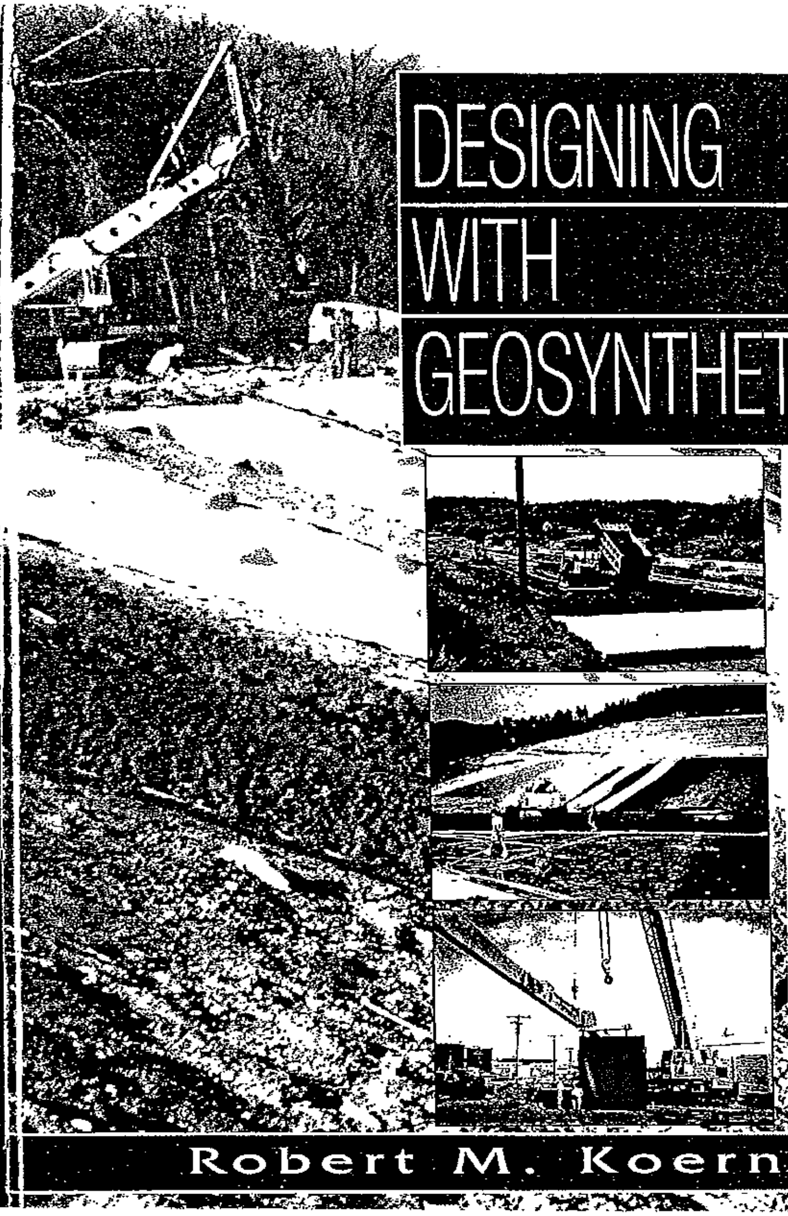
DESIGNING WITH GEOSYNTHETICS

Fourth Edition



Robert M. Koerner

Fourth Edition

Designing with Geosynthetics

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within the molecular structure. It eventually reacts with another polymer chain, creating a new free radical and causing chain scission. The reaction generally accelerates once it is triggered, as shown in the following equations.

$$R\cdot + O_2 \rightarrow ROO\cdot \quad (5.10)$$

$$ROO\cdot + RH \rightarrow ROOH + R\cdot \quad (5.11)$$

where

R· = free radical
ROO· = hydroperoxy free radical
RH = polymer chain
ROOH = oxidized polymer chain

Antioxidation additives (antioxidants) are added to the compound to scavenge these free radicals in order to halt, or at least to interfere with, the process. These additives, or stabilizers, are specific to each type of resin (recall Table 1.5). This area is very sophisticated and quite advanced with all the resin manufacturers being involved in a meaningful and positive way. The specific antioxidants that are used are usually proprietary (see Hsuan et al. [30] for a review of the topic). The removal of oxygen from the geomembrane's surface, of course, eliminates the concern. Thus once placed and covered with waste or liquid, degradation by oxidation should be greatly retarded. Conversely, exposed geomembranes or those covered by nonsaturated soil will be proportionately more susceptible to the phenomenon. It should be recognized that oxidation of polymers will eventually, perhaps after hundreds of years, cause degradation even in the absence of other types of degradation phenomena.

There are two related test methods that are used to track the amount and/or depletion of antioxidants. They are called *oxidative induction time* (OIT) tests and are performed with a DSC device as described in Section 1.2.2.

Standard OIT. (ASTM D3895); The oxidation is conducted at 35 kPa and 200°C. This test appears to misrepresent antioxidant packages containing thiosynergists and/or hindered amines due to the relatively high test temperature.

High Pressure OIT. (ASTM D5885); The oxidation is conducted at 3500 kPa and 150°C. This test can be used for all types of antioxidant packages and is the preferred test.

By conducting a series of simulated incubations at elevated temperatures, OIT testing can be conducted on retrieved specimens to monitor the antioxidant depletion rate. As will be seen in Section 5.1.5, this leads to lifetime prediction via Arrhenius modeling.

Synergistic Effects. Each of the previous degradation phenomena has been described individually and separately. In practice, however, it is likely that two or more mechanisms are acting simultaneously. For example, a waste-containment geomembrane may have anaerobic leachate above it and a partially saturated leak-detection network containing oxygen below it. Thus chemical degradation from above and oxidation degradation from below will be acting on the liner. Additionally, elevated temperature from decomposing solid waste and the local stress situation may complicate the situation further. Evaluation of these various phenomena is the essence of geomembrane lifetime prediction.

5.1.5 Lifetime Prediction Techniques

Clearly, the long time frames involved in evaluating individual degradation mechanisms at field-related temperatures and stresses, compounded by synergistic effects, are not providing answers regarding geomembrane behavior fast enough for the decision-making practices of today. Thus accelerated testing, either by high stress, elevated temperatures and/or aggressive liquids, is very compelling. As will be seen, all of the methods use these ways of accelerating the test, time-temperature superposition being of fundamental importance.

Stress-Limit Testing. Focusing almost exclusively on HDPE pipe for natural gas transmission, many institutions are active in various aspects of plastic pipe research and development. Stress-limit testing in the plastic pipes has proceeded to a point where there are generally accepted testing methods and standards. ASTM D1598 describes a standard experimental procedure and ASTM D2837 gives guidance on the interpretation of the results of the D1598 test method.

In these experiments, long pieces of unnotched pipe are capped and placed in a constant temperature environment; a room temperature of 23°C is usually used. The pipes are placed under various internal pressures, which mobilize different values of hoop stress in the pipe walls. The pipes are monitored until failure occurs, which is indicated by a sudden loss of pressure. Then the values of hoop stress are plotted versus failure times on a log-log scale (see Figure 5.15). If the graph is reasonably linear, a straight line is extrapolated to the desired, or design, lifetime, which is often 10^5 hours or 11.4 years. The stress at this failure time multiplied by an appropriate factor is called the *hydrostatic design basis stress.* While this is of interest for pipelines, the stress state of geomembranes is essentially unknown and is extremely difficult to model. Thus the technique is not of direct value for geomembrane design. It leads, however, to the next method.

Rate Process Method (RPM) for Pipes. Research at the Gas Institute of The Netherlands (Wolters [31]), uses the method of pipe aging that is most prevalent in Europe. The experiments are again performed using long pieces of unnotched pipe that are capped, but now they are placed in various constant-temperature environments. So as to accelerate the process, elevated temperature baths up to 80°C are used. The pipes are internally pressurized so that hoop stress occurs in the pipe walls. The pipes are monitored until failure occurs, resulting in sudden loss of pressure. Two distinct types of failures are found: ductile and brittle. The failure times corresponding to each applied pressure are recorded. A response curve is presented by plotting hoop stress against failure time on a log-log scale.

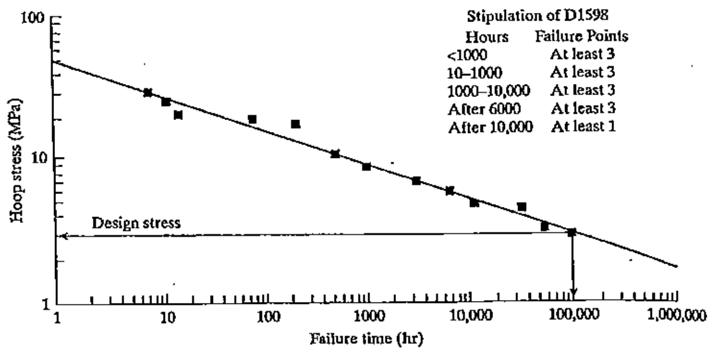

Figure 5.15 Schematic plot of time of failure versus pipe hoop stress for burst testing of unnotched MDPE pipe.

The rate process method (RPM) is then used to predict a failure curve at some temperature other than the high temperatures tested, that is, at a lower (field-related) temperature. This method is based on an absolute reaction rate theory and is explained in [32]. The relationships between the failure time and stress are expressed in the form of one of the following equations:

$$\log t_f = A_0 T^{-1} + A_1 T^{-1} \sigma \tag{5.12}$$

$$\log t_f = A_0 + A_1 T^{-1} + A_2 T^{-1} P \tag{5.13}$$

$$\log t_f = A_0 + A_1 T^{-1} + A_2 \log P \tag{5.14}$$

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where

t_f = time to failure,
T = temperature,
σ = tensile stress,
A_0 and A_1 = constants, and
P = internal pipe pressure proportional to the hoop stress in the pipe.

The application of RPM requires a minimum of two experimental failure curves at different elevated temperatures, generally above 40°C. The equation that yields the best correlation to these curves is then used in the prediction procedure for a response curve at a field-related temperature (e.g., 10 to 25°C). Two separate extrapolations are required, one for the ductile response and one for the brittle response. Three representative points are chosen on the ductile regions of the two experimental curves. One

curve will be selected for two points, and the other, for the remaining point. These data are substituted into the chosen equation to obtain the prediction equation for the ductile response of the curve at the desired (lower) temperature. The process is now repeated for the predicted brittle response curve at the same desired temperature. The intersection of these two lines defines the transition time.

Figure 5.16 shows two experimental failure curves that were conducted at temperatures of 80°C and 60°C along with the predicted curves at 20°C. The intersection of the linear portions of the 20°C curve represents the anticipated time for transition in the HDPE pipe from a ductile to a brittle behavior of the material. For pipe design, however, the intersection of the desired service lifetime, say 50 years, with the brittle curve as the focal point. A factor of safety is then placed on this value, for example, note that it is lowered in Figure 5.16. This value of stress is used as a limiting value for the internal pressure in the pipe.

Rate Process Method (RPM) for Geomembranes. A similar RPM method to that just described for HDPE pipes can be applied to HDPE geomembranes. The major difference is the method of stressing the material. The geomembrane tests are performed using a notched constant load test (NCTL) (recall Section 5.1.3). Figure 5.17 shows typical experimental curves at 50°C and 40°C, which are very similar to the behavior of MDPE pipe. Here distinct ductile and brittle regions can be seen along with a clearly defined transition time.

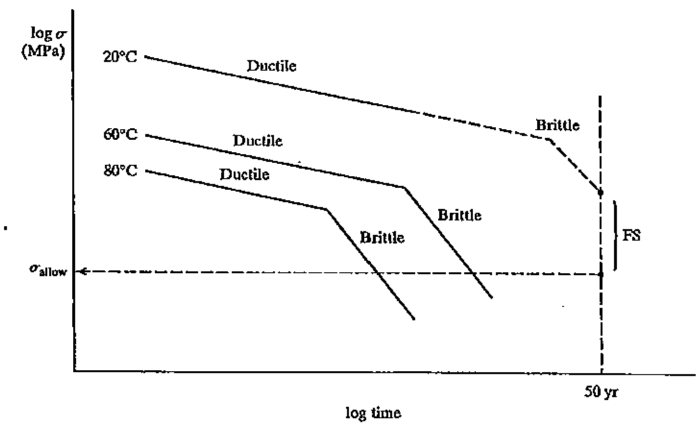


Figure 5.16 Burst test data for unnotched MDPE pipe in tap water. The intersection of the ductile portion of the 20°C line and 50 years has been lowered by the appropriate factor of safety.

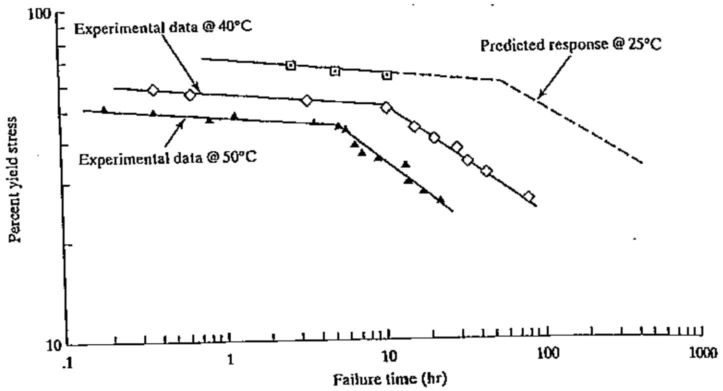


Figure 5.17 Notched constant load tests on HDPE geomembrane samples immersed in 10% Igepal/90% tap water solution.

In order to use these elevated temperature curves to obtain the transition time for a realistic temperature of a geomembrane beneath solid-waste or liquid impoundments (e.g., 20 to 25°C), only Eqs. (5.14) or (5.15) can be used, due to the data being plotted in a log-log scale. How the curves are shifted to the site-specific lower temperature is explained in detail in [32].

The process of predicting lifetime can now follow that outlined in Figure 5.16. A design lifetime can be assumed and a percent allowable stress can be determined. Conversely, a maximum allowable design stress can be given from which the unknown lifetime can be determined. Work is ongoing using this approach.

Hoechst Multiparameter Approach. The Hoechst research laboratory in Germany has been active in the long-term testing of polyethylene pipe since the 1950s. They have also applied their expertise and experience to the long-term behavior of HDPE geomembranes (Koch et al. [33]). The Hoechst long-term testing for a geomembrane sheet consists of the following procedure:

1. Perform a modified burst testing of pipe (of the same material as the geomembrane) with additional longitudinal stress to produce an isotropic biaxial stress state. Note that the site-specific liquid should be used.
2. Assume a given subsidence strain-versus-time profile.
3. Measure the stress relaxation curves in sheets that have been stressed biaxially at strain values encountered in field.
4. Use Steps 2 and 3 to predict the stress as a function of time.
5. See how these maximum stresses compare with the stress-lifetime curves determined in the normal constant stress-lifetime pipe measurements of Step 1. The constant stress-lifetime curves are modified (as in the normal pipe testing) to accommodate the effects of various chemicals and for seams.
6. Use the variable stress curves to predict failure from the constant stress-lifetime curves if linear degradation is assumed.

This approach should certainly be considered seriously. One of the main impediments to its viability is that pipe may have different stress conditions than geomembranes. Furthermore, the residual stresses could be quite different. Other studies of a related nature can be found in Hessell and John [34] and Gaube et al. [35].

Elevated Temperature and Arrhenius Modeling. Using an experimental chamber, as shown in Figure 5.18, Mitchell and Spanner [36] have superimposed compressive stress, chemical exposure, elevated temperature, and long testing time into a single experimental device. At the Geosynthetic Research Institute, twenty of these columns have been constructed with five each at 85, 75, 65, and 55°C constant temperatures (see Figure 5.18). Each is under a normal stress of 260 kPa and is under 300 mm of liquid head on its upper surface. The subgrade sand is dry and vented to the atmosphere. The test coupons are 1.5 mm thick HDPE geomembranes.

Coupons are removed periodically and evaluated for changes in numerous physical, mechanical, and chemical test properties. The anticipated behavior is shown in Figure 5.19a; however, at this time, only the A and B stages have been quantified.

For stage A, the antioxidant depletion time, the HDPE geomembrane selected results in approximately 200 years (Hsuan and Koerner [37]). On the basis of exhumed HDPE milk containers at the bottom of a landfill, the measured induction time (stage B) is from 20 to 30 years. Thus in a buried environment there is a time span of approximately 220 years with essentially no engineering-property degradation. This leads directly to stage C. Deciding on a maximum property change to establish stage C (e.g., a 50% reduction or *half-life* at each temperature) allows the plotting of another curve (see Figure 5.19b). This graph is inverse temperature versus reaction rate (actually the inverse time from Figure 5.19a) and is called the *Arrhenius curve*. The slope of the line is the activation energy divided by the gas constant.

We can now extrapolate graphically to a lower site-specific temperature, as shown by the dashed line on Figure 5.19b, or extend the curve analytically. Examples 5.4 and 5.5 illustrate how this is accomplished, using literature values for the activation energy (see [38] for additional details). The essential equation for the extrapolation is

$$\frac{r_{T\text{-test}}}{r_{T\text{-site}}} = e^{-\frac{E_{act}}{R}\left[\frac{1}{T\text{-test}} - \frac{1}{T\text{-site}}\right]} \tag{5.16}$$

where

E_{act}/R = slope of Arrhenius plot,
T-test = incubated (high) temperature, and
T-site = site-specific (lower) temperature.

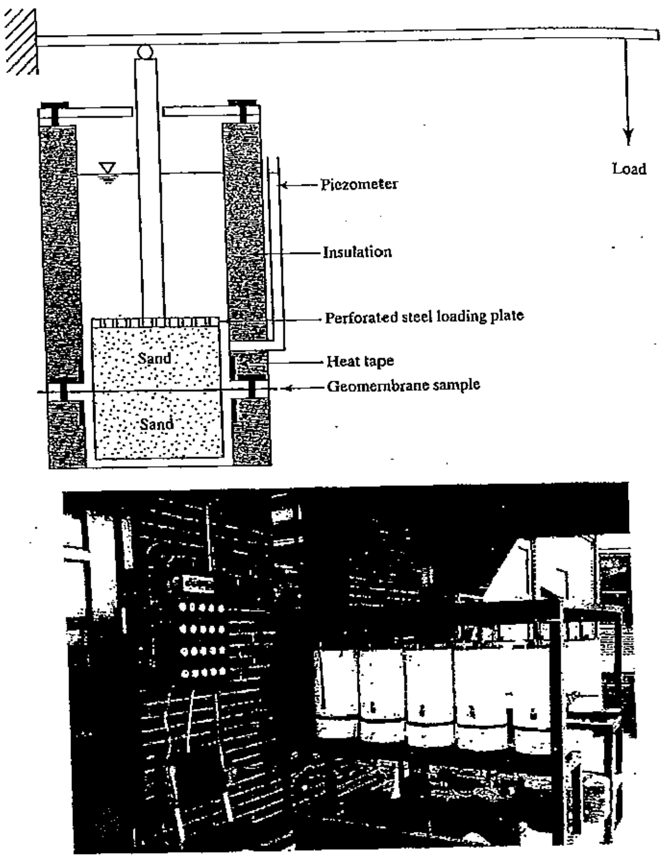
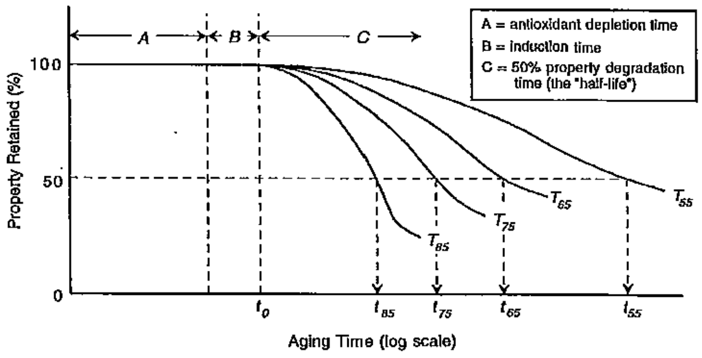


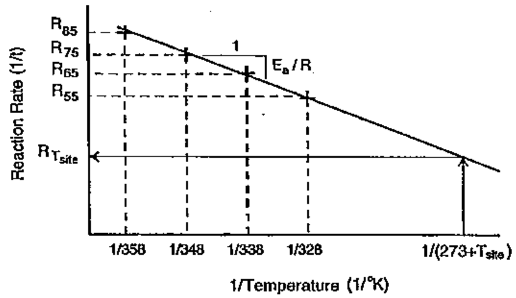
Figure 5.18 Incubation unit for accelerated aging and photograph of a number of similar units used at the Geosynthetic Research Institute.

Example 5.4

Using experimental data from Martin and Gardner [39] for the half-life of the tensile strength of a PBT plastic, the E_{act}/R value is −12,800 K. Determine the estimated life, extrapolating from the 93°C actual incubation temperature (which took 300 hours to complete) to a site-specific temperature of 20°C.



(a) Incubated property behavior



(b) Arrhenius plot for half-life property

Figure 5.19 Arrhenius modeling for lifetime prediction via elevated temperature aging.

Solution: After converting from centigrade to kelvin

$$\frac{r_{93^\circ C}}{r_{20^\circ C}} = e^{-\frac{E_{act}}{R}\left[\frac{1}{93+273}-\frac{1}{20+273}\right]}$$

$$= e^{-12,800\left[\frac{1}{366}-\frac{1}{293}\right]}$$

$$= 6083$$

If the 93°C reaction takes 300 hours to complete, the comparable 20°C reaction will take

$$r_{20^\circ C} = 6083(300)$$

$$= 1,825,000 \text{ hr}$$

$$= 208 \text{ yr}$$

Thus the predicted time for this particular polymer to reach 50% of its original strength at 20°C is approximately 200 years, its predicted lifetime for stage C.

Example 5.5

Using Underwriters Laboratory Standard [40] data for HDPE cable shielding, the E_{act}/R value is −14,000 K. This comes from the half-life of impact strength tests. One of the high-temperature tests was at 196°C and it took 1000 hours to obtain these data. What is the life expectancy of this material at 90°C?

Solution. After converting from centigrade to kelvin

$$\frac{r_{196^\circ C}}{r_{90^\circ C}} = e^{-\frac{E_{act}}{R}\left[\frac{1}{196+273}-\frac{1}{90+273}\right]}$$

$$= e^{-14,000\left[\frac{1}{469}-\frac{1}{363}\right]}$$

$$= 6104$$

If the 196°C reaction takes 1000 hours to complete, the comparable 90°C reaction will take

$$r_{90^\circ C} = 6104(1000)$$

$$= 6,104,000 \text{ hr}$$

$$= 697 \text{ yr}$$

Thus the predicted time for this particular polymer to reach 50% of its original impact strength at 90°C is approximately 700 years, its predicted lifetime for stage C.

5.1.6 Summary

This relatively long section on properties and test methods has, hopefully, served to illustrate the wealth of test methods available for the characterization and design considerations of geomembranes. Many of the established tests and standardized test methods have come by way of the plastics and rubber industries for nongeotechnical-related uses. This is fortunate, for it gives a base or reference plane to work from. However, for many some variation is required before they can be used in below-ground construction. Still others demand completely new tests and test methods. In standards-setting institutes the world over there is an awareness of the problems and vibrant activity to develop such test methods and procedures. Until they are available, however, we must act on intuition and develop methods that model the required design information as closely as possible. Many of the tests and information presented in this section are done in that light. It should also be obvious that the complexity of the tests have progressed from the quite simple thickness test on smooth geomembranes to the very complex degradation tests. Indeed, a very wide range of test methods are available.

Finally, a rather lengthy discussion of durability and aging gives insight into the potential service lifetime of geomembranes. In a buried environment, the lifetimes promise to be very long—for example, with stage A of Figure 5.19a being 200 years, stage B being 20 years and stage C being hundreds of years, the HDPE geomembrane being evaluated promises to far outlast other engineering materials in comparable situations. In my experience with geosynthetics over the past 20 years, my original conclusion was that geosynthetics were easy to place but wouldn't last very long; this has shifted dramatically to where I sense that geosynthetics have extremely long service lifetimes, but I have very real concerns as to the proper installation of geosynthetics. Clearly, the geosynthetic material must survive its initial placement if these long predicted lifetimes are to be achieved.

5.2 SURVIVABILITY REQUIREMENTS

For any of the design methods presented in this chapter to function properly, it is necessary that the geomembrane survive the packaging, transportation, handling, and installation demands that are placed on it. This aspect of design cannot be taken lightly or assumed simply to take care of itself. Yet there is a decided problem in formulating a generalized survivability design for every application, since each situation is unique. Some of the major variables affecting a given situation are the following:

- Storage at the manufacturing facility
- Handling at the manufacturing facility
- Transportation from the factory to the construction site
- Offloading at the site
- Storage conditions at the site
- Temperature extremes at the site
- Subgrade conditions at the site
- Deployment at the approximate location
- Movement into the final seaming location
- Treatment at the site during seaming

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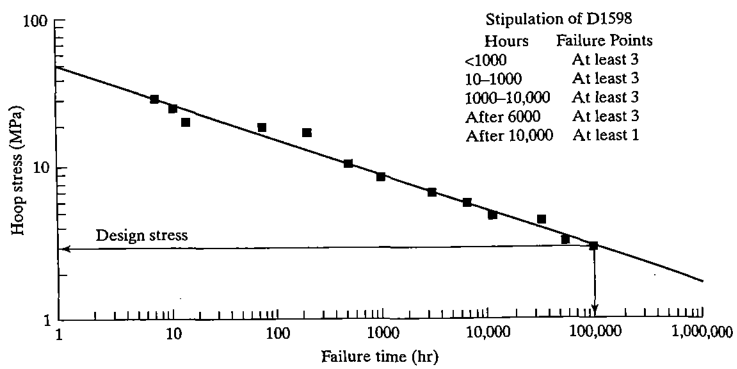

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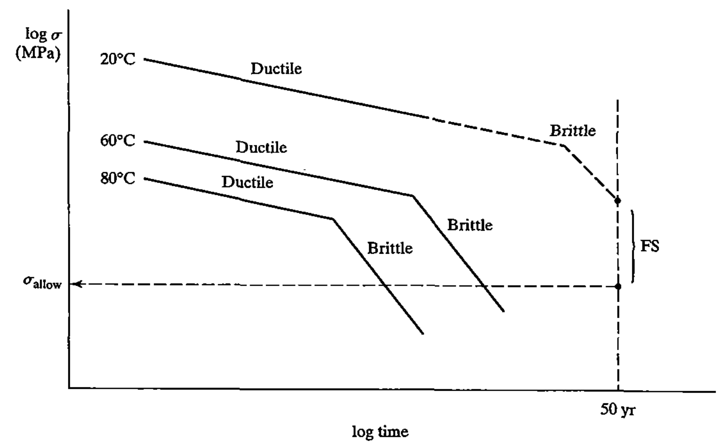

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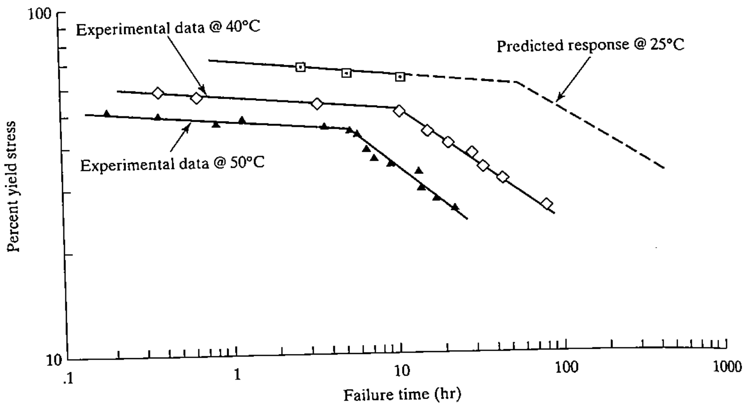

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6. Use the variable stress curves to predict failure from the constant stress-lifetime curves if linear degradation is assumed.

This approach should certainly be considered seriously. One of the main impediments to its viability is that pipe may have different stress conditions than geomembranes. Furthermore, the residual stresses could be quite different. Other studies of a related nature can be found in Hessell and John [34] and Gaube et al. [35].

Elevated Temperature and Arrhenius Modeling. Using an experimental chamber, as shown in Figure 5.18, Mitchell and Spanner [36] have superimposed compressive stress, chemical exposure, elevated temperature, and long testing time into a single experimental device. At the Geosynthetic Research Institute, twenty of these columns have been constructed with five each at 85, 75, 65, and 55°C constant temperatures (see Figure 5.18). Each is under a normal stress of 260 kPa and is under 300 mm of liquid head on its upper surface. The subgrade sand is dry and vented to the atmosphere. The test coupons are 1.5 mm thick HDPE geomembranes.

Coupons are removed periodically and evaluated for changes in numerous physical, mechanical, and chemical test properties. The anticipated behavior is shown in Figure 5.19a; however, at this time, only the A and B stages have been quantified.

For stage A, the antioxidant depletion time, the HDPE geomembrane selected results in approximately 200 years (Hsuan and Koerner [37]). On the basis of exhumed HDPE milk containers at the bottom of a landfill, the measured induction time (stage B) is from 20 to 30 years. Thus in a buried environment there is a time span of approximately 220 years with essentially no engineering-property degradation. This leads directly to stage C. Deciding on a maximum property change to establish stage C (e.g., a 50% reduction or *half-life* at each temperature) allows the plotting of another curve (see Figure 5.19b). This graph is inverse temperature versus reaction rate (actually the inverse time from Figure 5.19a) and is called the *Arrhenius curve*. The slope of the line is the activation energy divided by the gas constant.

We can now extrapolate graphically to a lower site-specific temperature, as shown by the dashed line on Figure 5.19b, or extend the curve analytically. Examples 5.4 and 5.5 illustrate how this is accomplished, using literature values for the activation energy (see [38] for additional details). The essential equation for the extrapolation is

$$\frac{r_{T\text{-test}}}{r_{T\text{-site}}} = e^{-\frac{E_{act}}{R}\left[\frac{1}{T\text{-test}} - \frac{1}{T\text{-site}}\right]} \tag{5.16}$$

where

E_{act}/R = slope of Arrhenius plot,
T-test = incubated (high) temperature, and
T-site = site-specific (lower) temperature.

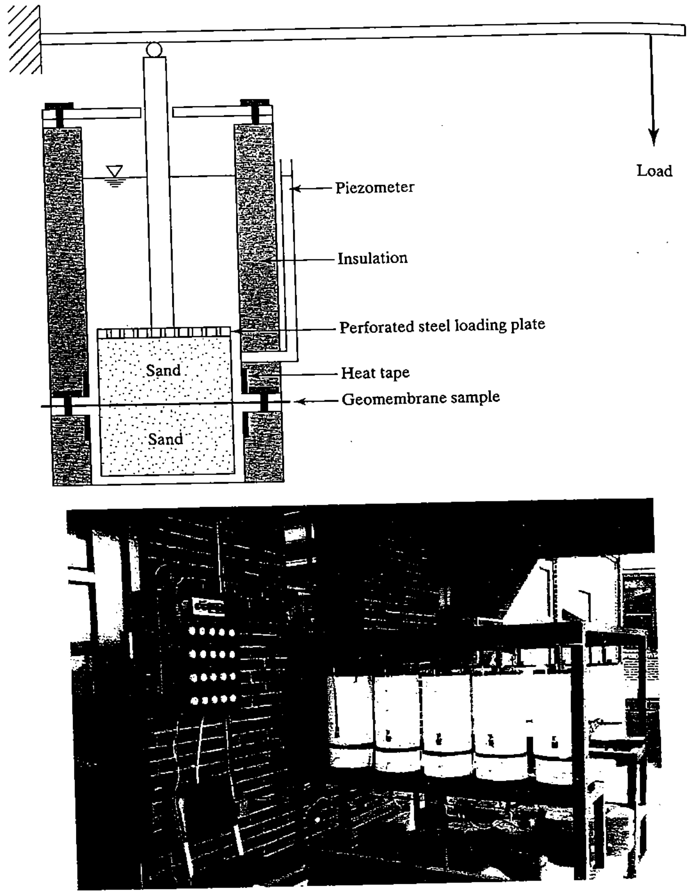
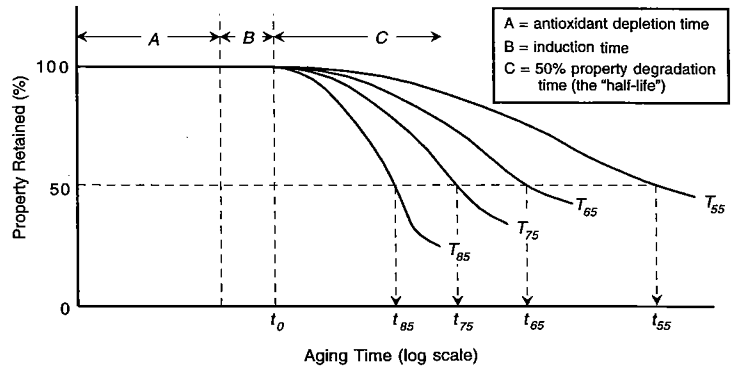


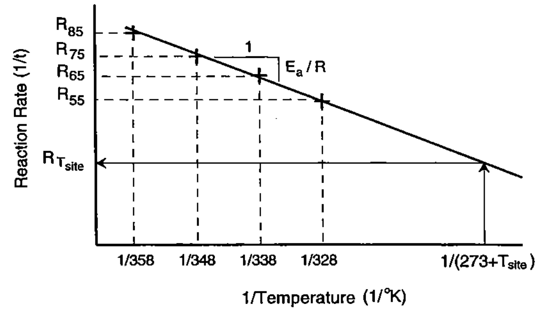
Figure 5.18 Incubation unit for accelerated aging and photograph of a number of similar units used at the Geosynthetic Research Institute.

Example 5.4

Using experimental data from Martin and Gardner [39] for the half-life of the tensile strength of a PBT plastic, the E_{act}/R value is −12,800 K. Determine the estimated life, extrapolating from the 93°C actual incubation temperature (which took 300 hours to complete) to a site-specific temperature of 20°C.



(a) Incubated property behavior



(b) Arrhenius plot for half-life property

Figure 5.19 Arrhenius modeling for lifetime prediction via elevated temperature aging.

Solution: After converting from centigrade to kelvin

$$\frac{r_{93^\circ C}}{r_{20^\circ C}} = e^{-\frac{E_{act}}{R}\left[\frac{1}{93+273} - \frac{1}{20+273}\right]}$$

$$= e^{-12,800\left[\frac{1}{366} - \frac{1}{293}\right]}$$

$$= 6083$$

If the 93°C reaction takes 300 hours to complete, the comparable 20°C reaction will take

$$r_{20^\circ C} = 6083(300)$$

$$= 1,825,000 \text{ hr}$$

$$= 208 \text{ yr}$$

Thus the predicted time for this particular polymer to reach 50% of its original strength at 20°C is approximately 200 years, its predicted lifetime for stage C.

Example 5.5

Using Underwriters Laboratory Standard [40] data for HDPE cable shielding, the E_{act}/R value is −14,000 K. This comes from the half-life of impact strength tests. One of the high-temperature tests was at 196°C and it took 1000 hours to obtain these data. What is the life expectancy of this material at 90°C?

Solution. After converting from centigrade to kelvin

$$\frac{r_{196^\circ C}}{r_{90^\circ C}} = e^{-\frac{E_{act}}{R}\left[\frac{1}{196+273} - \frac{1}{90+273}\right]}$$

$$= e^{-14,000\left[\frac{1}{469} - \frac{1}{363}\right]}$$

$$= 6104$$

If the 196°C reaction takes 1000 hours to complete, the comparable 90°C reaction will take

$$r_{90^\circ C} = 6104(1000)$$

$$= 6,104,000 \text{ hr}$$

$$= 697 \text{ yr}$$

Thus the predicted time for this particular polymer to reach 50% of its original impact strength at 90°C is approximately 700 years, its predicted lifetime for stage C.

5.1.6 Summary

This relatively long section on properties and test methods has, hopefully, served to illustrate the wealth of test methods available for the characterization and design considerations of geomembranes. Many of the established tests and standardized test methods have come by way of the plastics and rubber industries for nongeotechnical-related uses. This is fortunate, for it gives a base or reference plane to work from. However, for many some variation is required before they can be used in below-ground construction. Still others demand completely new tests and test methods. In standards-setting institutes the world over there is an awareness of the problems and vibrant activity to develop such test methods and procedures. Until they are available, however, we must act on intuition and develop methods that model the required design information as closely as possible. Many of the tests and information presented in this section are done in that light. It should also be obvious that the complexity of the tests have progressed from the quite simple thickness test on smooth geomembranes to the very complex degradation tests. Indeed, a very wide range of test methods are available.

Finally, a rather lengthy discussion of durability and aging gives insight into the potential service lifetime of geomembranes. In a buried environment, the lifetimes promise to be very long—for example, with stage A of Figure 5.19a being 200 years, stage B being 20 years and stage C being hundreds of years, the HDPE geomembrane being evaluated promises to far outlast other engineering materials in comparable situations. In my experience with geosynthetics over the past 20 years, my original conclusion was that geosynthetics were easy to place but wouldn't last very long; this has shifted dramatically to where I sense that geosynthetics have extremely long service lifetimes, but I have very real concerns as to the proper installation of geosynthetics. Clearly, the geosynthetic material must survive its initial placement if these long predicted lifetimes are to be achieved.

5.2 SURVIVABILITY REQUIREMENTS

For any of the design methods presented in this chapter to function properly, it is necessary that the geomembrane survive the packaging, transportation, handling, and installation demands that are placed on it. This aspect of design cannot be taken lightly or assumed simply to take care of itself. Yet there is a decided problem in formulating a generalized survivability design for every application, since each situation is unique. Some of the major variables affecting a given situation are the following:

- Storage at the manufacturing facility
- Handling at the manufacturing facility
- Transportation from the factory to the construction site
- Offloading at the site
- Storage conditions at the site
- Temperature extremes at the site
- Subgrade conditions at the site
- Deployment at the approximate location
- Movement into the final seaming location
- Treatment at the site during seaming