Establishing 100-Year Service Life for Corrugated HDPE Drainage Pipe

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Abstract

The design service life of corrugated high density polyethylene (HDPE) drainage pipe has been a subject of considerable debate and research over the past several years. While significant long-term performance data is available for smooth-walled polyethylene pipe, the data for corrugated drainage pipes is somewhat limited. This paper presents a method for determination of long-term service life of corrugated HDPE pipe by utilizing some of the current widely-accepted methods employed by the plastic pipe industry, while modifying them somewhat to take into account the unique geometry and installation conditions of buried corrugated pipe.

The process for long-term service life prediction is two-fold: First, the anticipated service conditions of the drainage pipe must be assessed, including such factors as environmental conditions, soil and traffic loads, and the resulting long-term stresses and strains evident in the pipe. Second, the capacity of the material and the manufactured pipe product must be assessed.

The service conditions of the pipe will vary by geographic location, based on temperature and soil and traffic loads. While deep installations may result in large compressive stresses on the pipe, shallow installation are more subject to bending and tensile stresses. Although these stress levels are typically lower in magnitude than the compressive stresses associated with deep burial conditions, they are considered a limiting condition as the material is more prone to failure in tension rather than compression. Recent research performed by Dr. Timothy McGrath for the Florida Department of Transportation on the limiting stress conditions of buried corrugated pipe is presented in this paper (McGrath and Hsuan, 2005).

The capacity of the material to resist failure is the second factor that must be addressed. Based on its wide use as a piping material (i.e. gas, water, industrial, oil field, etc…) polyethylene is a highly scrutinized material and its mechanisms of failure are well known. For corrugated drainage pipe, the primary mechanisms of material failure are slow crack growth and oxidation or chemical failure. Some recently proposed methods by Dr. Grace Hsuan for the Florida Department of Transportation to ensure long-term material resistance to these failure modes are presented in this paper (McGrath and Hsuan, 2005).

Evaluation of the Service Conditions of Buried Corrugated HDPE Pipe

Determination of the service conditions is the first step to evaluating the long-term performance of corrugated HDPE pipe. Flexible pipes rely on the soil for support, so the pipe-soil system must be considered when determining the service conditions. To determine the maximum demand placed on the pipe material, one needs to address the various loading conditions.

Typically, the total stress in the pipe is a combination of the bending stress due to deflection and the hoop compression stress due to soil pressure. This may be represented by Equation 1,

$$\sigma = \frac{P}{A} \pm \frac{Mc}{I} \qquad (1)$$

where

σ = stress in pipe wall, psi
P = hoop thrust in pipe wall, lb/in
A = wall area, in^2/in
M = moment in pipe wall, lb-in/in
c = distance from extreme fiber in pipe wall to centroidal axis, in
I = moment of inertia of pipe wall, in^4/in

Hoop stress is always compressive and increases with increasing hoop thrust (e.g. increased cover height). Polyethylene materials are much more resistant to compressive failure than tensile failure. Thus, the goal is to determine the maximum tensile stress in the pipe wall. Since the hoop compression stress is compressive, it will reduce the overall tensile stress in the pipe wall. To determine the maximum tensile stress, the hoop compression stress should be minimized while the bending stress maximized. The worst-case condition is thus shown to be shallow installations (low hoop thrust) with high deflections (large bending stress) (McGrath and Hsuan, 2005). It is interesting to note that if the pipe is properly installed, this type of condition should be rare as high deflections are typically not observed in shallow burials; such a condition is generally the result of poor installation practices.

Based on this installation condition, McGrath utilized Finite Element Analysis along with theoretical calculations using the AASHTO design method to determine that the strain limit for circumferential effects is 1.5% (McGrath and Hsuan, 2005). This assumes a total vertical deflection of 5% with minimal thrust. Using a long-term modulus of elasticity of 20,000 psi, which is a conservative value, the maximum long-term stress induced on the pipe wall is 300 psi. A factor of safety of 1.5 can be applied, resulting in stress and strain limits of **450 psi** and **2.25%**, respectively (McGrath recommends slightly more conservative values of 500 psi stress and 2.5% strain in his report to the Florida Department of Transportation).

Many states and municipalities limit vertical deflection of corrugated HDPE pipe to 7.5% rather than 5%. A limiting deflection of 7.5% would result in a strain limit of

2.25% and a long-term stress of 450 psi. Applying a factor of safety of 1.5 results in a strength limit of approximately **675 psi** based on an installation with 7.5% deflection.

The above calculations only take into account the circumferential stresses in the pipe. In order to adequately address the total state of stress in the pipe, longitudinal stresses must be addressed as well. Citing two papers from Dr. Ian Moore, McGrath shows that the longitudinal stresses in the pipe are on the same order of magnitude as the circumferential stresses, or approximately 300 psi, equivalent to 1.5% strain (McGrath and Hsuan, 2005).

To summarize, McGrath's work for the Florida DOT shows that the peak tensile stress in the pipe occurs at shallow installations and high deflections. Limiting the vertical deflection to 5% results in a peak long-term stress of around 300 psi, equivalent to a strain of 1.5%. If the deflection is limited to 7.5%, the peak long-term stress in the pipe is around 450 psi, equivalent to a strain of 2.3%. It should be emphasized that these peak stress levels refer to the general stress in the pipe, and are not associated with areas of stress concentration (McGrath and Hsuan, 2005).

In order to ensure 100-year service life, the capacity of the material must be able to withstand this demand, which is the subject of the next section of this paper.

Evaluation of the Long-Term Material Performance of Corrugated HDPE Pipe

It is well-known that high density polyethylene exhibits 3 modes of failure, depending on the stress level and chemical resistance evident in the material, as shown in Figure 1. Stage I failures are ductile in nature, and occur at very high stress levels (much greater stresses than evident in gravity flow or low pressure drainage pipe). Stage I failures are of little concern for corrugated HPDE pipe used for gravity flow drainage applications. Stage II failures are brittle types of fractures and occur at moderate stress levels. This is one of the primary failure modes for corrugated HDPE pipe, and has been a main motive for the evolution of material performance requirements over the past decade. This mode of failure is associated with slow crack growth, a phenomenon that occurs in polyethylene pipe that is typified by crack propagation at low stress levels. Current materials for corrugated HDPE pipe include an NCLS (Notched Constant Ligament Stress) test requirement per ASTM F2136, *Standard Test Method to Determine Slow Crack Growth Resistance of HDPE Resins or HDPE Corrugated Pipe,* to ensure resistance to slow crack growth and Stage II failures. Stage III failures occur as a result of chemical degradation of the material, and the steep curve associated with Stage III failures indicates that the material no longer has the capacity to withstand any load. In order to prevent the onset of Stage III failure in the pipe's anticipated service life, antioxidants are added to the material formulation.

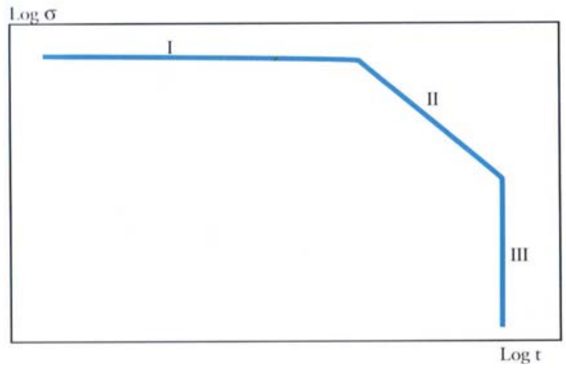

Figure 1: Relationship between stress and time to rupture for polyethylene (Janson 122)

To establish 100-year service life for corrugated HDPE drainage pipe, one must ensure that the stress level in the pipe is lower than the long-term tensile strength of the pipe, thus avoiding Stage I failure potential, and that the service stress and service conditions will not result in Stage II or Stage III failures prior to its anticipated service life. Since the first part of the paper established the maximum factored stress in the pipe to be 450 psi for 5% deflection and 675 psi for 7.5% deflection, these are the critical stress levels that will be evaluated for the service conditions of the pipe.

Resistance to Stress Cracking and Stage II Failure

To evaluate the material's resistance to Stage II failure, Hsuan proposed some new test methods to the Florida Department of Transportation. One of the primary tests was the evaluation of the junction between the corrugation and the liner, as shown in Figure 2 (McGrath and Hsuan 2005). This test specimen was chosen based on Hsuan and McGrath's prior work in NCHRP Report 429 (McGrath and Hsuan 1999), where slow crack growth failures were noted on field samples of corrugated HDPE pipe at the liner – corrugation junction, as shown in Figure 3. By the nature of the geometry of this junction, it will act as a stress concentration point where SCG failure is most likely to occur. This proposed junction test consists of a tensile load applied to the test specimen while immersed in a water bath.

To determine 100-year service life, the Rate Process Method (RPM) can be utilized, which takes advantage of the Arrhenius principle of time-temperature superposition to accelerate the test and extrapolate data to predict service life at the anticipated service temperature. RPM is widely used for long-term service life prediction of HDPE pressure pipe materials and is part of ASTM D2837, *Standard Test Method for Obtaining Hydrostatic Design Basis of Thermoplastic Pipe Materials or Pressure Design Basis for Thermoplastic Pipe Products*. This same method can be applied to corrugated HDPE pipe to determine the long-term service life.

RPM consists of an equation that relates failure time and stress as a function of temperature. The general equation is shown below in Equation 2,

$$\log t = A + \frac{B}{T} + \frac{C \log \sigma}{T} \qquad (2)$$

where

t = failure time (hr)
σ = applied stress
T = test temperature (K)
A,B,C = constants based on material and test conditions

A, B, and C in Equation 2 are dependent on the material and test conditions and are determined by performing junction stress tests to failure at various load and temperature conditions. Once the three constants are determined, the equation may be used to predict time to failure at other stress and temperature conditions where the materials properties are known to remain constant.

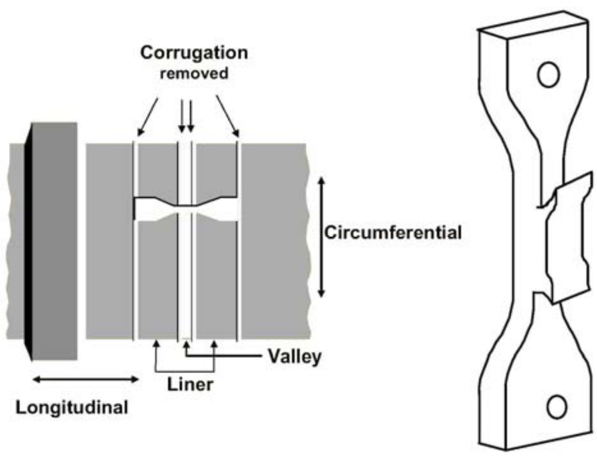

Figure 2: Diagram of junction specimen used for evaluating pipe's long-term resistance to Stage II failures (McGrath and Hsuan 2005).

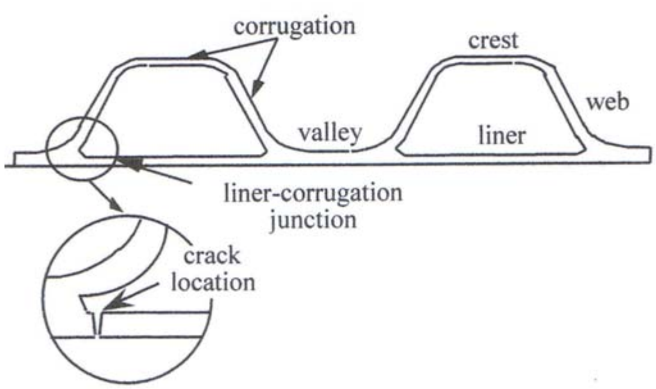

Figure 3: Location of liner-corrugation junction where cracks were observed in NCHRP Report 429 (McGrath and Hsuan 1999).

For the Florida DOT 100-year service life protocol, Dr. Hsuan requires junction tests to be performed at the following conditions to determine the 3 constants:

1) 80 deg. C, 650 psi stress
2) 80 deg. C, 450 psi stress
3) 70 deg. C, 650 psi stress

Once the 3 constants are determined, Equation 2 is used to determine if the time to failure at the required service conditions (500 psi stress and 23 deg. C for the state of Florida) is greater than 100 years. An example of the extrapolated data is shown in Figure 4 for one of the pipes used in the initial evaluation. The data clearly demonstrates that the RPM methodology is applicable to the evaluation of these types of specimens to predict slow crack growth failures. This example shows an estimated service life of well over 100 years for either the 500 psi condition associated with a 5% deflection or the 675 psi condition associated with a 7.5% deflection (in fact, in this example, a service condition of 1000 psi stress and 23 deg. C will give 100 year design life). It is the recommendation of the Plastics Pipe Institute to limit deflections to 7.5%, and initial tests show that the long-term performance of the material at the resulting factored stress level of 675 psi is well over 100 years.

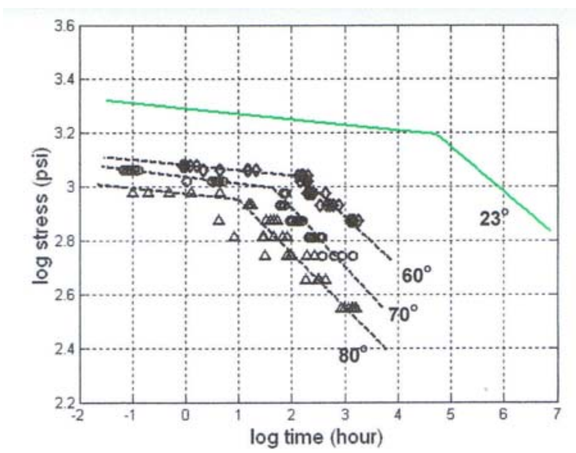

Figure 4: An example of a predicted 23 deg. C curve on a pipe junction in water (Hsuan and McGrath 2005).

Resistance to Oxidation and Stage III Failure

To ensure that Stage III failures don't occur in the pipe prior to its designed service life, further testing is needed. As discussed above, Stage III failures are prevented by adding antioxidants to the material formulation. The type and quantity of antioxidant play an important role in protecting the resin from oxidative degradation. Typically, as long as an antioxidant is present in the material, the polyethylene resin will be adequately protected from oxidation. Thus, if it can be shown that there will be some antioxidant present in the material over the 100 year service life, one can be assured that the pipe will not experience Stage III failure in this time period.

Hsuan shows that the overall oxidation mechanisms can be divided into three stages, shown in Figure 5 (Hsuan and Koerner, 1999).

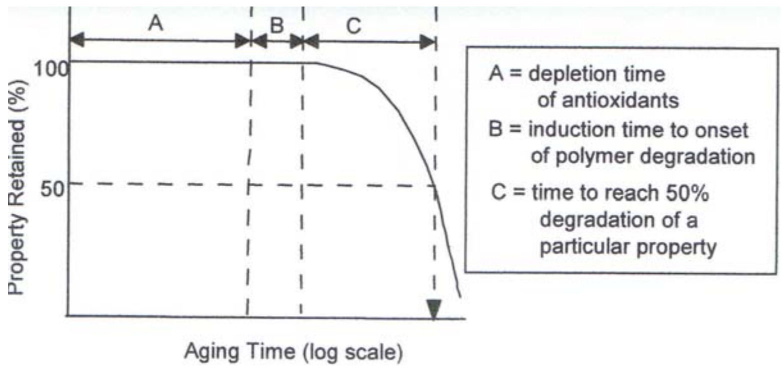

Figure 5: Three conceptual stages for oxidation of HDPE (Hsuan and Koerner, 1999)

It is critical that the onset of Stage III failures is beyond the anticipated service life of the pipe (100 years in this case). As shown in Figure 6, a lack of antioxidants or the wrong type of antioxidant can shift the Stage III failure curve to the left. If shifted far enough left, the service life of the pipe can be drastically shortened. However, if sufficient antioxidants are present, the onset of oxidation and Stage III failure can be pushed out to well over 500 years (Janson, 1995).

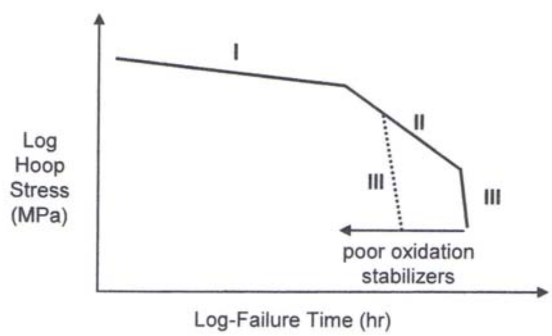

Figure 6: A lack of antioxidants will shift Stage III failures to the left, potentially limiting the service life (McGrath and Hsuan, 2005)

There are two primary tests available to determine the antioxidant activity in a polyethylene formulation: 1) The induction temperature (IT) test (also known as thermal stability) and 2) The oxidation induction time (OIT) test. The IT test is performed by heating a test specimen at a constant rate and recording the temperature at which oxidation initiates.. The OIT test is conducted by measuring the time to achieve oxidation at a given test temperature. Dr. Hsuan opted for the OIT test to evaluate the antioxidant activity of corrugated HDPE pipe for the Florida DOT protocol.

In order to adequately determine the sufficiency of the antioxidant at preventing Stage III failures prior to the pipe's intended service life, Hsuan proposed a minimum initial OIT value as well as a minimum retained value after incubation in an accelerated test environment. The minimum initial OIT value is 25 minutes, and is based off data from HDPE geomembranes in a soil/water environment. The retained OIT value is 3 minutes, and is to be measured after specimen incubation in a water bath at 85 deg. C for 187 days, while under a constant tensile stress of 250 psi to simulate field conditions. This incubation period and temperature was selected based on the Arrhenius equation and the desired service life of 100 years in a 23 deg. C environment. This work is detailed in the Florida DOT protocol (McGrath and Hsuan, 2005).

It should be noted that the proposed OIT requirements represent a very conservative approach to the service life estimation, since they require no onset of oxidation prior to the 100 year design service life. As shown in Figure 5, there is still considerable time after the depletion of antioxidants before material property degradation will occur.

Conclusion

In order to establish 100-year service life for corrugated HDPE pipe for drainage and low-pressure applications, the installation conditions must be evaluated to determine the demand placed on the pipe, and the material properties must be evaluated to determine its capacity to meet the demand. Dr. Tim McGrath has determined that the maximum factored tensile stress in a pipe with a vertical deflection of 5% is 500 psi corresponding to a strain of 2.5% (McGrath and Hsuan, 2005). It can then be shown that the maximum tensile stress in a 7.5% deflected pipe is 675 psi corresponding to a strain of 3.38%. To determine the material's capability at meeting these demands, Dr. Hsuan has shown that by performing elevated temperature testing at multiple stresses and applying the Rate Process Method to forecast Stage II performance at the design service temperature and stress level (500 psi for 5% deflection limits, 675 psi for 7.5% deflection limits), along with appropriate antioxidant performance tests to ensure that Stage III failures will not occur prior to 100 years (McGrath and Hsuan, 2005), HDPE corrugated pipe can be evaluated for a 100 year service life .

References

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