Degradation of Geotextiles", Geosynthetics '89 Conference, San Diego, CA, pp 501-511.

Murray, R.S., and Quirk, J.P., :The Physical Swelling of Clays in Solvents", Soil Science Society of America Journal, Vol 46, pp 865-868.

Discusses the difference between intra-crystalline swelling and swelling between individual clay minerals. The former accounts for one-third of the total swelling volume. Weak trends have been seen between cations and swelling in water. Solvents and swelling have been studied using basal spacing but are limited to clay surface separations of less than 1 nanometer. This means that the distance is no more than a few molecule diameters and that the forces that occur at this spacing are strong and depend more on the properties of the molecule than the bulk fluid properties. The swelling that occurs between clay particles involves a larger spacing which allows the application of bulk fluid properties to predict swelling.

This study used two soils: loam containing 80% clay and Willalooka illite. Both soils had calcium as the major exchangeable cation, similar surface areas, and particle densities. The effect of exposing the clay soils to organic solvents was a linear increase in swelling with increase in dielectric constant. Swelling was reported in m^3/g.

The author discusses the effects of cation hydration on the short distance regime and the primary and secondary hydration shell molecules. In addition, discussion is given with regard to electrostatic forces between surfaces. A qualitative model is given that explains the distance of swelling to be a function of the cation valence, the eletronic charge, surface charge density, static dielectric constant, and the circumference of the cation.

Oakley, R.E.,"Design and Performance of Earth-lined Containment Systems", Geotechnical Practice for Waste Disposal '87, In Proceedings of a Specialty Conference, ASCE, University of Michigan, Ann Arbor, MI, June 1987, pp 117-137.

Safe earth-lined waste containment systems can be designed and constructed by (1) developing a thorough understanding of the foundation soils and ground water conditions at the site; (2) Selecting appropriate clay or clayey soils for the system liner that exhibit proper structural and permeability characteristics; (3) design the collection system to achieve all desirable technical and regulatory criteria; and (4) with proper consideration to material selection, moisture control, soil placement, and processing, compaction methodology and climatic effects.

Patterson, C.L., "Geosynthetic Modeling System-CBC Version 1.00 GM System's User Manuel", EPA/600/2-88/029, EPA Cincinatti, OH,
PB89-151195, Jan 1988.

Computer model designed to calculate a variety of design problems under five main categories: (1) Flexible Membrane Liners; (2) Leachate Collection and Removal Systems; (3) Leachate Collection (continued); (4) Ramp and Standpipe Considerations; and (5) Surface Water Collection and Removal Systems. Each main menu item has a submenu listing the types of calculations possible. The submenus include the following for each main menu item:

(1) permeability (pseudo and DeMinimis), tensile stress (liner weight and downdrag), subsidence, anchorage, and stability of soil cover.
(2) transmissivity (planar flow, operations, creep, and response time), permittivity.
(3) filter (retention of soil, clogging by soil), strength (sliding, settlement, support), strain (settlement).
(4) ramp (sliding, drainage, wheel loading), standpipe (down drag, puncture of FML).
(5) transmissivity, shear failure, tensile stress, settlement, wind lift.

Data needed for computations includes physical dimensions of impoundment, soil properties, FML properties, operational requirements, hydraulic gradients, stress and strain, tension, climatic conditions, construction equipment, appertunances, waste properties, among others.

See also PB89-151187 for diskettes; PB88-131263 for guidance document.

Peirce, J.J., Sallfors, G., and Peterson, E., "Clay Liner Construction and Quality Control", Journal of Environmental Engineering, Vol 112, No 1, Feb 1986, pp 13-25.

Comparison of handling, preparation and compaction of clay soils used for construction of liners in the field with moisture control, thickness, liner size, and tests.

Soil liner material choice begins with geologic investigation. Process soil by removing organic matter and sieving for both rocks and large clods. Wet soil by mixing with water and allowing to cure for about a week. Lifts are reported as non-compacted and compacted thicknesses. Thinner soil layers can be used with FMLs. Paper lists several sites and how they handled, prepared, and compacted the clay liners in the field including type of impoundment, preliminary soil tests, soil preparation, liner/lift thickness, moisture control, compaction equipment used, liner size, and type of liner tests. Discusses three commercial laboratory's methods of preparing soil samples for the hydraulic conductivity tests.

RCRA Guidance Document: landfill Design, Liner Systems and Final Cover, PB87-157657, EPA Washington, DC, 33 pps.

The guidance document does not specify the exact specifications for the design of liner systems or landfills but does provide a design that can comply with the regulations. A listing of items under Guidance includes:

- construct liner above the highest water table
- leachate collection systems and removal
- chemical resistance
- leak detection sysem
- primary and secondary liner systems

The text plainly discusses the fact that soil liners can have low permeability but will not prevent the movement of liquids. Minimization of movement can be designed for but not complete retainment. However, the text gives generous trust to membrane liners and their ability to prevent the movement of leachate. In this respect, the soil liner is a "back-up" to the impenetrable membrane liner. EPA also states that they are still accepting research information on the efficiency and effectiveness of soil and membrane liners.

The drainage media around the leachate collection system should have a permeability of 1×10^{-3} at a minimum thickness of 1 foot, and 2% minimum slope. At least 4 orders of magnitude difference in permeability should exist between the leachate collection media and any soil liner lying below it. The collection system should be protected from soil infiltration by using a geosythetic textile.

Specific guidance for membranes includes a minimum thickness of 30 mils and protection from damage by using a 6 inch subgrade and protective cover (USCS sand, SP). Soil liners should be compacted to a thickness of 2 feet and permeability less than 1×10^{-7} when in contact with the leachate of that impoundment. Soil liners cannot contain lenses, cracks, channels, root holes, or other nonuniformities. Lifts used to make each layer should not be greater than 6 inches to maximize compaction efforts.

Specific waste/liner incompatabilities were given:
- chlorinated solvents dissolve PVC
- aromatic hydrocarbons dissolve CSPE
- concentrated organics increase permeability of clays by several orders of magnitude
- oily wastes dissolve asphalts
- acids dissolve concrete and lime based materials
- high inorganics affect clays
- low pH affects clays
- inorganics at high and low pH also affect clays

Robertson, W.D., Barker, J.F., LeBeau, Y. and Marcoux, S., "Contamination of an Unconfined Sand Aquifer by Waste Pulp Liquor: A Case Study", Ground Water, Vol 22, No 2, Mar/Apr 1984, pp 191-197.

Ground water sampling strategy when waste was discharged into a sand pit included using multi-level piezometers to provide three-dimensional map of contaminant plume. Discusses attenuation of various components of the waste, migration rates, hydrodynamic dispersion, horizontal and vertical components of the plume movement, and effects of dilution at the plume leading edge.

Rogowski, A.S., Weinrich, B.E., and Simmons, D.E., "Permeability Assessment in a Compacted Clay Liner", The 8th Annual Madison Waste Conference: Municipal and Industrial Waste, Madison WI, Sept 18-19, 1985, pp 315-337.

A field scale clay liner was contructed to test hydraulic conductivity to determine primary and secondary flow mechanisms. It was determined that the primary flow was through preferential flowpaths and larger, continuous pores. The field test was 30 ft by 75 ft and utilized leachate collection systems to determine infiltration and flow rates of the leachate. A sampling grid was used such that attentuation measurements could be made at each 3 ft by 3 ft section of the entire test facility. Clay soil used was 86% passing the #200 sieve, 35/23/12 Atterberg limits (liquid limit, plastic limit, and plasticity index). A sheepsfoot roller was used for the base and a smaller vibrating roller was used at the edges. Liner was contructed wet of optimum. Iso-maps were made showing density, moisture content, water requirements, infiltration rates, and hydraulic conductivities.

Results showed that zones of higher conductivities, higher infiltration rates, and percolation correlated to the zones that were not fully saturated. The preferential flow paths were actually areas with lower compaction density.

Rollin, A.L., Vidovic, A., Denis, R., and Marcotte, M., "Evaluation of HDPE Geomembrane Field Welding Techniques: Need to Improve Reliability of Quality Seams", Intn'l Conference of Geosynthetics '89, San Diego, CA pp 443-455.

The text is difficult to read but there are valuable diagrams. A graph of membrane thickness versus maximum welding speed indicates that an acceptable welding range occurs by comparing the weak and strong peal strengths. The graph of seam peel strength versus welding speed indicates that the influence of dirt or clay particles on the seam strength causes the initial strength to decrease, whereas if the membrane is dry and clean, the seam strength starts higher and still decreases and plateaus to a value higher than when dirty.

The same can be said when comparing dry and wet membranes while seaming. The graph of peel strength versus geomembrane thickness shows a clear increase in strength (150 x 10^2/m to 200 x 10^2 with a doubling of thickness. The welding speed also affects the welding seam at different overlap welding thicknesses. A typical welding speed is 2.5 to 3 meter/ minute. Then the material is preheated before welding, the seam peel strength optimizes between a temperature range. This range is different for different materials. For HDPE the range is 100 to 120 C. Similarly, the pressure applied directly after the weld is made optimizes with peel strength at different membrane thicknesses. For HDPE, the optimum strength occurs when pressure applied is between 300 and 440 kN/m^2.

The author critiques the destructive method (ASTM D638) and nondestructive method (ASTM D413). Neither test was designed for the application it is used for today with hazardous wastes. The use of the Shear test result is qualifiable not quantifiable. The Peel Test has been updated to include a peel strength acceptance requirement coefficient, C, which is generally 0.70. and represents the ratio between the peel strength at break point and the tensile strength at yield.

Rossman, L.A., and Haxo, H.E., Jr., "A Rule-Based Inference System For Predicting Liner/Waste Compatibility", EPA/600/D-85/212, EPA Cincinatti OH, PB86-102647, Sept 1985.

This study looked specifically at PVC to illustrate how expert opinion could be placed in a structured system that less experienced personnel could use to determine whether waste/liner compatability exists. The "production system" (basis of expert systems) was used which is a collection of rules and scoring procedures for utilizing immersion test results into (waste/liner compatability) conclusions. The program uses IF/THEN statements for the rules, a database to store the "answers", and a control system sorts out the importance level of each "answer". THEN statements can be associated with a "certainty percentage" or

other scoring mechanism.

The production system for PVC approached the following problems: inadequate elongation retention, excessive plasticizer loss, excessive waste absorption, and violations of service-ability limits. For example, the service-ability limits, like weight gain, are tested using a variety of IF/THEN statements to determine whether gain is by water or waste. The use of production or expert systems will reduce the problems associated with differences in professional opinion, help direct the investigation, and save time.

Schubert, W.R., "Bentonite Matting in Composite Lining Sysems", Geotechnical Practice for Waste Disposal '87, In Proceedings of a Specialty Conference, ASCE, University of Michigan, Ann Arbor, MI, June 1987, pp 784-797.

Schwope, A.D., Costas, P., and Lyman, W., "Resistance of Flexible Membrane Liners to Chemicals and Wastes", EPA/600/2-85/127, EPA Cincinatti OH, PB86-119955, Oct 1985.

A collection of qualitative and quantitative information from vendors of FMLs and their compatability with various wastes were rated (not rated as basis for selection or appropriateness for any individual application). A chemical resistance matrix is provided along with a summary of published data.

Skopp, J. and Warrick, A.W., "A Two-phase Model for the Miscible Displacement of Reactive Solutes in Soils", Soil Science Society of America Proceedings, Vol 38, No 4, Jul/Aug 1974, pp 545-550.

Numerical modeling using pore geometry.

Theng, B.K.G., "Clay-Polymer Interactions: Summary and Perspectives", Clay and Clay Minerals, Vol 30, No 1, (1982), pp 1-10.

Clay-polymer interactions are important when determining the relationships between soil and humus. Polymers interact with the soil surface because they are long-chained, flexible, multisegmented, and polyfunctional and can attach to the surface with numerous bonds per molecule. Interest in this is due to the desorption of water molecules when the polymer is adsorbed. Author describes the gain in entropy as the driving mechanism for the desorption/adsorption. Random coils of polymers attach to the surface in flattened configurations allowing for significant adsorption energies to develop as many segments adsorb. Author states that an average of 40% of available segments can adsorb to the clay surface. When the polymers are charged, the adsorption process is further complicated by effects due to pH and ionic strength.

Villaume, J.F., Lowe, P.C., and Unites, D.F., "Recovery of Coal Gasification Wastes: An Innovtive Approach", In Proceedings of the Third National Symposium on Aquifer Restoration and Ground Water Monitoring, National Water Well Association, Columbus, OH, May 25-27, 1983, pp 434-445.

This paper was referenced by RSKLab regarding the effect high hydraulic gradients has on the permeability measurements of clays in contact with solvents. The only discussion that relates to this topic is about the capillary pressure required to move coal tar through sand and gravel media. The critical height of fluid needed to overcome the capillary pressure is a function of the interfacial tension, the contact angle, the radius of the pore throat, the radius of the pore, gravity, and the densities of the solute and solvent.

If the contaminant liquid height does not exceed this critical value, the contaminant will not flow. The dominant transport mechanism would then be Fickian diffusion.

Wallace, R.B., "The Benefits of Construction Quality Assurance of Lining Systems Installation: Real or Perceived?", Geosynthetics '89 Conference, San Diego, CA, Volume I, pp 84-94.

This paper is a review of 50 CQA programs used since the passage of HSWA. Potential benefits of a CQA program are: higher quality construction, fewer problems during and subsequent to construction, facilitated investigation and remediation of problems that do occur after commencement of operations, potential lower costs, and better protection of human health and the environment. Cost of CQA program runs 10 to 15% of total lining system cost. Of the 50 sites, panel repairs made that were identified by CQA represented 74% of total. Seam repairs made equaled 33% of total. Overall, repairs detected by CQA was 40%. This represents a significant contribution to the success of the installation.

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