Geomembranes Used in Dam Waterproofing and Lifetime Prediction

1.0 Relevant Applications
2.0 Geomembranes
3.0 Degradation and Lifetime Prediction
4.0 GM Lifetime Prediction
5.0 Summary and Recommendations
1.0 Relevant Applications

1.1 Earth and Earth/Rock Dams
1.2 Roller Compacted Concrete Dams
1.3 Concrete and Masonry Dams

(First, let’s look at some leakers)!
Downstream Masonry Dam Water Markings
Major Upstream Vertical Crack in Concrete Dam
Downstream Seepage in Concrete Dam
Same Dam as Before with Upstream Water Level Increased!
1.1 Earth and Earth/Rock Dams

- GM placed against upstream face
- Stone rip-rap placed above GM
- Requires GT cushion between GM and rip-rap... GT mass is critical issue and a crisp design method is available
- Typ. slopes are 2/1 to 4/1 (26° to 14°)
Tailings Dam, Eigenbrod, et al., 1984
The GM before GT & rip rap covering
THE GEOMEMBRANE IS THE ONLY WATERTIGHT ELEMENT OF THE DAM
MORAVKA DAM,
Czech Republic,
26,400 m² installed in
80 days
1.2 Roller Compacted Concrete Dams

- consists of cement/soil mixture
- placed and compacted in horizontal lifts
- results in steep sloping or vertical face
- upstream GM waterproofing methods:
  (a) rip-rap/GT/GM if sloping, or if vertical
  (b) channel inserts placed in RCC for subsequent GM fixity, or if vertical
  (c) prefabricated panels of GM/GT/concrete panels
- several case histories available; see following
Method (a) – Rip-rap/GT/GM

- for sloping upstream surfaces, the method is identical to earth and earth/rock dams
- critical aspect becomes the stability of the rip-rap for steep slopes
- when > 2 to 1 (26°); a different strategy must be used (method “b” or “c”)

Method (b) – Channel Insert (or Profiles) Placed on Formwork Before RCC Placement

Placing vertical profiles

Joining edges of profiles
Insert and Channel Will be Embedded in RCC
After RCC Cures, Panels are Stripped and GM inserted between Profiles and attached accordingly.
Method (c) – GM Attached to Panels

- CARPI – Winchester Method
- concrete panels ~ 100-150 mm thick
- factory precast with GT/GM facing
- at site, panels used for upstream falsework
- GM is protected accordingly
Placing geocomposite on precast concrete panels
GT (white) Against Concrete; GM Above
Cured Panels Being Placed; Note Edge Strips
Initially Placed Panels; GM to Interior
Welding PVC strips along panels
Placement of RCC Using Panels as Falsework
1.3 Concrete and Masonry Dams

- GM in vertical strips ~ 2 m wide
- held against dam by metal batten strips
- anchor bolts must be installed first
- this is the major cost item
- several clever schemes available
- following is the CARPI-method
Typical Layout of GM Panels

- Geomembrane panels
- 1 to 3 m (typ.)
- Drainage collection system behind GM panels
- Outlet drain (through dam)
- Stainless steel batten strips or "profiles"
CARPI Method of Attaching Geomembrane Panels to Dam Face Using Continuous "Profiles"
Work in Progress – Inserting Anchor Belts
Placing GM/GT Composite Within Profiles
Photo Taken in 1996
When GM was 15-year in Service
DAMS WITH COMPLICATED SHAPE, GIROTTE DAM, France

What a Design? It needed Help!
Geocomposite mechanically fastened
Concrete and Masonry Dam Rehabilitation in Italian Alps by ENEL (after Cazzuffi, 1987)

<table>
<thead>
<tr>
<th>Name</th>
<th>Sabetta</th>
<th>Bartone</th>
<th>Miller</th>
<th>Nero</th>
<th>Locone</th>
<th>Castroceioni</th>
<th>Cignana</th>
<th>Barbellino</th>
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<tbody>
<tr>
<td>Height (m)</td>
<td>32</td>
<td>37</td>
<td>11</td>
<td>40</td>
<td>13</td>
<td>67</td>
<td>58</td>
<td>69</td>
</tr>
<tr>
<td>Age (years)</td>
<td>30</td>
<td>60</td>
<td>62</td>
<td>63</td>
<td>new</td>
<td>new</td>
<td>62</td>
<td>61</td>
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<tr>
<td>Area (m²)</td>
<td>2600</td>
<td>3500</td>
<td>1500</td>
<td>4000</td>
<td>28,000</td>
<td>46,000</td>
<td>10,000</td>
<td>5500</td>
</tr>
<tr>
<td>Type</td>
<td>TS</td>
<td>TS</td>
<td>PVC</td>
<td>PVC</td>
<td>TS</td>
<td>PVC</td>
<td>PVC</td>
<td>PVC</td>
</tr>
<tr>
<td>Thickness (mm)</td>
<td>2.0</td>
<td>2.0</td>
<td>1.8</td>
<td>1.9</td>
<td>1.5</td>
<td>1.2</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>Drainage</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
</tbody>
</table>

Problematic  Successful
Some Observations

- Work initiated in Italy by ENEL and CARPI
- 2004 report by Intl. Comm. on Large Dams shows 380 dams retrofitted using GMs
- Majority are in Europe and China
- Very few in USA; an obvious reluctance exists (why???)
- Let’s assume its polymer lifetime!
2.0 Geomembranes

- name obtained by parent resin, yet
- all geomembranes are formulations
- specially formulated PVC used widely
- patented products by one company
- parallel PVC product or other comparable resins are desirable
- let’s see what’s available
Commonly Used Geomembranes and Their Approximate Weight Percentage Formulations

<table>
<thead>
<tr>
<th>Type</th>
<th>Resin</th>
<th>Plasticizer</th>
<th>Fillers</th>
<th>Carbon Black</th>
<th>Additives</th>
</tr>
</thead>
<tbody>
<tr>
<td>HDPE</td>
<td>95-98</td>
<td>0</td>
<td>0</td>
<td>2-3</td>
<td>0.25-1</td>
</tr>
<tr>
<td>LLDPE</td>
<td>94-96</td>
<td>0</td>
<td>0</td>
<td>1-3</td>
<td>0.25-4</td>
</tr>
<tr>
<td>fPP</td>
<td>85-98</td>
<td>0</td>
<td>0-13</td>
<td>2-4</td>
<td>0.25-2</td>
</tr>
<tr>
<td>PVC</td>
<td>50-70</td>
<td>25-35</td>
<td>0-10</td>
<td>2-5</td>
<td>2-5</td>
</tr>
<tr>
<td>CSPE</td>
<td>40-60</td>
<td>0</td>
<td>30-40</td>
<td>5-10</td>
<td>5-15</td>
</tr>
<tr>
<td>EPDM</td>
<td>25-30</td>
<td>0</td>
<td>20-40</td>
<td>20-40</td>
<td>1-5</td>
</tr>
</tbody>
</table>

HDPE = high density polyethylene  
LLDPE = linear low density polyethylene  
fPP = flexible propylene  
PVC = polyvinyl chloride (plasticized)  
CSPE = chlorosulfonated polyethylene  
EPDM = ethylene propylene diene terpolymer
Important Issues

- within same polymer type, different AO’s, plasticizers, and fillers will give vastly different performance
- comparison of performance (field and lab) must be done on same polymer and its specific formulation
- particularly the case for exposed versus nonexposed applications
3.0 Degradation and Lifetime Prediction

Degradation Mechanisms

- oxidation (all types)
- hydrolytic (all types)
- chemical (all types)
- stress cracking (HDPE only)
- plasticizer extraction (PVC only)
- crosslinking (TS’s only)
- ultraviolet (exposed only)
In General:

Reaction will cause ductile-to-brittle behavior

\[ \text{Stress } (\sigma) \]
\[ \text{Strain } (\varepsilon) \]

\( \varepsilon_f \) decreases
\( E \) increases
\( \sigma_f \) increases some
then decreases

Thus, a limit could be the time required for a 50% reduction in “\( \varepsilon_f \)”; this is called a “halflife” value and is a good target
Investigative Options*

(a) “try, wait and see”
   - without monitoring
   - with monitoring

(b) let others “try, wait and see”
   - without monitoring
   - with monitoring

(c) perform accelerated laboratory studies

*Let’s look into option “c” or else we don’t have anything to present !!!!
Time-Temperature Superposition

- most (all?) degradation mechanisms occur proportionate to temperature
- higher the temperature; faster the reaction
- holds for oxidation, hydrolysis, chemical, ultraviolet, migration, biological, radioactive mechanisms (but does not apply to stress)
- target is a predetermined change in some engineering property, e.g., “50% failure strain”
Lifetime Prediction

- following is common for many materials, including plastics (100’s of references)
- uses time-temperature superposition
- then plots data on Arrhenius graph for extrapolation down to the site-specific temperature
- 3-stages are defined…
Incubated Property Behavior

A = Antioxidant depletion  
B = Induction time  
C = Half-life of property
Incubated Property Behavior

A = Antioxidant depletion
B = Induction time
C = Half-life of property
Arrhenius Plot for Stage “C” (1/2 Life)

Reaction Rate \( (1/t_i) \)

\[ \frac{1}{T_i}, \frac{1}{t_i} \]

\[ 1/T_{site} \]
In General…

- above is for HDPE, LLDPE, and fPP
- for PVC; Stage A is plasticizer migration
- for CSPE & EPDM; Stage A is crosslinking
- let’s see some numbers!
4.0 Geomembrane Lifetime Prediction

- its all time-temperature superposition
- followed by Arrhenius plotting
- governs entire plastics industry
- GRI work on nonexposed HDPE follows… (it was driven by landfill concerns)
- EPA sponsored all of the work (about 7-years and expensive)
4.1 Behavior of HDPE Geomembranes

Diagram of compression column for incubation at different temperatures (Setup simulates GM beneath landfills)
(a) Depletion of Antioxidants

Standard OIT versus incubation time plot
Assuming that the service lifetime is 20°C and the OIT of unstabilized HDPE fluff is 0.5 min. in standard test and 25 min. in high pressure test

(a) for standard-OIT tests:
\[
\ln (OIT) = \ln(P) + (S) \cdot (t)
\]
\[
\ln (0.5) = \ln (80.5) + (-0.0033)\cdot(t)
\]
\[t = 2397 \text{ months (200 years)}\]

(b) for high pressure-OIT tests:
\[
\ln (OIT) = \ln(P) + (S) \cdot (t)
\]
\[
\ln (25) = \ln (210) + (-0.0014)\cdot(t)
\]
\[t = 2590 \text{ months (215 years)}\]
(b) Induction Time

- we retrieved HDPE containers from the bottom of a failed landfill
- adjacent articles were 25-30 yrs. old
- containers were unstabilized HDPE
- 1 water jug and 3 milk containers
- tested old vs. new specimens
Predicted Induction Time

- it’s based on lean data
- if samples were 25-30 yrs. old and typical of new containers …
- properties just beginning to degrade
- therefore, induction time ~ 30 yrs.
(c) Time to Reach Half-life

- need slope of Arrhenius curve
- GRI data just becoming available
- Viebke, et al. (1994) found for unstabilized polyethylene pipe over temperature range of 115 to 70°C

\[ E = 80 \text{ kJ/mol} \]

- at 115°C the reaction time was 90 days
Extrapolation from 115°C to 20°C (site-specific)

\[
\frac{R_{r@115}}{R_{r@20}} = e^{\frac{-E_{act}}{RT}\left[\frac{1}{115+273} - \frac{1}{20+273}\right]}
\]

\[
\frac{R_{r@115}}{R_{r@20}} = e^{\frac{-80,000}{8.314}\left[\frac{1}{388} - \frac{1}{293}\right]}
\]

\[
\frac{R_{r@115}}{R_{r@20}} = e^{8.04} = 3027 \text{ (times faster at 115°C than 20°C)}
\]

Thus,

\[
R_{r@20} = (3027)(90)
\]

\[
= 272,000 \text{ days}
\]

\[
= 746 \text{ years}
\]
(d) **Summarizing the Previous Calculations**

<table>
<thead>
<tr>
<th>Stage</th>
<th>Description</th>
<th>Duration (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Antioxidant Depletion</td>
<td>200</td>
</tr>
<tr>
<td>B</td>
<td>Induction Time</td>
<td>30</td>
</tr>
<tr>
<td>C</td>
<td>Halflife of Engineering Property</td>
<td>740</td>
</tr>
<tr>
<td>Total</td>
<td>Lifetime Estimate*</td>
<td>~ 970</td>
</tr>
</tbody>
</table>

*to halflife of strain at failure at 20°C exposure temperature!
Dry Cell Liner Temperature

Dry Cell Cover Temperatures

Temperature Readings via Thermocouples Placed Directly on the Geomembranes Beneath and Above a Municipal Solid Waste Landfill in Pennsylvania

Now the Bad News!
## Lifetime Prediction of HDPE at Elevated Field Service Temperatures

<table>
<thead>
<tr>
<th>Field Temperature</th>
<th>Stage “A” (yrs.)</th>
<th>Stage “B” (years)</th>
<th>Stage “C” (yrs.)</th>
<th>Total Ave. Years</th>
</tr>
</thead>
<tbody>
<tr>
<td>C (deg)</td>
<td>F (deg)</td>
<td>Std OIT</td>
<td>HP-OIT</td>
<td>Ref. 1</td>
</tr>
<tr>
<td>20</td>
<td>68</td>
<td>200</td>
<td>215</td>
<td>30</td>
</tr>
<tr>
<td>25</td>
<td>77</td>
<td>135</td>
<td>144</td>
<td>25</td>
</tr>
<tr>
<td>30</td>
<td>86</td>
<td>95</td>
<td>98</td>
<td>20</td>
</tr>
<tr>
<td>35</td>
<td>95</td>
<td>65</td>
<td>67</td>
<td>15</td>
</tr>
<tr>
<td>40</td>
<td>104</td>
<td>45</td>
<td>47</td>
<td>10</td>
</tr>
</tbody>
</table>

Notes: Stage “A” measured values from G. Hsuan research  
Stage “B” estimated values from field samples  
Stage “C” literature values from Martin & Gardner\(^{17}\) and Viebke, et al.\(^{18}\)
### 4.2 Halflife of Different Nonexposed Geomembranes*

<table>
<thead>
<tr>
<th>Material</th>
<th>Halflife Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>HDPE</td>
<td>see previous</td>
</tr>
<tr>
<td>LLDPE</td>
<td>somewhat less</td>
</tr>
<tr>
<td>fPP</td>
<td>somewhat less</td>
</tr>
<tr>
<td>PIB, IIR, EPDM</td>
<td>seam concerns</td>
</tr>
<tr>
<td>PVC-P</td>
<td>plasticizer dependent</td>
</tr>
</tbody>
</table>

*this is essentially arm-waving; a tremendous research effort is necessary to quantify*
4.3 Exposed Durability and Lifetime

- degradation mechanisms are the same as nonexposed “plus” ultraviolet and high ambient temperatures
- both are more severe than other mechanisms
- experimental approach is completely different
- laboratory weatherometers are used which impose UV, elevated temperature and moisture
- predictive methods are available; but very approximate (example will follow)
The wavelength spectrum of visible and UV solar radiation. (After Q-Panel Co., Cleveland, OH)
## Various Accelerated Weathering Devices

<table>
<thead>
<tr>
<th>Weathering Device</th>
<th>Test Standard</th>
<th>Special Items</th>
<th>Radiation (nm)</th>
<th>Temperature (°C)</th>
<th>Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xenon Arc</td>
<td>ASTM G155, ASTM D4355</td>
<td>borosilicate filters</td>
<td>300 – 800</td>
<td>60-65</td>
<td>spray</td>
</tr>
<tr>
<td>Ultraviolet Fluorescent</td>
<td>ASTM G154, GRI-GM11</td>
<td>solar eye system</td>
<td>300 – 400</td>
<td>65-75</td>
<td>condensation</td>
</tr>
<tr>
<td>EMMAQUA (Outdoor)</td>
<td>ASTM G90</td>
<td>none</td>
<td>full solar range</td>
<td>40-60</td>
<td>spray</td>
</tr>
</tbody>
</table>
Predictive Methodology

Example: A geotextile reached its halflife elongation in Xenon Arc device (517.8 W/m²) in 2000 hours. What is the equivalent lifetime in Philadelphia exposure? Note: Jewell (J) = watts (W) x seconds (sec)

Solution:

\[ E_{\text{test}} = (517.8)(2000)(3600)(1 \times 10^{-6}) \]

\[ = 3728 \text{ MJ/m}^2 \]

\[ E_{\text{Phila}} = (5021 \text{ MJ/m}^2 - \text{yr.})(1/4 \text{ sun time}) \]

\[ = 1255 \text{ MJ/m}^2 - \text{year} \]

\[ T_{\text{Phila}} = \frac{3728}{1255} = 2.97 \text{ years} \]

Thus: Acceleration Factor of the Weatherometer is

\[ AF = \frac{(2.97)(365)}{(2000)(1/24)} = 13! \]
Comment:

- previous example was for a geotextile
- geomembranes are much more durable due to their lower surface area and more AO’s (e.g., a 50-yr GM would require 3.8-yrs of testing)
- formulations (plasticizers and antioxidants are critical issues)
- light color is an important consideration
- to evaluate GMs is a lengthy process
## 5.0 Summary & Recommendations

<table>
<thead>
<tr>
<th>Dam Application</th>
<th>UV-Exposed</th>
<th>Temperature</th>
<th>Freeze/Thaw Cycle</th>
<th>Wet/Dry Cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earth or Earth Rock</td>
<td>no</td>
<td>below ambient</td>
<td>varies</td>
<td>yes</td>
</tr>
<tr>
<td>Roller compacted concrete</td>
<td>no</td>
<td>below ambient</td>
<td>nominal</td>
<td>yes</td>
</tr>
<tr>
<td>Masonry or Concrete</td>
<td>yes</td>
<td>ambient</td>
<td>yes</td>
<td>yes</td>
</tr>
</tbody>
</table>
Recommendations

- GMs well suited for dam waterproofing
- **covered durability** of GMs is excellent
- **exposed durability** is significantly shorter
- GM polymer and formulation is critical
- additives (e.g., antioxidants and plasticizers) are particularly critical
- GSI will mount a major initiative (CPHyS)
- GMs won’t always be the best solution; but they should always be considered
Your attention and interest is appreciated!