8.1 Durability Overview

One of the advantages of corrugated HDPE and PP pipes over traditional materials such as steel and concrete is their durability in a vast variety of service conditions. Plastics are known to be resistant to abrasion and corrosion; as a result, their service life can often exceed that of competing materials. For example, the first known cross-highway corrugated HDPE culvert pipe was a 24 in. (600 mm) diameter pipe installed by the Ohio DOT in Noble County in September 1981. It was chosen due to the aggressive soil conditions (abrasive and acidic mine drainage conditions with pH levels ranging from 2.5 to 4.0.) which were rapidly deteriorating the other traditional culvert materials, causing them to fail within a few years. The corrugated HDPE pipe is still performing nearly 40 years later with no discernible wear or changes in performance (1)

Another example that demonstrates the durability and strength of corrugated HDPE pipe is the Pennsylvania deep bury study, in which a 24 in. (600 mm) diameter corrugated HDPE pipe was installed in 1987 underneath Interstate I-279 north of Pittsburgh (1). The test installation consisted of 576 feet (160 m) of pipe length with a maximum fill height of 100 feet (30.5 m). It has been the subject of numerous studies and evaluations and is still in place today, demonstrating the capability of the pipe to perform in extreme conditions.

This chapter will first identify some of the factors that influence the durability of corrugated HDPE and PP pipes and will conclude with procedures for determining the service life of corrugated HDPE pipes manufactured with virgin materials, corrugated HDPE pipes containing recycled content, and corrugated PP pipes.

8.2 Factors Influencing Durability

The primary factors that influence the durability of corrugated HDPE and PP pipes include the following: stress cracking (also known as slow crack growth), ultraviolet (UV) radiation, oxidation, chemical attack, abrasion and wear, effects of extreme temperatures, rodent attack, and flammability. Of these factors, the first three (stress cracking, UV radiation, and oxidation) are the primary factors that govern the service life of corrugated HDPE and PP pipes. The remaining factors may have more intermittent or localized effects on the durability of the pipes, but they do not typically factor into the service life protocols for the overall pipe system.

8.2.1 Stress Cracking or Slow Crack Growth

One of the most important factors affecting the durability of corrugated HDPE pipe is stress cracking, also known as slow crack growth (SCG). Stress cracking or SCG is a failure mechanism in which brittle cracks form and slowly propagate through a plastic material placed under sustained tensile stresses. It is more prevalent in polyethylene than in polypropylene. Pipe standards have established minimum performance requirements through both the Notched and Un-Notched Constant Ligament Stress (NCLS and UCLS) tests to ensure the stress crack resistance of the material is adequate for the given application.

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The SCG failure mechanism has been well documented for polyethylene pipe materials and the phenomenon is illustrated in Figure 8.1, courtesy of Peacock (2). When a load is applied perpendicular to the direction of a notch, the notch (denoted as crack opening displacement or COD in Figure 8.1) will open. Over time, the load applied results in continued stress that creates microscopic voids at the tip of the notch, known as crazing. Eventually, the stressed fibrils in this craze zone begin to fracture. As this occurs, a new craze zone is established further into the specimen. The craze-crack process continues until the specimen fails via ductile yielding when the remaining ligament stress exceeds the yield strength of the material. The mechanism can occur both under sustained tensile loads as well as cyclical loads. SCG failures resulting from a sustained applied stress condition are referred to as creep crack growth (CCG) failures in this handbook, while SCG failures resulting from continued application of small cyclical loads are referred to as fatigue crack growth (FCG) failures.

Broadly speaking, the SCG mechanism is comprised of two phases: 1) the crack initiation phase and 2) the crack propagation phase. The crack initiation phase is accelerated by the presence of a stress riser such as a void, notch, or contaminant. For virgin PE materials, the SCG mechanism can be effectively analyzed by testing and observing artificially notched specimens held under a constant load. Tests are typically conducted at elevated temperatures to shorten the failure times. The purpose of the artificial notch is to provide a stress concentration site that accelerates crack initiation. The time to crack initiation and the rate of crack growth or propagation can be determined by monitoring the COD throughout the loading period. Additionally, observation of the notch tip with a traveling optical microscope throughout the loading process can identify when fracture first occurs, aiding in the distinction between the crack initiation and propagation phases. Linear elastic fracture mechanics (LEFM) have been used to describe the rate of crack propagation for virgin PE materials, as shown in Eqn. 8.1 (3).

$$\frac{da}{dt} = A \cdot {K_I}^m \qquad \text{(Eqn. 8.1)}$$

where:

$\frac{da}{dt}$ = Rate of crack propagation,
A, m = Material-dependent constants, and
K_I = Stress intensity factor for load normal to crack plane.

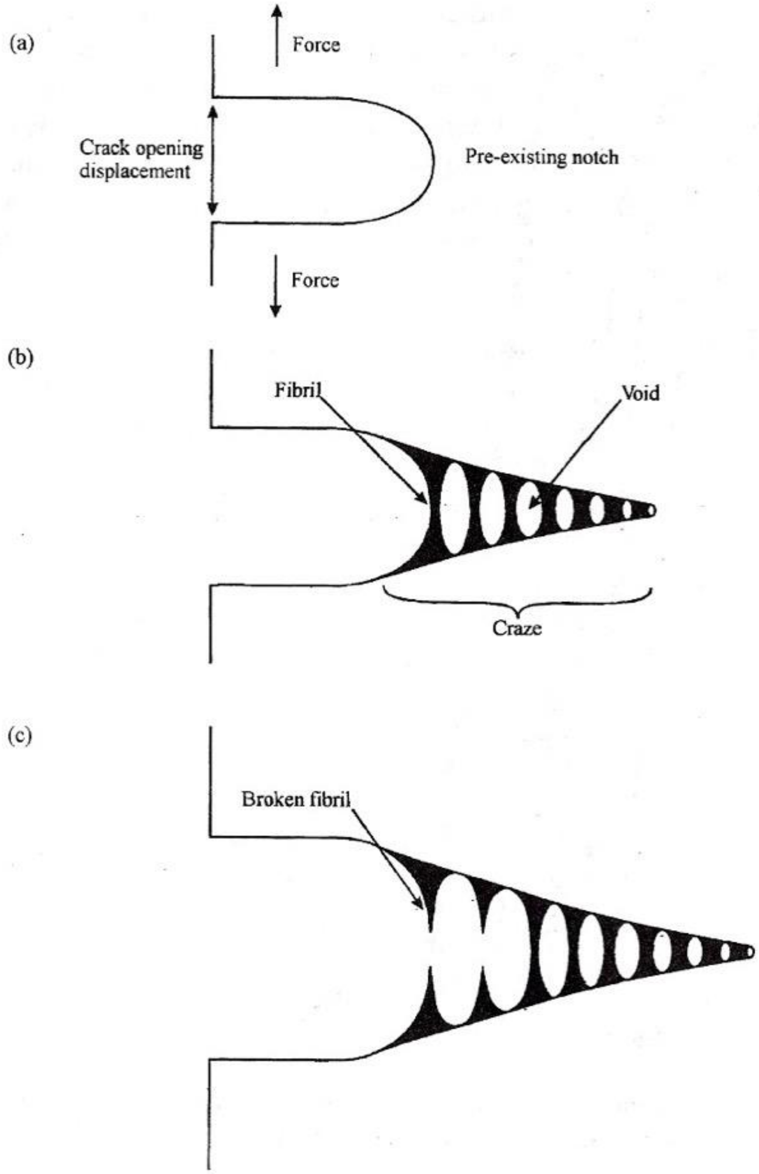

Figure 8.1: Illustration of the SCG mechanism from Peacock (2). (a) a void or pre-existing notch acts as a stress concentration point; (b) Under constant or cyclical loads normal to the notch, the notch opening widens and micro-voids start to form in a zone at the tip of the notch; this development of micro-voids is known as crazing; (c) over time, the fibrils start to yield and break, and a new craze zone develops further into the specimen.

For corrugated HDPE pipes containing PCR content, these traditional methods of assessing the SCG mechanism are insufficient since they do not properly address the effect of contaminants on the overall SCG performance of the material. This is because the traditional methods involve testing and evaluating artificially notched specimens, and the stress

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intensity factor resulting from a sharp notch greatly overwhelms and masks any contribution to the SCG mechanism that may be associated from irregular contaminants. Because of this, the effect of the contaminant on crack initiation and propagation will not be effectively known unless a contaminant happens to be located directly in front of the notch tip along the path of crack propagation. These contaminants are of significant importance in accurately assessing the service life, relative to SCG, for pipes that contain PCR materials. This is due to crack initiation sites that are typically much larger and more variable than the stress risers typically found in virgin materials. For example, a typical stress riser in a pipe manufactured with virgin materials may be a spherical carbon black particle on the order of 60 to 70 nm (approximately 2.5×10^{-6} in.) in size. By contrast, a contaminant in a pipe containing PCR content may be up to 0.18 mm (0.007 in.) in size and very irregular, based on an 80-mesh filtration screen commonly used in the production process. While tests on notched specimens may be useful for assessing the SCR and the rate of crack propagation of the base polymer in a PCR material blend, they do not give a good indication of the overall service life of PCR materials. This is due to the crack initiation and propagation rates generated by a sharp artificial notch which are different than those generated from randomly-oriented irregular contaminants. For these reasons, a new test method – the Un-Notched Constant Ligament Stress (UCLS) test, published as ASTM F3181 (4) – was developed to assess both the crack initiation (t_{CI}) and crack propagation (t_{CP}) phases of the SCG mechanism for pipes manufactured with recycled materials. The basis of the UCLS is shown in Eqn. 8.2. As the amount and size of contaminants increases, the timeframe associated t_{CI} decreases due to the increased crack initiation sites present. On the other hand, the timeframe associated with t_{CP} is primarily a function of the SCR of the base polymer and is somewhat independent of the effect of contaminants. A desired service life can be achieved by: (a) reducing the amount and/or size of contaminants (through better filtration, use of cleaner materials, etc.), thereby increasing t_{CI}; (b) by using a more SCR base polymer that is more SCR, thereby increasing t_{CP}; or, (c) a combination thereof.

$$t_{SCG} = t_{CI} + t_{CP} \tag{Eqn. 8.2}$$

where:

t_{SCG} = Total time to failure via the SCG mechanism,
t_{CI} = Portion of SCG time related to crack initiation, and
t_{CP} = Portion of SCG time related to crack propagation.

8.2.2 Ultraviolet (UV) Radiation

Ultraviolet (UV) radiation can accelerate the deterioration in both corrugated HDPE and PP pipes if the compounds are not stabilized or protected properly. There are two approaches typically used to protect the polymer from UV degradation. The first approach is to screen, or shield, the polymer from the UV radiation. This is accomplished by incorporating additives into the compound that will either absorb or reflect the radiation. The second approach is to incorporate some type of stabilizer that protects the base polymer chemically.

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The most common and effective shielding agent to protect HDPE pipes from UV degradation is called carbon black. Most pipe standards include a requirement to add 2.0 to 4.0% of finely-dispersed carbon black to effectively protect the base polymer from degradation. This level of carbon loading has been shown to be effective at protecting HDPE coated cables and other outdoor products for up to 50 years of sun exposure (5). In the case of drainage pipes, it is only necessary to protect them while they are stored outside or transported on a truck, as once the pipes are buried, they are not subject to UV radiation. The reason for the upper limit of carbon black is that excessive amounts will tend to make the pipe more brittle and prone to impact failures. Corrugated PP pipes are typically protected from UV degradation by either including chemical stabilizers as an additive to the base resin, by using carbon black or titanium dioxide as a shield, or by employing a combination of the two.

It should be noted that UV radiation will only penetrate and affect the surface of a corrugated HDPE or PP pipe. The majority of the pipe wall will remain largely unaffected by the UV radiation in terms of structural properties.

8.2.3 Oxidation

Polymers such as polypropylene and polyethylene are susceptible to oxidation, a chemical process in which the polymer degrades in the presence of oxygen. Oxidation is accelerated at higher temperatures, which makes it especially a concern during the processing of the pipe. To protect the polymer from oxidation, both during processing of the pipe as well as while the pipe is in service, manufacturers include antioxidants into their material formulations. The antioxidants can be incorporated directly into the resin pellets from the resin supplier or they can be added in the form of a masterbatch at the pipe processing plant.

The antioxidants are gradually depleted over time, and an adequate amount should be used such that oxidation of the base resin does not occur before the intended service life of the pipe.

8.2.4 Chemical Resistance

The chemical resistance of a pipe material is important, particularly for pipes used for storm sewer and culvert applications in metropolitan areas. These pipes can be exposed to a variety of high concentrations of oils, salts, fuels, and other chemical compounds that enter the pipe system after a significant storm event or after an accidental spill. Both polyethylene and polypropylene are inert and stable materials and resistant to most types of chemicals. They are not degraded by pH extremes or by aggressive salts, both of which can be observed in various drainage environments. The Plastics Pipe Institute has published a technical report, *TR-19: Chemical Resistance of Thermoplastic Piping Materials*, that details chemical resistance data for several types of plastics and is recommended as a resource with regards to this subject (6).

In general, there are two mechanisms by which chemicals attack plastics. The first mechanism is chemical solvation or permeation, in which the chemicals (which can be in

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gaseous or liquid form) pass through the polymer without damaging or affecting its chemistry. Sometimes these chemicals can be removed from the polymer, but that is not always the case. Chemical solvation or permeation can affect the color and texture of the plastic, but its mechanical properties are generally not significantly affected for the anticipated chemical concentrations expected within storm and drainage pipes. For pipes used in potable water applications, it is important to avoid exposing the pipe to toxic chemicals that could permeate through the plastic and affect the water inside the pipe. However, this is not a concern for pipes used in storm sewer and other drainage applications.

The second mechanism of chemical attack on plastics is one which alters the polymer's chemical structure through oxidation, chain scission, crosslinking, or substitution reactions. This type of attack is irreversible and can significantly affect the pipe's mechanical properties. Some chemicals that can alter the structure of polyethylene and polypropylene when placed in prolonged sustained contact at high concentrations include: wet chlorine gas; liquid chlorine; sulfuric acid at 100% concentration, and fluorine gas. However, these chemicals are not present in high concentrations in storm drainage systems.

8.2.5 Abrasion and Wear

Corrugated polyethylene and polypropylene pipes are both extremely resistant to abrasion and wear, making them excellent materials for drainage applications that carry a variety of abrasive effluents. There have been several laboratory studies conducted to measure the wear and abrasion rates of polyethylene and polypropylene pipe materials relative to other pipe materials. For example, a test known as the Darmstadt Test developed by the Institute of Technology in Darmstadt, Germany, evaluated the effects of tilting an abrasive slurry back and forth at a frequency of 21.6 cycles per minute within various 3-ft (1 m) sections of pipes (7). The study showed that after 600,000 load cycles, the wall loss of HDPE pipe was just 0.012 in (0.3 mm), five times less than the wall loss observed in reinforced concrete pipe. Another interesting study was conducted by the Saskatchewan Research Council in 1975 (8) and compared the performance of various 2-in. (50 mm) diameter pipes subjected to two different abrasive slurries, one consisting of coarse sand (30-mesh) and the other fine sand (48-mesh). The slurry test ran for three weeks at a velocity of 15 fps (4.6 m/s) and seven weeks at a velocity of 7 fps (2.1 m/s). The wear rate of the polyethylene pipe material was significantly lower than both the steel and aluminum pipe materials. The results are summarized in Table 8.1.

The abrasion of a given pipe system will be a function of many parameters, including the flow velocity of the effluent, the types of abrasive materials present in the effluent, the temperature and pH of the effluent, and the influence of other chemicals that may be present. Because of these variables, it is difficult to quantitatively compare the performance of HDPE and PP pipe systems relative to the other pipe materials in all of these test environments. However, based on the 50 years of history of corrugated plastic pipes in a variety of aggressive installation conditions from mining applications to conditions with highly acidic soils, it is clear that their resistance to abrasion and wear is superior to virtually every other material.

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Table 8.1: Extrapolated annual wear rates of various pipe materials in laboratory study conducted by Saskatchewan Research Council (8)

Material	Wear Rate in/yr (mm/yr)			
	Coarse Sand (30 mesh)		Fine Sand (48 mesh)	
	Velocity = 7 fps (2.1 m/s)	Velocity = 15 fps (4.6 m/s)	Velocity = 7 fps (2.1 m/s)	Velocity = 15 fps (4.6 m/s)
Steel	0.030 (0.65)	0.070 (1.81)	0.001 (0.04)	0.001 (0.02)
Aluminum	0.070 (1.81)	0.294 (7.48)	0.005 (0.14)	0.034 (0.86)
Polyethylene	0.002 (0.06)	0.018 (0.46)	0.00 (0.00)	0.002 (0.06)

8.2.6 Extreme Temperatures

Corrugated HDPE and PP pipes can function well in both hot and cold temperatures, but some mechanical properties such as stiffness, tensile strength, and impact resistance can change with temperature. Research by McNish and VanHoose (9) found that both the tensile strength and flexural modulus of HDPE and PP decrease with increasing temperature, and design recommendations are shown in Table 8.2. The design values are somewhat conservative and are based on typical extrusion-grade HDPE and PP materials for pipe applications. Most thermoplastic pipe design guides conservatively assume an in-ground service temperature of 73 deg. F (23 deg. C). As a result, the tensile strength and flexural modulus at this temperature is typically used in design calculations.

Corrugated PP pipe can become brittle at temperatures below freezing since the glass transition temperature (i.e., the temperature at which the polymer transitions from soft and flexible to hard and glassy) of polypropylene is approximately 30 deg. F (0 deg. C.) Because of this, care should be taken to avoid impact loads when handling and installing corrugated PP pipe in temperatures below freezing. Corrugated HDPE pipe is not as sensitive to brittle cracking in cold temperatures, due to the glass transition temperature of HDPE being approximately -150 deg. F (-100 deg. C).

Care should also be taken when handling both corrugated HDPE and PP pipes at temperatures above 100 deg. F (40 deg. C), when the pipes will be more flexible. It is particularly important to take care when backfilling very warm pipes into cooler soils, as the contraction of the pipes upon cooling could lead to joint separation if the temperature difference is extreme. Backfilling and compacting the soil in lifts will help equalize the temperatures and mitigate any issues related to temperature differential between the backfill soils and the pipe in extreme conditions.

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Table 8.2: Suggested design properties for corrugated HDPE and PP pipes as a function of temperature (9)

Temp. deg. F (deg. C)	Corrugated HDPE Pipe Design Properties				Corrugated PP Pipe Design Properties			
	Initial		Long-term		Initial		Long-term	
	Modulus (psi)	Tensile Strength (psi)	Modulus (psi)	Tensile Strength (psi)	Modulus (psi)	Tensile Strength (psi)	Modulus (psi)	Tensile Strength (psi)
-22 (-30)	301,000	5,200	128,000	900	266,000	4,900	111,000	1,000
-4 (-20)	209,000	4,900	66,000	900	255,000	4,600	66,000	1,000
32 (0)	165,000	4,000	42,000	900	206,000	4,500	37,000	1,000
50 (10)	152,000	3,900	30,000	900	186,000	4,000	37,000	1,000
73 (23)	110,000	3,000	22,000	900	175,000	3,500	27,000	1,000
113 (45)	78,000	2,400	16,000	450-720	110,000	2,900	26,000	500-800
149 (65)	59,000	1,600	n/a	270-540	100,000	2,100	n/a	300-500

8.2.7 Rodent and Microbial Attack

Corrugated HDPE pipes and corrugated PP pipes have not been found to serve as an attractive nutrient for rodents or other animals. There are no known microbes that attack these materials. Neither HDPE nor PP are nutrient mediums for bacteria, fungi, spores, or other biological attack.

8.2.8 Flammability

Both corrugated HDPE and PP pipes can burn in certain conditions; however, these conditions are extreme and rare. The melting points of HDPE and PP are 270 deg. F (130 deg. C) and 340 deg. F (170 deg. C), respectively. The flash ignition temperature of HDPE is 645 deg. F (341 deg. C), and the self-ignition temperature is 660 deg. F (349 deg. C), both when tested in accordance with ASTM D1929, Standard Test Method for Ignition Properties of Plastics. The flash point as determined by the Cleveland Open Cup Method (ASTM D92) is 430 deg. F (221 deg. C). In general, flammability is not a concern for pipes used in storm sewer systems, because there is not sufficient oxygen present to sustain a flame. However, there are applications in which flammability is a concern for corrugated HDPE and PP pipes, and proper preventative steps should be taken. For example, if a corrugated HDPE or PP pipe is used as a culvert in an area susceptible to wildfires, it is recommended to protect the pipe with either a concrete or metal end section.

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8.3 Service Life

8.3.1 Service Life of Corrugated HDPE Pipe

The global failure modes that govern the service life of HDPE pipes have been well-documented. When subjected to tensile stress, HDPE exhibits three distinct failure regimes or stages, as illustrated in Figure 8.2 (3). At higher stresses, the primary failure mode is ductile yielding, known as Stage I failure. An example of this failure mode might be a sudden burst in a pressure pipe, due to a pressure surge or sustained high internal pressures. Stage I failures are not typical in gravity-flow corrugated drainage pipes, since these pipes are not subjected to high internal or external pressures. Additionally, since in-field deflections are limited to 5% in highway and railroad applications, corrugated HDPE pipes are not subjected to bending strains that are sufficiently high to result in Stage I failures. Stage II failures are more brittle in nature and occur at lower stresses and longer durations. Figure 8.2 shows that the slope of the Stage II failure curve is steeper than that of the Stage I curve, which indicates that this failure mode is less sensitive to stress. Stage II failure is are caused by the SCG mechanism and is the predominant failure mode for corrugated HDPE drainage pipes. Stage III failures occur when the HDPE material has deteriorated due to oxidation, UV degradation, or other chemical attack. Figure 8.2 illustrates that the curve for Stage III failures is relatively independent of stress level, which implies that the material is no longer capable of carrying any load. It is important to prevent the occurrence of Stage III failures prior to the end of a pipe's intended service life. This can be done by ensuring that the material is sufficiently stabilized through the addition of antioxidants as well as carbon black for protection against UV degradation.

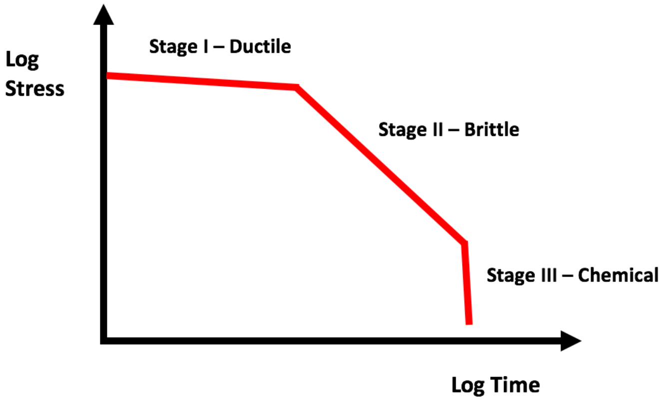

Figure 8.2: Illustration of HDPE pipe failure modes when subjected to tensile stress (3)

Another potential mode of failure for plastic pipes that can influence the service life is cracking due to fatigue. The mechanism for fatigue-related cracking on PE materials has been shown to be similar to that of cracking caused by constant tensile loads (10) (11) (3) . Fatigue testing on cracked round bar (CRB) specimens has shown that their failure curves exhibit a ductile to brittle transition, similar to that shown in Figure 8.2, when testing at

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various stress intensity factors, and the CRB fatigue test has been used to effectively rank virgin PE materials according to their stress-crack resistance [(4), (5), (6), (7), (8), (9)]. Research conducted by Villanova University on corrugated HDPE pipes manufactured with both virgin and recycled materials installed underneath an active commuter railroad indicated that fatigue cracking is not a concern that limits service life, even when tested to stress levels four times those observed in the field (3).

8.3.2 Service Life of Pipes Manufactured with Virgin Materials

The service life of corrugated HDPE pipes manufactured with virgin materials can range between 50 years to more than 100 years, depending upon the resin formulations, the installation conditions, and the loads applied. Pipes manufactured for highway applications are typically required to have a service life of 75 years. This service life is ensured by limiting the field deflections to 5% and manufacturing the pipes with resins that have a stress crack resistance of at least 24 hours[1] when tested in accordance with ASTM F2136 and a thermal stability of 220 deg. C when tested in accordance with ASTM D3350 (17). These material performance requirements were designed to ensure that Stage II and III failures do not occur prior to the desired service life for these pipe applications.

Some agencies such as Pennsylvania DOT and Florida DOT require a 100-year service life for their culvert and storm drainage pipes. In 2005, Florida DOT developed a test protocol for corrugated HDPE pipes to ensure that they meet the 100-year service life requirement. Pennsylvania DOT later adopted the same protocol, which was based on research conducted for Florida DOT (18). Since then, the Florida DOT protocol has become the standard method to establish a 100-year service life for corrugated HDPE pipes manufactured with virgin materials.

Florida Department of Transportation 100-Year Service Life Protocol

The Florida 100-year service life protocol was established to ensure that pipes are manufactured with materials of sufficient SCR to prevent Stage II brittle failures and with sufficient antioxidants to prevent Stage III chemical failures, prior to 100 years of service. To accomplish this, it was first necessary to determine the worst-case loading condition for corrugated HDPE pipes relative to these failure modes. Since both Stage II and Stage III failures occur under tension, the worst-case loading condition is one in which peak tensile stresses are generated in the pipe wall. Finite element modeling and analysis using the AASHTO design procedures showed that the installation condition that resulted in the highest tensile stresses in the pipe wall was one in which the pipe had a minimal amount of soil cover (to minimize hoop compression stresses, which offset tensile stresses in the pipe wall) and a maximum amount of bending (or deflection). Since Florida's in-field deflection limit is 5%, this deflection was used in the analysis. Neglecting hoop compression (thrust)

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[1] When tested on specimens taken from compression-molded plaques; if specimens are taken directly from the pipe liner, the NCLS value must be at least 18 hours.

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and assuming the maximum allowed vertical deflection of 5%, the peak circumferential tensile strain in the pipe wall was shown to be approximately 1.7%[2]. Since a certain amount of compressive thrust will always be present in the wall of a buried pipe, a peak tensile strain of 1.5% was used. Finite element analysis and a literature review also showed that the maximum longitudinal tensile strain expected in pipes with installation conditions in Florida was close to 1.5%. Assuming a long-term (100-year) modulus of elasticity of 20,000 psi for HDPE, the long-term stress in the pipe wall is calculated to be $\sigma = E^*\varepsilon = (20{,}000 \text{ psi})^*(1.5\%) = 300$ psi (2068 kPa). Applying a factor of safety of 1.5 results in a factored maximum wall stress of 450 psi (3102 kPa), which was rounded up to 500 psi (3447 kPa) in the Florida DOT analysis (18).

Stage II Failure Analysis – Slow Crack Growth (SCG)

To assess the service life of the pipe relative to Stage II stress cracking, a qualification test known as the "junction test" was developed. It was observed that the junction between the inner liner and the outer corrugation created a stress riser in the pipe that could lead to stress cracking, if a large enough tensile stress existed in that section of pipe (see Figure 8.3). The Florida DOT developed a test to evaluate specimens sampled from the junction section of pipe to test the resistance to stress cracking. The test involves evaluating junction specimens in an elevated temperature water bath and applying Arrhenius principles and Popelar shift factors (18) to shift the elevated temperature data to predict the service life at lower temperature service conditions. Figure 8.4 presents an illustration of the junction specimens. By testing at a minimum of three temperature / stress conditions and using Popelar shift factors to shift the data to the service temperature, the slope of the Stage II brittle cracking curve can be determined, and the service life predicted for any given stress. Figure 8.5 presents an illustration of the elevated temperature data and the shifted mastercurve. In addition to the junction specimens, Florida DOT also requires testing of other longitudinal profiles and mold seams that may become stress risers in the same test conditions. It should be noted that these tests are viewed as one-time qualification tests for each manufacturer and are not considered to be routine QC/QA tests.

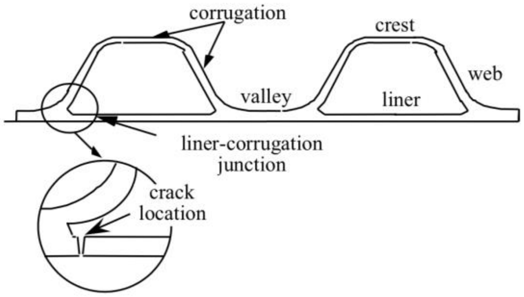

Figure 8.3: Illustration of the junction between the liner and corrugation (18)

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[2] The AASHTO design equation for determining the bending strain in the pipe wall is $\varepsilon_b = D_f(\Delta/D)(c_{out}/R)$, where D_f is the shape factor, Δ is the vertical deflection, D is the pipe centroidal diameter, c_{out} is the distance from the centroid of the profile to the extreme fiber, and R is the centroidal radius of the pipe.

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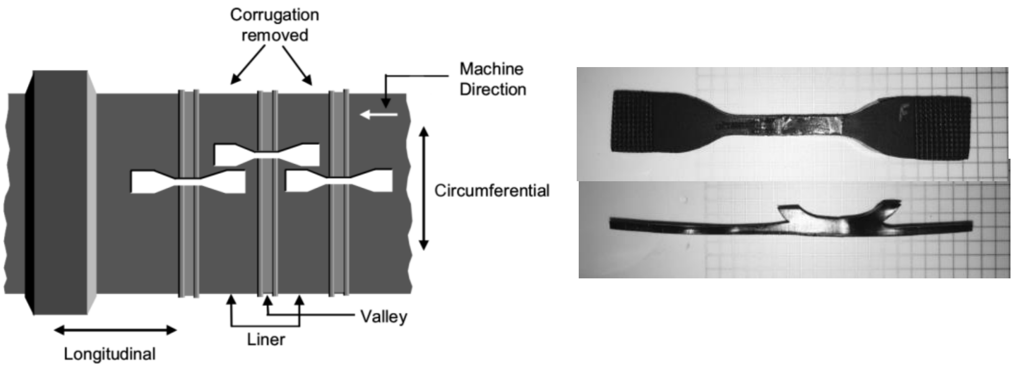

Figure 8.4: Illustration of junction specimen sampling procedure and images of specimens

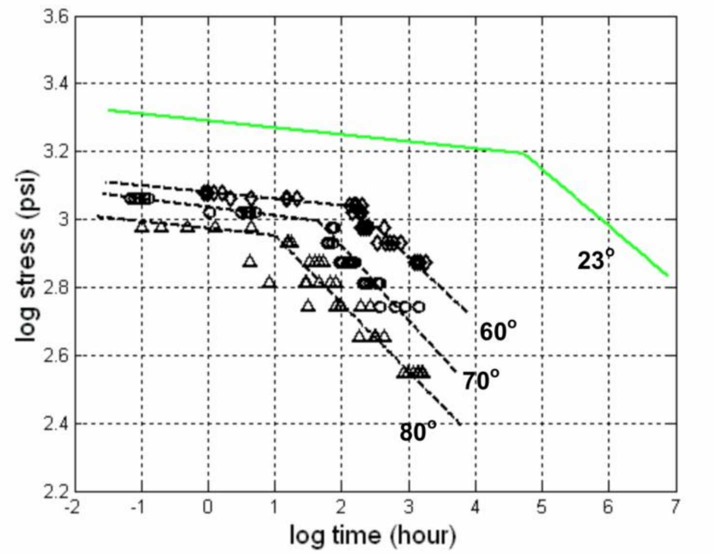

Figure 8.5: Illustration of shifting elevated temperature data to a master curve at service temperature 73 deg F (23 deg. C) (18)

For a service life of 100 years, Florida DOT established minimum performance criteria for the junction test (and other longitudinal profiles and mold seams) at each of the three temperature / stress conditions, based on the lower confidence limit of the shifted mastercurve to a service temperature of 73 deg. F (23 deg. C) and a service stress of 500 psi (3447 kPa). The minimum required failure times for each test condition are included in Table 8.3. If these minimum failure times are met, the pipe is expected to last 100 years before Stage II brittle cracking occurs. Generally, lower service temperatures and/or lower stresses will result in a longer pipe service life.

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Table 8.3: Florida DOT minimum failure times required for junction specimens (and other longitudinal profiles and mold seams) to qualify pipes for 100-year service life applications at a service condition of 73 deg. F (23 deg. C) and 500 psi (3.4 MPa) stress (18). Lower service temperatures or stresses will result in a service life in excess of 100 years, provided these minimum failure times are met.

Test Condition	Test Temperature, deg. F (deg. C)	Test Stress, psi (kPa)	Minimum Average Failure Time of 5 Specimens (hrs.)
I	176 (80)	650 (4481)	110
II	176 (80)	450 (3102)	430
III	158 (70)	650 (4481)	500

Stage III Analysis – Oxidation / Chemical Failure

The final step in the Florida DOT protocol is to ensure that the pipes are properly stabilized to prevent Stage III failure prior to 100 years of service. Stage III failure occurs when the polymer degrades due to oxidation, and it is prevented by incorporating antioxidants into the resin formulation. Since the antioxidants protect the base resin from oxidative degradation, it is important to know how long they will last in various environments and conditions such that the service life of the pipe relative to oxidative failure can be determined. The Florida DOT research identified three conceptual stages in the oxidation mechanism: (1) the time to deplete the antioxidants present in the polymer; (2) the onset of oxidation, and (3) time until the mechanical properties of the polymer have degraded by 50%. These conceptual stages are illustrated in Figure 8.6.

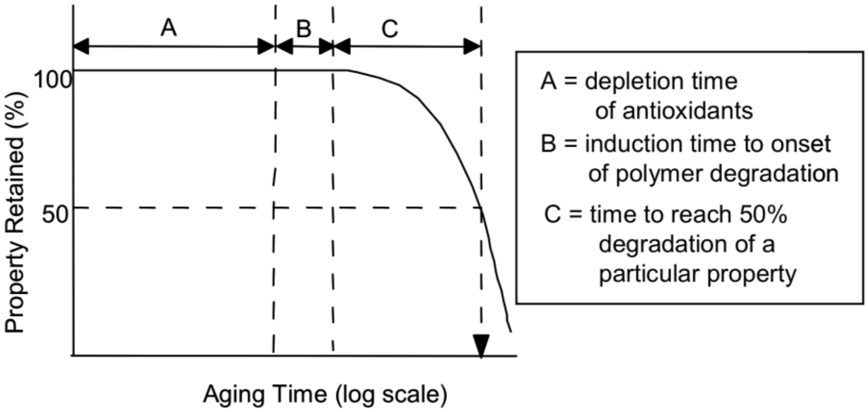

Figure 8.6: Conceptual stages of polymer degradation due to oxidation identified in Florida DOT research (18)

Since corrugated HDPE pipes are exposed to both water and air, it was important to determine which presents the worst conditions related to oxidation. The Florida DOT research found that the depletion of antioxidants was significantly greater in water than in air, although oxidation is somewhat suppressed in water over air due to the lower content of oxygen in water. Florida DOT elected to conservatively base their service life protocol only on the time to deplete the antioxidants (stage A from Figure 8.6), and thus water was selected to be the medium in which to conduct testing.

There are two primary tests to determine the stability of a polymer with regards to oxidation. The first test is known as the thermal stability test and is detailed in ASTM D3350 (17) It involves gradually heating up the polymer at a rate of 50 deg. F (10 deg. C) per minute until oxidation takes place. ASTM D3350 requires a minimum induction temperature of 428 deg F. (220 deg. C) to ensure that the polymer is sufficiently stabilized for both production and service purposes. The second test is known as the oxidation induction time (OIT) test and is detailed in ASTM D3895 (20). It involves measuring the amount of time it takes for a polymer to oxidize when held at a constant temperature of 392 deg. F (200 deg. C) in a pure oxygen atmosphere. Florida DOT uses the OIT test for its service life protocol and based on a variety of aging tests, Florida DOT conservatively established a minimum OIT of 25 minutes for pipes in 100-year service life applications. Additionally, to ensure that some antioxidant is still present in the polymer after 100 years of service (corresponding to the end of Stage A in Figure 8.6, such that no degradation of the base resin has yet occurred), Florida DOT requires pipe manufacturers to qualify their antioxidant formulations using an elevated temperature incubation test. Based on the Arrhenius equation shown in Eqn. 8.3, the amount of time to incubate the specimen in an elevated temperature bath can be calculated to simulate 100 years of service at a service temperature of 73 deg. F (23 deg. C).

At a test temperature of 176 deg. F (80 deg. C), the incubation time is calculated as follows:

$$k = Ae^{-\frac{E_A}{RT}} \qquad \text{(Eqn. 8.3)}$$

where:

k = rate constant;
A = pre-exponential factor (constant);
E_A = activation energy = 75,000 J/mol for unstabilized PE;
R = gas constant = 8.341 J/mol; and,
T = temperature of reaction, K.

For a service life of 100 years at a service temperature of 73 deg. F (23 deg. C), the incubation time at a test temperature of 176 deg. F (80 deg. C) is calculated by plugging in the appropriate values into equation 8.3, as shown below.

$$k_{Svc} = Ae^{-\frac{E_A}{RT_{Svc}}} = \frac{1}{100\,yrs} = \frac{1}{876{,}000\,hrs}$$

$$k_{Test} = Ae^{-\frac{E_A}{RT_{Test}}} = \frac{1}{t}$$

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Solving these two equations for t, the incubation time at 176 deg. F (80 deg. C) equivalent to 100 years at 73 deg. F (23 deg. C), yields

$$t = 876{,}000 * exp\left[\left(\frac{E_A}{R}\right) * \left(\frac{1}{T_{Svc}} - \frac{1}{T_{Test}}\right)\right]$$

$$= 876{,}000 * exp\left[\left(\frac{75{,}000}{8.341}\right) * \left(\frac{1}{296} - \frac{1}{353}\right)\right]$$

$$= 6{,}389 \text{ hrs.} = 265 \text{ days}$$

Additionally, Florida DOT requires the incubated test specimens to be held at a constant stress of 250 psi (1.7 MPa). Upon completion of the incubation test, a final OIT test and Melt Index (MI) test is conducted on the test specimen to ensure some antioxidant is still remaining and no degradation of the polymer has occurred. The final OIT requirement is 3 minutes, and the final MI must be within 20% of the original MI. A summary of the Florida DOT's requirements to prevent Stage III failures before 100 years at a service temperature of 73 deg. F (23 deg. C) is shown in Table 8.4. Note that other test temperatures have also been deemed acceptable for incubation testing by Florida DOT through the use of the exposure time calculations included in Eqn. 8.3.

Table 8.4: Florida DOT requirements to ensure 100-year service life relative to Stage III (oxidation) failures

Property	Test Method	Incubation Conditions	Requirement
Initial OIT	ASTM D3895	N/A	25 minutes
OIT after incubation	ASTM D3895	265 days @ 176 deg. F (80 deg. C)	3 minutes
Initial MI	ASTM D1238	N/A	< 0.40 g/10 minutes
MI after incubation	ASTM D1238	265 days @ 176 deg. F (80 deg. C)	+/- 20% of initial value

Conclusions Regarding Florida DOT 100-year Service Life Protocol

The Florida DOT protocol for establishing 100-year service life of corrugated HDPE pipes manufactured with virgin materials is a rigorous protocol that is based on well-known scientific principles that govern the long-term performance of polyethylene materials. The protocol effectively evaluates the pipes with regards to the two service-life limiting failure mechanisms for corrugated HDPE pipe materials – namely, Stage II slow crack growth failures and Stage III chemical (oxidative) failures. The criteria set forth in the protocol ensure that failures will not occur prior to 100 years of service. There are several conservative assumptions used in the protocol that are worthy of noting here:

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- The protocol is designed to ensure cracking does not occur at the junction between the outer corrugation and the inner liner. This is a conservative assumption since the inner liner is not a significant structural component of the pipe. Its primary purpose is to provide a smooth waterway for improved hydraulics. As such, some researchers have suggested that circumferential cracking of the liner should not be considered a service-limiting condition and have proposed that the true service life should be only based on the crack resistance of the outer corrugation, the primary structural component of the pipe (23).
- The service temperature upon which the calculations are based is 73 deg. F (23 deg. C). There are very few locations in North America where the average service temperature of a buried pipe is this warm. The service life of a pipe that meets the conditions of the Florida protocol will be significantly longer in cooler climates.
- The calculated tensile wall stress of 500 psi (3.4 MPa) is conservative. Most buried pipe installation conditions result in a net compressive stress on the pipe wall, even when the pipe is deflected to 5% or more.
- The Stage III analysis is based on the time it takes for the antioxidants to be depleted from the pipe. In reality, there is a considerable amount of service life remaining after this stage (see Stages B and C in Figure 8.5).

Service Life of Pipes Manufactured with Recycled Materials

The service life of corrugated HDPE pipes manufactured with recycled materials must take into account the effects of contaminants on the stress cracking mechanism, since their presence will be more likely in recycled materials than in virgin materials. Critically-sized contaminants will act as a stress riser that could potentially lead to stress cracking in the material. The service life relative to the stress cracking mechanism is then a combination of the time it takes for cracks to initiate (t_{ci}) plus the time for the cracks to propagate (t_{cp}) as illustrated in Figure 8.7.

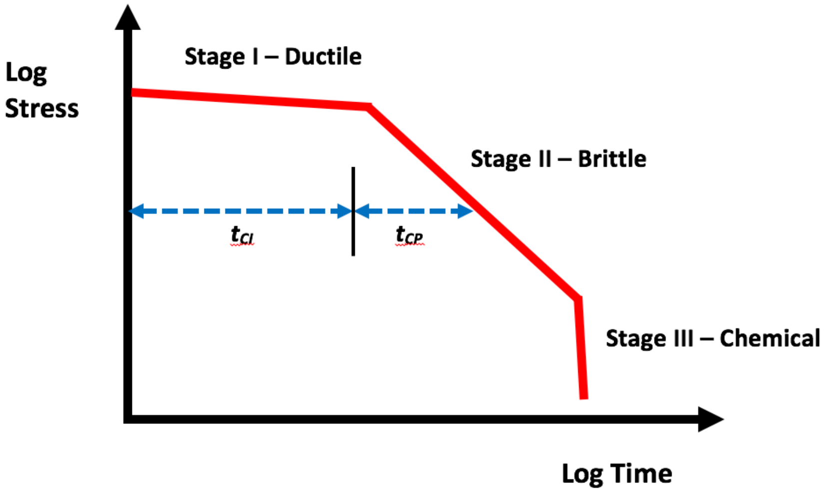

Figure 8.7: The service life of pipes manufactured with recycled materials relative to Stage II cracking is a function of the time for cracks to initiate, t_{ci}, plus the time for them to propagate, t_{cp}.

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The effect of these contaminants on the stress cracking mechanism is evaluated with the Un-Notched Constant Ligament Stress (UCLS) test, published as ASTM F3181 (4). An advantage of the UCLS test, as compared to the NCLS test, is that it is conducted in water without the presence of a surfactant. Because of this, traditional time-temperature superposition methods can be used to shift elevated temperature data to predict the service life at lower service temperatures. This process and methodology was thoroughly formulated and validated in two research projects evaluating the performance of corrugated HDPE pipes manufactured with recycled materials. The first research project evaluated the performance of these pipes relative to cyclical loading in shallow-cover commuter railroad applications as well as sustained loads from soil pressure (3). In this research, both the Rate Process Method (22) and the Popelar Shift Method (19) were used to shift elevated temperature UCLS data to project the service life at lower-temperature service conditions. Through this effort, a service life prediction model was developed. The Popelar Shift Method was shown to be more conservative and was used in the development of the service life prediction model. The model was validated on highly-deflected full-scale pipes in the laboratory for a variety of material blends. Figure 8.8 shows a typical master curve resulting from the application of the service life prediction model to one of the corrugated HDPE pipes manufactured with 49% post-consumer recycled materials used in the study. As illustrated by the dashed lines in the figure, this pipe would be expected to last well over 100 years when evaluated in the same conditions as those required in by Florida DOT 100-year service life protocol (namely, a wall stress of 500 psi (3447 kPa) and a service temperature of 73 deg. F (23 deg. C)).

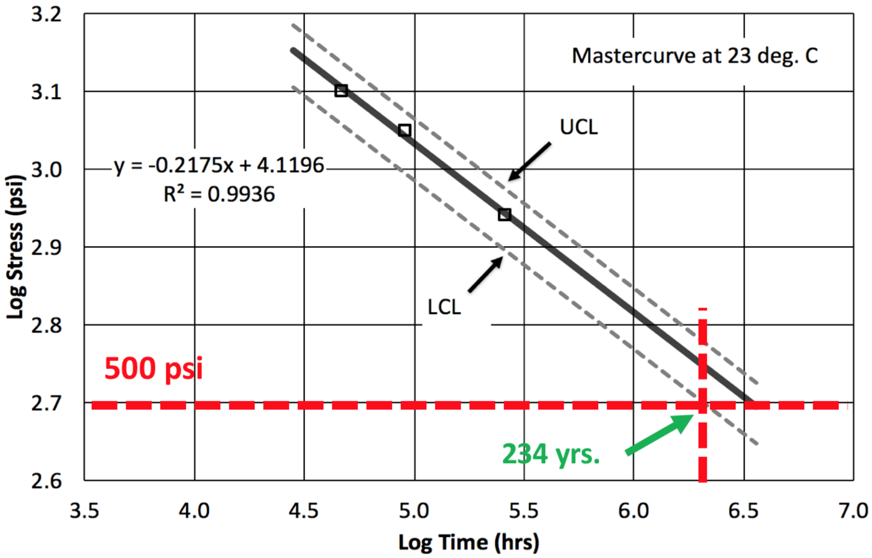

Figure 8.8: Service life projection for 30-in. (70 cm) diameter pipe manufactured with 49% post-consumer recycled materials based on applying Popelar Shift Factors to UCLS test results at three independent test conditions (80 deg. C / 650 psi, 70 deg. C, 650 psi, and 80 deg. C, 450 psi)

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The second research project that contributed to the development of the service life protocol for corrugated HDPE pipes manufactured with recycled materials was the National Cooperative Highway Research Program (NCHRP) Project 4-39 (Pluimer et al. 2017). This research project involved both field and laboratory evaluation of nine different full-scale 30-in. (76 cm) diameter corrugated HDPE pipes manufactured with various blends of virgin and post-consumer recycled materials. The blends were selected based on research conducted in the NCHRP Project 4-32 (Thomas and Cuttino 2012). The UCLS failure data was used to predict the long-term performance of these pipes in the field through application of the Popelar Shift Factors. The projected failure curves were validated on full-scale pipes in both the field and laboratory. This was done by creating an extreme installation condition that resulted in tensile strains in excess of 3.0% in the outer pipe springline and inner pipe invert and crown. These high strains allowed stress cracking to be observed in a relatively short period of time, thereby validating the service life prediction model established for each pipe. Each of the pipes that were predicted to develop cracks within a one-year timeframe and were observed to do so in the experiment. Figure 8.9 shows the the laboratory and experimental set up used for generating the high tensile strains on the full-scale pipes. Figure A shows a pipe deflected to 20% vertical deflection in the laboratory, creating tensile wall strains in excess of 3% in the outer springline and inner crown and invert; Figure B shows a loading mechanism to simulate 30 feet of cover on a buried pipe with poor compaction, resulting in large bending strains on the pipe wall (Pluimer et al. 2017).

Figure 8.9: Laboratory and field testing on full scale pipes to validate the service life prediction model established by shifting elevated temperature UCLS data to service conditions.

Based on these two research projects, a recommended procedure for determining the service life of corrugated HDPE pipes manufactured with recycled materials was established.

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Procedure for Determining Service Life of Corrugated HDPE Pipes Manufactured with Recycled Materials Using the UCLS Test[3]

The service life of corrugated HDPE pipes manufactured with recycled materials is governed by the stress crack resistance of the material. The effects of contaminants on stress cracking is assessed by testing un-notched test specimens in accordance with the UCLS test (ASTM F3181 2016). To find the service life of corrugated HDPE pipes manufactured with recycled materials using the UCLS test, the following steps should be followed:

1. Prepare compression-molded UCLS plaques according to the procedure outlined in ASTM F3181. The plaques can be prepared from resin blends or from chips taken directly from the pipe wall. It is important they are properly homogenized.

2. Prepare at least 15 UCLS test specimens from the plaques in accordance to the dimensions and procedures outlined in ASTM F3181.

3. Conduct the UCLS test in accordance to ASTM F3181 on five specimens, at a minimum of three test conditions each and to the point of failure. Record the individual and average failure times of the five specimens at each condition, as well as the coefficient of variation (i.e., the standard deviation of the failure times divided by the average failure time). The average must be calculated on a log basis, and the minimum suggested test conditions are as follows:

    a. Condition I: 176 deg. F (80 deg. C), 650 psi (4.48 MPa) stress
    b. Condition II: 176 deg, F (80 deg. C), 450 psi (3.10 MPa) stress
    c. Condition III: 158 deg. F, (70 deg. C), 650 psi (4.48 MPa) stress

4. Use the Popelar Shift Method (PSM) multiplication factors shown in Eqn. 8.4 and Eqn. 8.5 to shift the elevated temperature (T2, deg. C) average failure times (determined on a log basis) from Step 3 to the projected failure times at the desired in-ground service temperature (T1, deg. C). A conservative assumption for T1, is 23 deg. F (23 ddeg. C) although lower temperatures may be used for northern climates.

$$\text{Stress Shift Factor} = e^{0.0116\,(T2-T1)} \qquad \text{(Eqn. 8.4)}$$
$$\text{Time Shift Factor} = e^{0.109\,(T2-T1)} \qquad \text{(Eqn. 8.5)}$$

5. Plot the resulting three (or more, if additional conditions were evaluated) shifted average data points on a log-log scale, with Log Time on the Y-axis and Log Stress on the Y-axis. Determine the best-fit curve for the data points, which should be linear on a log-log scale.

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[3] Procedure adapted from *"Evaluation of Corrugated HDPE Pipes Manufactured with Recycled Content in Commuter Rail Applications"*, dissertation by Michael Pluimer, PhD, Proquest publishing, 2016 (12); and *"NCHRP Report 870: Field Performance of Corrugated HDPE Pipes Manufactured with Recycled Materials"* by Michael Pluimer, PhD and Rick Thomas, National Academy of Sciences, 2018 (19).

6. Calculate the 95% lower confidence limit (LCL) for each of the shifted average data points by using the Student's t-distribution, as shown in 8.6. Use the largest COV from the three (or more) data sets obtained in Step 3 for determination of the LCL.

$$LCL_{95\%} = \bar{X} - t_{(n-1)}\left(\frac{COV * \bar{X}}{\sqrt{n}}\right) \qquad \text{(Eqn. 8.6)}$$

where:

$LCL_{95\%}$ = Lower 95% Confidence Limit;
$\bar{X}$ = Log-based average of 5 test specimens;
$t_{(n-1)}$ = Student's t value at (n-1) degrees of freedom = 2.132;
COV = Maximum coefficient of variation of 5 test specimens; and,
n = Number of test specimens at each condition = 5.

7. Determine the best-fit curve for the three (or more) LCL data points.

8. Extrapolate the LCL curve to the desired factored service stress condition in order to determine the predicted service life relative to Stage II brittle cracking. An illustration of the average and LCL curves for a typical pipe manufactured with 49% PCR is shown in Figure 8.10. In this example, the predicted service life relative to Stage II brittle cracking is 234 years.

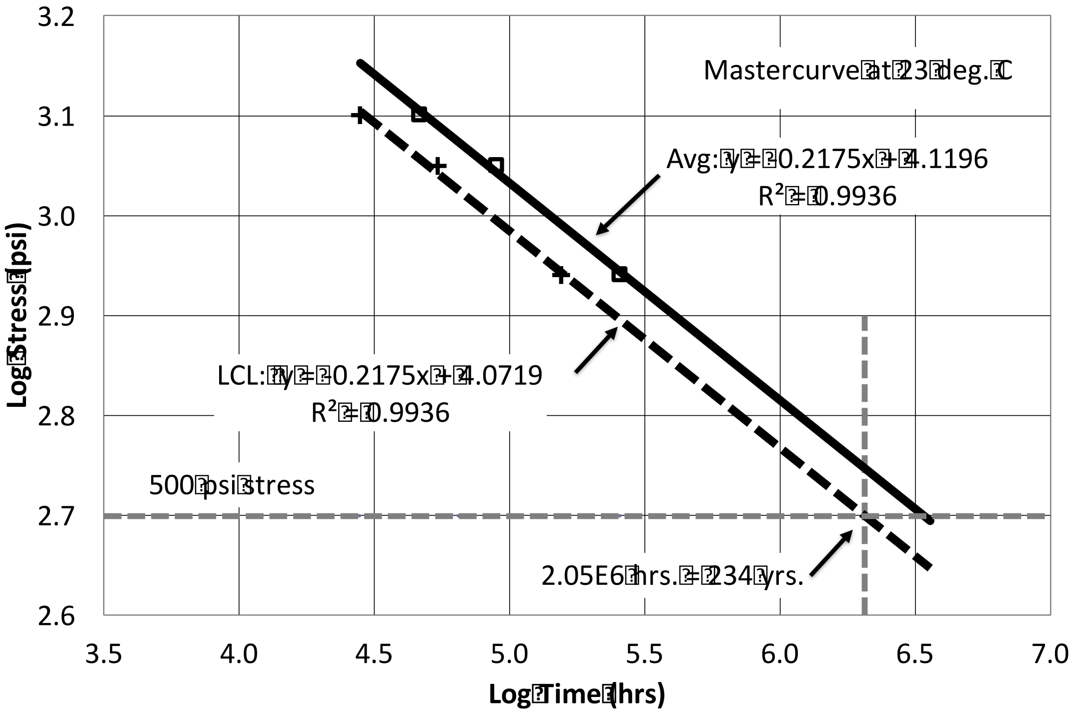

Figure 8.10: Illustration of procedure for predicting service life of a typical pipe manufactured with 49% PCR at service conditions of 23 °C and 3.4 MPa (500 psi) stress, based on application of Popelar multiplication factors to UCLS failure data

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Determining Minimum UCLS Values to Ensure a Desired Service Life[4]

The UCLS test requirement to achieve a desired service life can be determined by back-calculating from the desired performance at the service conditions, as shown in the following equations. A similar methodology was employed by the Florida DOT to determine the minimum junction test performance requirements to ensure 100-year service life for virgin HDPE pipes (21). In this approach the statistical adjustments and test specimens differ in the analysis. The calculations require determination of the slope of the brittle failure curve, represented generically by Eqn. 8.7.

$$m = {[Y_1 - Y_2]}\Big/{[X_1 - X_2]} \qquad \text{(Eqn. 8.7)}$$

where:

m = Slope of brittle failure curve at the desired service temperature, and
(X_1, Y_1) and (X_2, Y_2) = Any two points on the curve.

If the slope of the curve and one data point are known (or fixed), then one can solve for any other data point on the curve. By selecting (X_1, Y_1) to correspond to a point on the shifted curve generated from Popelar-shifted test values and (X_2, Y_2) to correspond to a point on the curve based on the service conditions, Eqn. 8.7 can be adjusted as in Eqn. 8.8. The minimum required failure time at a given test condition can then be calculated by solving for t_T, as shown in Eqn. 8.9.

$$m = {[\log(SF_\sigma * \sigma_T) - \log(\sigma_{SVC})]}\Big/{[\log(SF_t * t_T) - \log(t_{SVC})]} \qquad \text{(Eqn. 8.8)}$$

$$\Rightarrow \; t_T = {10^C}\big/{SF_t} \qquad \text{(Eqn. 8.9)}$$

where:

t_T = Minimum required average failure time at test condition, hrs.;
m = Slope of brittle failure curve;
$SF_\square$ = Popelar stress shift factor from Eqn. 8.4;
SF_t = Popelar time shift factor from Eqn. 8.5;
σ_T = Stress at test condition, psi;
σ_{SVC} = Stress at service condition, psi;
t_{SVC} = Required service life at service conditions, hrs.; and,
C = $\left[\frac{\log(SF_\sigma * \sigma_T) - \log(\sigma_{SVC})}{m}\right] + \log(t_{SVC})$ (Eqn. 8.10)

The Popelar stress and shift factors are dependent on the service and test temperatures; thus if multiple test temperatures are used (e.g. 158 deg. F (70 deg. C) and 176 deg. F (80 deg.

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[4] Procedure adapted from *"Evaluation of Corrugated HDPE Pipes Manufactured with Recycled Content in Commuter Rail Applications"*, dissertation by Michael Pluimer, PhD, Proquest publishing, 2016 (12); and *"NCHRP Report 870: Field Performance of Corrugated HDPE Pipes Manufactured with Recycled Materials"* by Michael Pluimer, PhD and Rick Thomas, National Academy of Sciences, 2018 (19).

C), as suggested in Step 3 above), the shift factors will differ for each condition.

To obtain 95% confidence that the minimum average failure times calculated from Eqn. 8.9 will result in the desired projected service life requirements, these failure times must be statistically adjusted to account for any scatter in the data. This adjustment is done by setting the minimum failure time calculated from Eqn. 8.9 equal to the LCL, as shown in Eqn. 8.11, and solving for $\bar{X}_{95\%}$ as shown in Eqn. 8.12.

$$LCL_{95\%} = t_T = \bar{X}_{95\%} - t_{(n-1)} \left({COV * \bar{X}_{95\%}} \Big/ {\sqrt{n}} \right) \qquad \text{(Eqn. 8.11)}$$

$$\bar{X}_{95\%} = \frac{t_T}{\left[1 - \left({t_{(n-1)} * COV} \Big/ {\sqrt{n}} \right) \right]} \qquad \text{(Eqn. 8.12)}$$

where:

$LCL_{95\%}$ = Lower 95% Confidence Limit;
$\bar{X}_{95\%}$= Average failure time needed for 95% confidence, hrs.;
t_T = Minimum required average failure time from Eqn. 3.8, hrs.;
$t_{(n-1)}$ = Student’s t value at (n-1) degrees of freedom = 2.132;
COV = Typical coefficient of variation of test data = 0.5; and,
n = Number of test specimens at each condition = 5.

Based on Eqn. 8.8 through Eqn. 8.12, the minimum UCLS performance requirements can be established for any given service condition related to service temperature and wall stress.

Example calculations for minimum UCLS criteria

For the purposes of illustration, consider the service conditions required by the Florida DOT for 100-year service life applications of corrugated HDPE pipes manufactured with virgin materials. The Florida DOT requires that corrugated HDPE pipes should last 100 years at a wall stress 500 psi (3447 kPa) and an underground temperature of 73 deg. F (23 deg. C) (48). It should be noted that this wall stress, based on a factored wall strain of 2.25%[5] and long-term modulus of 20,000 psi (137,895 kPa) exceeds the tensile wall stresses present in typical installations. Additionally, most states have lower underground temperatures than 73 deg. F (23 deg. C). Nonetheless, these design assumptions can be considered as conservative lower in the absence of other design data.

In order to complete the calculations, it is necessary to know the slope of the brittle failure curve as well as the coefficient of variation in the UCLS datasets. Based on the data reported in NCHRP Report 870 (Pluimer et al. 2017),a brittle slope of -0.20 and a COV of 0.50 are considered to be appropriate for the calculations.

To determine the minimum UCLS requirements at Condition I 176 deg. F (80 deg. C), 650

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[5] Florida DOT determined that the worst-case installation condition resulted in a wall strain of 1.5% (21). This was factored by 1.5, resulting in a factored wall strain of 2.25%.

psi (4.48 mPa) stress, based on a desired service life of 100 years (876,000 hrs) at 500 psi (3.4 mPa) stress and 73 deg. F (23 deg. C), the following calculations are performed:

1. Using Eqn. 8.4 and Eqn.8.5, calculate the stress and time shift factors:

Stress Shift Factor = $SF_{\sigma} = e^{0.0116\,(80-23)} = 1.937$
Time Shift Factor = $SF_{t} = e^{0.109\,(80-23)} = 499.2$

2. Using Eqn. 8.10, calculate C:

$$C = \left[\frac{\log(SF_{\sigma}*\sigma_T)-\log(\sigma_{SVC})}{m}\right]+\log(t_{SVC}) = \left[\frac{\log(1.937*650)-\log(500)}{-0.20}\right]+\log(876{,}000)$$
C = 3.937

3. Using Eqn. 8.7, calculate the minimum average failure time, $t_{T,650,80}$, at the 176 deg. F (80 deg. C), 650 psi (4.48 mPa) stress condition:

$$t_{T,650,80} = {10^{C}}/{SF_t} = {10^{3.937}}/{499.2} = \mathbf{17.33\ hrs.}$$

4. To account for the scatter in the data, the calculation in Step 3 should be considered the LCL for the 80 °C, 650 psi (4.48 mPa) condition. Ensure 95% confidence that the average failure time meets this requirement by using Eqn. 8.12 to statistically adjust this number and determine the actual test requirement for the minimum average failure time:

$$\bar{X}_{95\%,650,80} = \frac{t_{T,650,80}}{\left[1-\left({t_{(n-1)}*COV}/{\sqrt{n}}\right)\right]} = \frac{17.33}{\left[1-\left({2.132*0.5}/{\sqrt{5}}\right)\right]} = \mathbf{33.1\ hrs.}$$

Similarly, to determine the minimum UCLS requirements at Condition II [176 deg. F (80 deg. C), 450 psi (3.10 mPa) stress], based on a desired service life of 100 years (876,000 hrs) at 500 psi (3.4 MPa) stress and 73 deg. F (23 deg. C), the following calculations are performed:

1. Using Eqn. 8.4 and Eqn. 8.5, calculate the stress and time shift factors:

Stress Shift Factor = $SF_{\square} = e^{0.0116\,(80-23)} = 1.937$
Time Shift Factor = $SF_{t} = e^{0.109\,(80-23)} = 499.2$

2. Using Eqn. 8.10, calculate *C*:

$$C = \left[\frac{\log(SF_{\sigma}*\sigma_T)-\log(\sigma_{SVC})}{m}\right]+\log(t_{SVC}) = \left[\frac{\log(1.937*450)-\log(500)}{-0.20}\right]+\log(876000)$$
C = 4.736

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3. Using Eqn. 8.9, calculate the minimum average failure time, $t_{T,450,80}$, at the 80°C, 450 psi (3.10 mPa) stress condition:

$$t_{T,450,80} = 10^{C}/_{SF_t} = 10^{4.736}/_{499.2} = \mathbf{109.0}\ \boldsymbol{hrs}.$$

4. To account for the scatter in the data, the calculation in Step 3 should be considered the LCL for the 80°C, 450 psi (3.10 mPa) condition. Ensure 95% confidence that the average failure time meets this requirement, by using Eqn. 8.12 to statistically adjust this number and determine the actual test requirement for the minimum average failure time:

$$\bar{X}_{95\%,450,80} = \frac{t_{T,450,80}}{\left[1-\left(t_{(n-1)} * COV/_{\sqrt{n}}\right)\right]} = \frac{109.0}{\left[1-\left(2.132 * 0.5/_{\sqrt{5}}\right)\right]} = \mathbf{208.3}\ \boldsymbol{hrs}.$$

Finally, determine the minimum UCLS requirements at Condition III [70°C, 4.48 MPa (650 psi stress)], based on a desired service life of 100 years (876,000 hrs) at 3.4 MPa (500 psi) stress and 23°C, by the following calculations:

1. Using Eqn. 8.4 and Eqn. 8.5, calculate the stress and time shift factors:

Stress Shift Factor = $SF_{\square}$ = $e^{0.0116\ (70-23)}$ = 1.725
Time Shift Factor = SF_t = $e^{0.109\ (70-23)}$ = 167.8

2. Using Eqn. 8.10, calculate C:

$$C = \left[\frac{\log(SF_{\sigma} * \sigma_T) - \log(\sigma_{SVC})}{m}\right] + \log(t_{SVC}) = \left[\frac{\log(1.725 * 650) - \log(500)}{-0.20}\right] + \log(876000)$$
C = 4.189

3. Using Eqn. 8.9, calculate the minimum average failure time, $t_{T,650,70}$, at the 70 °C, 650 psi (4.48 mPa) stress condition:

$$t_{T,650,70} = 10^{C}/_{SF_t} = 10^{3.937}/_{167.8} = \mathbf{92.1}\ \boldsymbol{hrs}.$$

4. Account for the scatter in the data by the calculation in Step 3 and consider that to be the LCL for the 70°C, 650 psi (4.48 MPa) condition. To ensure 95% confidence that the average failure time meets this requirement, use Eqn. 8.12 to statistically adjust this number and determine the actual test requirement for the minimum average failure time:

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$$\bar{X}_{95\%,650,70} = \frac{t_{T,650,70}}{\left[1-\left(t_{(n-1)} * COV\big/\sqrt{n}\right)\right]} = \frac{92.1}{\left[1-\left(2.132 * 0.5\big/\sqrt{5}\right)\right]} = \mathbf{175.9\ hrs.}$$

Simplified method for establishing criteria for UCLS test[6]

Since the slopes of the brittle Popelar shifted master curves presented in NCHRP Report 870 are consistently -0.20 or less, it is sufficient to conduct UCLS testing at only one condition to establish performance requirements for pipes containing recycled materials. Condition I [80°C / 650 psi (4.48 MPa) stress] is the most severe condition, so it is appropriate to consider this condition for the minimum test requirement to ensure 100-year service life for pipes manufactured with recycled materials. Using Condition I as the test condition and assuming a brittle slope of -0.20, Eqn. 8.9 can be simplified to determine the minimum UCLS failure time to ensure 100-year service life:

$$t = \left(\frac{8760 \cdot t_{SVC}}{SF_t}\right) * \left(\frac{\sigma_{SVC}}{650 \cdot SF_\sigma}\right)^5 \qquad \text{(Eqn. 8.13)}$$

where:

t = Minimum required average failure time at 80 deg. C, 650 psi condition, hrs.;
SF_t = Popelar time shift factor = $e^{0.109(80-T)}$;
SF_σ = Popelar stress shift factor = $e^{0.0116(80-T)}$;
T = Service temperature, deg. C;
σ_{SVC} = Design service stress, psi; and,
t_{SVC} = Required service life at service conditions, yrs.

To ensure 95% confidence that the minimum average failure time calculated from Eqn. 8.13 will result in the desired service life, the failure time must be statistically adjusted to account for the scatter in the data. The average failure time needed to ensure 95% confidence is calculated from Eqn. 8.14:

$$\bar{X}_{95\%} = 1.911 \cdot t \qquad \text{(Eqn. 8.14)}$$

where:

$\bar{X}_{95\%}$= Average failure time needed for 95% confidence, hrs.,
t = Minimum required average failure time from Eqn. 8.11, hrs.

The average UCLS failure time of the five test specimens shall not be less than that calculated in Eqn. 8.14 (rounded up to the nearest integer), and no specimen shall fail in less than that calculated in Eqn. 8.13 (rounded up to the nearest integer).

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[6] Procedure adapted from *"Evaluation of Corrugated HDPE Pipes Manufactured with Recycled Content in Commuter Rail Applications"*, dissertation by Michael Pluimer, PhD, Proquest publishing, 2016 (12); and *"NCHRP Report 870: Field Performance of Corrugated HDPE Pipes Manufactured with Recycled Materials"* by Michael Pluimer, PhD and Rick Thomas, National Academy of Sciences, 2018 (19).

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For simplicity, design engineers and specifiers may choose to conservatively assume a factored design stress of 500 psi (3.4 MPa) and a buried pipe temperature of 73°F (23°C), which are the conditions assumed by the Florida DOT for its 100-year service applications. If this is the case, the minimum average UCLS value (at the 80 deg. C / 650 psi test condition) for 5 specimens should be 34 hours, and no single specimen shall fail in less than 18 hours, as illustrated in the example calculations:

Calculate the Popelar Shift Factors to shift the data from the test temperature of 176 deg. F (80 deg. C) to the service temperature of 73 deg. F (23 deg. C):

SF_t = Popelar time shift factor = $e^{0.109(80-23)}$ = **499.2**
SF_σ = Popelar stress shift factor = $e^{0.0116(80-23)}$ = **1.937**

Calculate the minimum required average failure time for five UCLS test specimens at Condition I (80 deg. C, 650 psi stress) to ensure a service life of 100 years at a service temperature of 73 deg. F (23 deg. C):

$$t = \left(\frac{8760 \cdot t_{SVC}}{SF_t}\right) * \left(\frac{\sigma_{SVC}}{650 \cdot SF_\sigma}\right)^5 = \left(\frac{8760 \cdot 100}{499.2}\right) * \left(\frac{500}{650 \cdot 1.937}\right)^5 = \mathbf{17.33\ hrs.}$$

Adjust this minimum required average failure time upward to account for the scatter in the data. This provides 95% confidence that all test specimens will fail above this minimum failure time:

$$\bar{X}_{95\%} = 1.911 \cdot t = 1.911 \cdot 17.33\ hrs. = \mathbf{33.1\ hrs.}$$

Rounding up, the average failure time of the five specimens must be greater than or equal to 34 hours, and no specimen shall fail in less than 18 hours, This step is to ensure that the pipe will last 100 years at a service condition of 73 deg. F (23 deg. C) and 500 psi (3.4 MPa) stress.

8.3.3 Service Life of Corrugated PP Pipe

Whereas the failure modes that govern service life for HDPE pipes are Stage II brittle cracking (the SCG mechanism) and Stage III chemical failures (oxidation), the primary failure mode that governs the service life of corrugated PP pipe is oxidation. Stress cracking via the SCG mechanism generally is not a service-limiting concern for corrugated PP pipes, due to the SCR of polypropylene being inherently greater than that of polyethylene. However, polypropylene tends to oxidize at a faster rate than polyethylene, and this effect must be accounted for by the addition of antioxidants to the resin formulation.

As with corrugated HDPE pipes manufactured with virgin materials, the most robust method for determining the service life of corrugated PP pipes is the Florida DOT protocol. The Florida DOT protocol for ensuring 100-year service life of corrugated PP pipe is identical to

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the oxidation portion of its protocol for corrugated HDPE pipe, with the exception that the activation energy of polypropylene is 70,000 J/mol as opposed to 75,000 J/mol for unstabilized HDPE. In order to qualify an antioxidant formulation for corrugated PP pipes in 100-year service applications, Florida DOT requires the compound to have an initial OIT value of 25 minutes and a residual OIT of at least three minutes after incubating in an 185 deg. F (85 deg. C) water bath for 265 days. As with corrugated HDPE pipes, the Florida DOT test method allows for other incubation temperatures, provided that the incubation durations are calculated as previously described for corrugated HDPE pipes and using the appropriate activation energy for polypropylene. Additionally, it requires a liner NCLS value of 100 hours (with no single specimen failing in less than 71 hours), in order to ensure that the SCR of the material was not adversely affected in the production process. If these parameters are met, the pipes are approved for 100-year service life applications in the state of Florida.

The only other potential service-limiting concern for corrugated PP pipe is cold-temperature brittle cracking. However, this failure mode can be prevented by incorporating impact modifiers into the compound and ensuring proper handling of the pipes during installation.

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