

Chapter 1

Engineering Properties of Polyethylene

INTRODUCTION

A fundamental understanding of material characteristics is an inherent part of the design process for any piping system. With such an understanding, the piping designer can use the properties of the material to design for optimum performance. This chapter provides basic information that should assist the reader in understanding how polyethylene's (PE's) material characteristics influence its engineering behavior.

PE is a thermoplastic, which means that it is a polymeric material that can be softened and formed into useful shapes by the application of heat and pressure and which hardens when cooled. PE is a member of the polyolefins family, which also includes polypropylene. As a group of materials, the polyolefins generally possess low water absorption, moderate to low gas permeability, good toughness and flexibility at low temperatures, and a relatively low heat resistance. PE plastics form flexible but tough products and possess excellent resistance to many chemicals.

POLYMER CHARACTERISTICS

In general terms, the performance capability of PE in piping applications is determined by three main parameters: density, molecular weight, and molecular weight distribution. Each of these polymer properties has an effect on the physical performance associated with a specific PE resin. The general effect of variation in these three physical properties as related to polymer performance is shown in Table 1-1.

Density

PE is a semicrystalline polymer composed of long, chain-like molecules of varying lengths and numbers of side branches. As the number of side branches increases, polymer crystallinity and hence, density decreases because the molecules cannot pack as

Table 1-1 Effects of density, molecular weight, and molecular weight distribution

Property	As Density Increases	As Molecular Weight Increases	As Molecular Weight Distribution Broadens
Tensile	Increases	Increases	—
Stiffness	Increases	Increases slightly	Decreases
Impact strength	Decreases	Increases	Decreases
Low temperature brittleness	Increases	Decreases	Decreases
Abrasion resistance	Increases	Increases	—
Hardness	Increases	Increases slightly	—
Softening point	Increases	—	Increases
Stress crack resistance	Decreases	Increases	Increases
Permeability	Decreases	Increases slightly	—
Chemical resistance	Increases	Increases	—
Melt strength	—	Increases	Increases

closely together. Density affects many of the physical properties associated with the performance of the finished pipe. Properties such as stress crack resistance, tensile strength, and stiffness are all affected by the base resin density of the polymer as shown in Table 1-1.

Base resin density refers to the density of the natural PE that has not been compounded with additives and/or colorants. Within this range, the materials are generically referred to as either medium or high density in nature. PE pipe resins with a base resin density in the range of 0.935 to 0.941 grams per cubic centimeter (g/cc) are referred to as medium density PE. PE pipe base resins in the range of 0.941 to 0.945 g/cc are commonly referred to as high-density polyethylenes (HDPEs). Industry practice has shown that base resin (unpigmented) densities in the range of 0.936 to 0.945 g/cc offer a highly beneficial combination of performance properties for the majority of piping applications.

The addition of carbon black to the base PE resin does have an impact on the compounded density of the material. The addition of 2 to 2.5 percent carbon black raises the compounded material density on the order of 0.009–0.011 g/cc. The variability in the actual percentage of carbon black incorporated can have a moderate effect on comparative density values. As a result, industry practice as established by ASTM standard is to provide comparative values on the base resin density as this is a better indicator of the polymer crystallinity.

Molecular Weight

PE resins are composed of a number of molecular chains of varying lengths. As a result, the molecular weight of the resin is the average of the weight of each of these chains. The average weight may be determined using sophisticated scientific techniques, such as gel permeation chromatography or size-exclusion chromatography. For PE of a given density, the effect of increasing molecular weight on physical properties is shown in Table 1-1.

A very rough indicator of the molecular weight of a polymer may be obtained using the melt index technique of analysis as described in ASTM D1238¹. The melt index technique is an inexpensive means of comparing, in a relative manner, the molecular weight of PEs having similar structure. Resins with a relatively low average molecular

weight will have a comparatively high melt index. Conversely, resins with a relatively high molecular weight will yield a lower melt index. From this relationship, we can associate changes in physical properties (as shown in Table 1-1) with changes in melt index of the material. It is important not to use melt index alone as a definitive indicator of molecular weight because variations in polymer structure can affect both molecular weight and melt index.

Molecular Weight Distribution

Molecular weight distribution (MWD) refers to the statistical grouping of the individual molecular chains within a PE resin. Resins made up of molecules that vary considerably in molecular weight are considered to have a broad MWD. When most of the molecules are nearly the same length, the MWD is considered narrow. The effect of broadening the MWD of a PE resin having a given density and molecular weight is shown in Table 1-1.

Recent Advances

It should be noted that recent advances in polymer technology have led to the development and introduction of even higher density resins for use in piping applications. These new materials that have base resin densities as high as 0.952 g/cc in combination with higher molecular weight and bimodal molecular weight distribution are generally recognized as offering higher levels of technical performance under ISO standards for PE piping that are common outside of North America. These higher levels of technical performance are not yet recognized within the North American standards system.

MECHANICAL PROPERTIES

Viscoelasticity

PE is characterized as a viscoelastic construction material. Because of its molecular nature, PE is a complex combination of elastic-like and fluid-like elements. As a result, this material displays properties that are intermediate to crystalline metals and very high viscosity fluids. Figure 1-1 is the traditional diagrammatic representation of PE in which the springs represent those components of the PE matrix that respond to loading in a traditional elastic manner in accordance with Hooke's law. The dashpots represent fluid elements of the polymer that respond to load much as a Newtonian fluid.

As a result of the viscoelastic character of the polymer, the tensile stress-strain curve for PE is divided into three distinct regions. The first of these is an initial linear deformation in response to the load imposed that is generally recoverable when the load is removed. In the second stage of loading, deformation continues but at an ever decreasing rate. Thus, the slope of the stress-strain curve is constantly changing, attesting to its curvilinear nature. Deformation in the second stage may not be fully recoverable. The final stage of the stress-strain curve for PE is characterized by necking down followed by distinct elongation or extension ultimately ending in ductile rupture of the material.

The viscoelastic nature of PE provides for two unique engineering characteristics that are employed in the design of HDPE water piping systems. These are *creep* and *stress relaxation*.

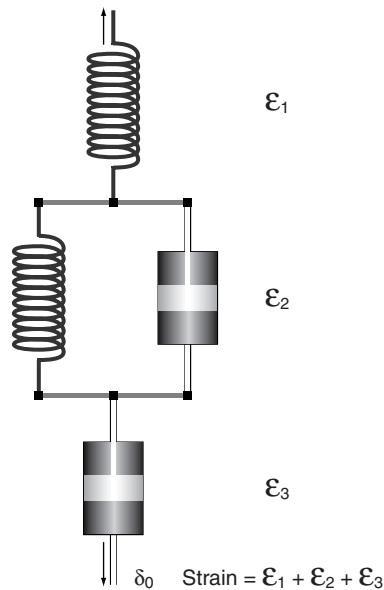


Figure 1-1 Traditional model of HDPE

Creep is not an engineering concern as it relates to PE piping materials. Creep refers to the response of PE, over time, to a constant static load. When HDPE is subjected to a constant static load, it deforms immediately to a strain predicted by the stress–strain modulus determined from the tensile stress–strain curve. The material continues to deform indefinitely at an ever decreasing rate. If the load is high enough, the material may yield or rupture. This time-dependent viscous flow component of deformation is called creep. This asserts that the long-term properties of PE are not adequately predicted by the results of short-term testing, such as tensile strength. As such, PE piping materials are designed in accordance with longer-term tests such as hydrostatic testing and testing for resistance to slow crack growth, which when used in accordance with industry recommended practice, the resultant deformation caused by sustained loading, or creep, is not sufficiently large to be an engineering concern.

Stress relaxation is another unique property arising from the viscoelastic nature of PE. When subjected to a constant strain (deformation of a specific degree) that is maintained over time, the load or stress generated by the deformation slowly decreases over time. This is of considerable importance to the design of PE piping systems.

Because of its viscoelastic nature, the response of PE piping systems to loading is time-dependent. The effective modulus of elasticity is significantly reduced by the duration of the loading because of the creep and stress relaxation characteristics of PE. An instantaneous modulus for sudden events such as water hammer can be as high as 150,000 psi at 73°F (23°C). For slightly longer duration, but short-term events such as soil settlement and live loadings, the effective modulus for PE is roughly 110,000 to 120,000 psi at 73°F (23°C), and as a long-term property, the effective long-term modulus calculates to be approximately 20,000 to 38,000 psi. This modulus becomes the criteria for the long-term design life of PE piping systems.

This same time-dependent response to loading is also what gives PE its unique resiliency and resistance to sudden, comparatively short-term loading phenomena.

Such is the case with PE's resistance to water hammer, which will be discussed in more detail in subsequent sections.

PE is a thermoplastic and, as such, its properties are temperature dependent as well as dependent on the duration of loading. Therefore, the absolute value of the engineering properties of PE will vary in relation to the temperature at which the specific tests are conducted. Industry convention is to design PE piping systems using engineering properties established at the standard temperature of 73°F (23°C) and then employ industry established temperature compensating multipliers to provide for the service condition temperatures.

Tensile Strength

Tensile strength is a short-term property that provides a basis for classification or comparison when established at specific conditions of temperature and rate of loading but is of limited significance from a design perspective. The tensile strength of PE is typically determined in accordance with ASTM D638². In this test, PE specimens are prepared and pulled in a controlled environment at a constant rate of strain.

Any material will deform when a force is applied. The amount of deformation per unit length is termed the *strain*, and the force per cross-sectional area is termed the *stress*. As it relates to tensile testing of PE pipe grades, strain is generally approximated by assuming a straight-line relationship to stress at lower stress levels (up to 30 percent of the tensile yield point), and it is reversible. That is, the material deforms but will over time recover its original shape when the stress is removed. The strain in this region is referred to as the elastic strain because it is reversible. The Modulus of Elasticity (or Young's Modulus) is the ratio between the stress and strain in this reversible region.

At stress levels generally greater than 50 percent, strain is no longer proportional to stress and is not reversible, that is, the slope of the stress-strain curve changes at an increasing rate. At these higher stress levels, the materials begin to deform such that the original dimensions are not recoverable. In actual testing of PE pipe grade materials, this stage is characterized by initiation of a distinct "necking" of the tensile specimen. This is called the *plastic strain region*. The point at which stress causes a material to deform beyond the elastic region is termed the *tensile strength at yield*. The stress required to ultimately break the test specimen is called the *ultimate tensile strength* or the *tensile strength at break*. (See Figure 1-2.)

Of equal importance is the percent elongation obtained during tensile testing because this information can provide a relative indication of the ductility of the polymer being evaluated. Materials with relatively high levels of elongation are indicative of highly ductile performance as pipe. Modern pipe grade PEs will demonstrate elongations of 400 to 800 percent or more between yield and ultimate tensile rupture. It is also typical that tensile strength at yield and tensile strength at break are similar values; that is, once the material yields, the load required to continue specimen elongation and eventually break the specimen changes very little.

Compressive Properties

Compressive forces act in the opposite direction to tensile forces. The effect of compressive force on PE can be measured on a tensile test apparatus using the protocol described in ASTM D6953. At small strains (up to 3 percent for most PE pipe resins), the compressive modulus is about equal to the elastic modulus. However, unlike tensile loading, which can result in a failure, compression produces a slow and infinite yielding that seldom leads to a failure. For this reason, it is customary to report compressive

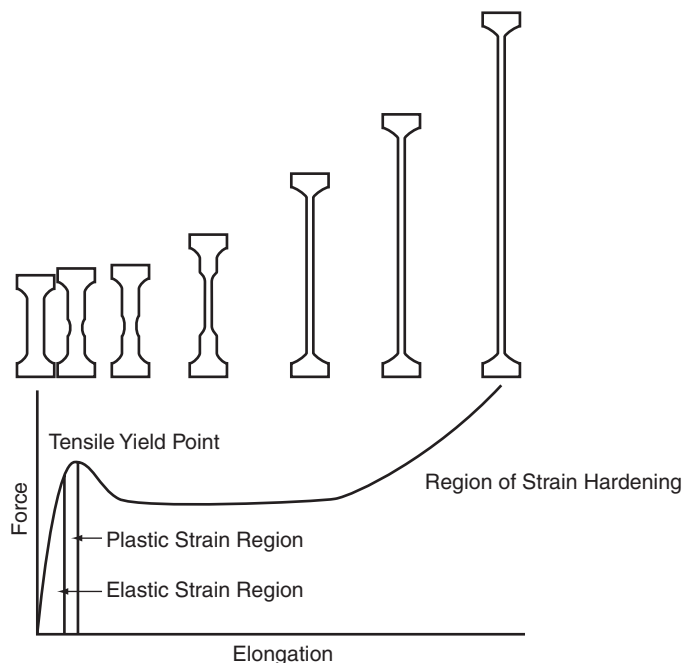


Figure 1-2 Generalized tensile stress–strain curve for PE pipe grades

strength as the stress required to deform the test specimen to a specific strain. Under conditions of mild compression, the general engineering assumption is that the effective compressive modulus is essentially equivalent to the effective tensile modulus.

Flexural Properties

The flexural strength of a material is the maximum stress in the outer fiber of a test specimen at rupture. Because most PE pipe resins do not break under this test, the true flexural strength of these materials cannot be determined. As such, the flexural modulus is typically calculated on the basis of the amount of stress required to obtain a 2 percent strain in the outer fiber. The prevailing test method is ASTM D790⁴. Depending on the density of the base resin, the effective flexural modulus of PE can range from 80,000 to 160,000 psi. The flexural modulus of PE is a short-term property that provides a basis for classification but is of limited significance from a design perspective.

Impact Properties

The amount of energy that a material can absorb without breaking or fracturing is referred to as the impact strength of that material. ASTM D256⁵ describes the two most commonly used tests for PE pipe compounds, the Izod Impact Test and the Charpy Impact Test. Both test methods measure the ability of a PE specimen to absorb energy on failure. Obviously, test information such as this is used to make a relative comparison of the material's resistance to failure on impact under defined circumstances. In this regard, PE is a very tough material demonstrating Izod impact resistance values in the range of 10–12 ft-lbf/in. at standard room temperature. This is the range in which PE pipe grades will bend or deflect in response to Izod impact testing. These values will change to some degree as the temperature at which the test

is conducted changes. When Izod impact testing is conducted at very low temperature ($< 0^{\circ}\text{F}$), fracture may occur.

Abrasion Resistance

PE demonstrates outstanding abrasion resistance under potable water flow conditions. Moreover, the abrasion resistant nature of this material has resulted in the widespread use of PE pipe for liquid slurry handling applications. However, the factors that affect the wear resistance of liquid slurry pipelines are diverse. In addition to flow velocity, one must consider the type of flow regime: laminar (single phase or double phase) or turbulent flow; presence, size, angularity, and concentration of suspended solids; and angle of impingement. While these factors are germane to slurry handling applications, they will have little or no effect on the abrasion resistance of PE pipe used in the transport of clean potable water. At higher flow velocities typical of potable water distribution, there is no erosional effect on PE pipe.

OTHER PHYSICAL PROPERTIES

Permeability

The rate of transmission of gases and vapors through polymeric materials varies with the structure of both the permeating molecules and the polymer. Permeability is directly related to the crystallinity of the PE and the size and polarity of the molecule attempting to permeate through the matrix. The higher the crystallinity (the higher the density), the more resistant is the polymer to permeation. PE resins used for the manufacture of water pipe in accordance with ANSI/AWWA C906⁶ possess density ranges that make them highly resistant to most types of permeation.

The designer should be aware, however, that all piping systems are susceptible to permeation of light hydrocarbon contaminants that may be present in the soil. With continued exposure over time, these contaminants can permeate from the soil into the pipe itself either through the wall of a plastic pipe or through the elastomeric gasketed joint of a mechanically joined piping system. For this reason, special care should be taken when installing potable water lines through contaminated soils regardless of the type of pipe material (concrete, plastic, ductile iron, etc.).

From ANSI/AWWA C906, Sec. 4.1:

“The selection of materials is critical for water service and distribution piping in locations where the pipe will be exposed to significant concentrations of pollutants comprised of low molecular weight petroleum products or organic solvents or their vapors. Research has documented that pipe materials, such as PE, polybutylene, polyvinyl chloride, and asbestos cement and elastomers, such as used in jointing gaskets and packing glands, are subject to permeation by lower molecular weight organic solvents or petroleum products. If a water pipe must pass through a contaminated area or an area subject to contamination, consult with pipe manufacturers regarding permeation of pipe walls, jointing materials, etc., before selecting materials for use in that area.”

Temperature Effects

PE is a thermoplastic polymer. As such, its physical properties change in response to temperature. These property changes are reversible as the temperature fluctuates. The physical properties of PE are normally determined and published at standard

laboratory conditions of 73°F (23°C) with the understanding that the absolute values may change in response to temperature.

For example, the pressure rating of a PE pipe relates directly to the hydrostatic design basis (HDB) of the material from which it is produced. Traditionally, this design property is established at 73°F (23°C). However, as temperature increases, the viscoelastic nature of the polymer yields a lower modulus of elasticity, lower tensile strength, and lower stiffness. As a result, the hydrostatic strength of the material decreases, which yields a lower pressure rating for a specific pipe DR. The effect is reversible in that once the temperature decreases again to standard condition, the pressure capability of the product returns to its normal design basis. However, the elevated temperature pressure rating is always applied for elevated temperature service conditions.

Buried potable water systems typically operate in a range below 73°F (23°C). In these situations, the pressure capability of the pipe may actually exceed the design pressure class ratings listed in ANSI/AWWA C901 and C906. The current industry practice is to set the pressure rating of the pipe at 73°F (23°C) as the standard and consider any added strength at lower service temperatures as an additional factor of safety for design purposes.

The coefficient of linear expansion for unrestrained PE is generally accepted to be 1.2×10^{-4} in./in./°F. This suggests that unrestrained PE will expand or contract considerably in response to thermal fluctuation. It should be pointed out, however, that while the coefficient of expansion for PE is fairly high compared to metal piping products, the modulus of elasticity is comparatively low, approximately $1/300$ of steel for example. This suggests that the tensile or compressive stresses associated with a temperature change are comparatively low and can be addressed in the design and installation of the piping system. Thermal expansion and contraction effects must be taken into account for surface, above grade, and marine applications where pipe restraint may be limited. But with buried installations, soil friction frequently provides considerable restraint against thermal expansion and contraction movement. In smaller diameter installation, such as those less than 12-in. nominal outside diameter, soil friction restraint can be enhanced by snaking the pipe side to side in the trench prior to backfilling. Additional restraint against movement can be provided with in-line anchors. (See Chapter 8.)

In consideration of its thermal properties, PE pipe must be joined using methods that provide longitudinal thrust restraint such as heat fusion, electrofusion, flange connections, and restrained mechanical connections. Additionally, fittings used within the system should possess sufficient pull-out resistance in light of anticipated movement caused by thermal expansion or contraction. Finally, PE pipe should be stabilized or anchored at its termination points to other, more rigid piping or appurtenances to avoid potential stress concentration at the point of transition or to avoid excessive bending moments on system fittings. The reader is referred to Chapter 8 of this manual for more information regarding control of pull-out forces.

Electrical Properties

PE is an excellent insulator and does not conduct electricity. The typical electrical properties of PE are shown in Table 1-2.

Table 1-2 Electrical properties of PE

Electrical Property	Units	Test Method	Value
Volume Resistivity	ohms-cm	ASTM D257	$> 10^{16}$
Surface Resistivity	ohms	ASTM D257	$> 10^{13}$
Arc Resistance	seconds	ASTM D495	200 to 250
Dielectric Strength	volts/mil	ASTM D149	450 to 1,000
Dielectric Constant	—	ASTM D150	2.25 to 2.35 @ 60 Hz
Dissipation Factor	—	ASTM D150	> 0.0005 @ 60 Hz

CHEMICAL PROPERTIES

Chemical Resistance

An integral part of any piping system design is the assessment of the chemical environment to which the piping will be exposed and the impact it may have on the design life of the pipe. Generally, PE is widely recognized for its unique chemical resistance. As such, this piping material has found extensive utilization in the transport of a variety of aggressive chemicals.

To assist the designer in the selection of PE for piping applications, chemical resistance charts have been published that provide some basic guidelines regarding the suitability of PE as a piping material in the presence of various chemicals. A very comprehensive chemical resistance chart has been published by the Plastics Pipe Institute (PPI) in the *Handbook of Polyethylene Pipe*⁷.

It is important to note that chemical resistance tables are only a guideline. Data such as this is generally developed on the basis of laboratory tests involving the evaluation of tensile coupons immersed in various concentrations of the reference chemicals. As such, these charts provide a relative indication of the suitability of PE when exposed. They do not assess the impact that continual exposure to these chemicals may have on various aspects of long-term performance nor do they address the effect produced by exposure to various combinations of the chemicals listed. Additionally, these chemical resistance tables do not take into consideration the affect of stress (loading), magnitude of the stress, or duration of application of such stress. In light of this, it is recommended that the designer use responsible judgment in the interpretation of this type of data and its utilization for design purposes. Additional information is available from PPI Technical Report TR-19⁸. Alternatively, the reader is referred to the pipe manufacturer who may have actual field experience under similar specific service conditions.

Corrosion

PE used in water piping applications is an electrically nonconductive polymer and not adversely affected by naturally occurring soil conditions. As such, it is not subject to galvanic action and does not rust or corrode. This aspect of PE pipe means that cathodic protection is not required to protect the long-term integrity of the pipe even in the most corrosive environments. Proper consideration should be given to any metal fittings that may be used to join the pipe or system components.

Tuberculation

The potential for tuberculation of PE pipe is minimal. Tuberculation typically occurs in response to the deposition of soluble encrustants onto the surface of the pipe and subsequent corrosive action with the base material of the pipe. Properly extruded, PE pipe has an extremely smooth surface, which provides minimal opportunity for the precipitation of minerals such as calcium carbonate and the like onto the interior surface. PE itself is inert and therefore not prone to galvanic action, which these solubles may initiate in other piping materials.

Resistance to Slow Crack Growth

PE piping manufactured in accordance with the requirements of ANSI/AWWA C901 or C906 is resistant to slow crack growth when used in typical potable water systems. Research in the area of slow crack growth combined with continual advancements in material science have resulted in HDPE piping products that when manufactured and installed in accordance with these standards are designed to provide sustained resistance to slow crack growth phenomena such as environmental stress cracking. To understand the significance of this statement, one must first understand the nature of slow crack growth and pipe failure in general.

Excluding third party damage phenomena, such as dig-ins, etc., pipe failure may occur in one of three ways. First is the sudden yielding of the pipe profile in response to a stress level beyond the design capability of the material itself. Generally, this is referred to as Stage I type failure and is typically ductile-mechanical in nature and appearance. The pressure class designations and working pressure-rating methodology presented in ANSI/AWWA C906 are developed within the constraints of these material capabilities. The material requirements stipulated in ANSI/AWWA C906 combined with additional pipe requirements, such as workmanship, dimensional specifications for each pressure class, and the five-second pressure test, provide a basis for resistance to this type of failure over the design life of the PE piping system.

The second mode of pipe failure is the result of slow crack growth. Generally, this is referred to as Stage II brittle-mechanical type failure. In this mode, pipe failure is characterized by very small slit-type failures in the pipe wall that initiate at points of mechanical stress concentration associated with inhomogeneities in the pipe wall or at imperfections on the inner pipe surface. Typically, these types of failures are slower in nature and occur as a three-stage process: crack initiation, crack propagation, and final ligament yield that results in pipe failure. This type of failure phenomena may be the result of exposure to more aggressive conditions such as elevated temperature (> 140°F [60°C]) or the oxidation reduction potential (ORP) of the water system, which is a function of chemical concentration (chlorine, chloramines, chlorine dioxide, ozone, dissolved oxygen, etc.) or other factors that are not typical of the majority of potable water applications. ANSI/AWWA C906 places specific requirements on the pipe manufactured in accordance with this standard to guard against Stage II type failures while in potable water service.

ANSI/AWWA C906 requires that all pipe must be produced from a material for which a PPI hydrostatic design basis (HDB) has been recommended. This requirement ensures that stress-rupture data for pipe specimens produced from the listed material is reviewed in accordance with the protocol in PPI's TR-3 to ensure that it meets the stress-rating requirements of ASTM D2837. The stress-rupture data is further analyzed to ensure that it "validates." That is, additional higher temperature stress-rupture tests are conducted to validate that the slope of the regression curve obtained at a specific temperature does not change until some time after the 100,000-hour requirement

established within ASTM D2837. Second, ANSI/AWWA C906 also has specific performance requirements for the manufactured pipe or fittings such as thermal stability, the elevated-temperature sustained-pressure test, and the bend back test, which minimize the potential for Type II failures in typical potable water service applications.

As a safeguard against Type II failure phenomenon, piping products manufactured in accordance with ANSI/AWWA C906 are produced from PE resins that are highly resistant to environmental stress cracking as determined by the tests described below.

Laboratory tests to assess resistance to environmental stress cracking include ASTM D1693⁹ and ASTM F1473¹⁰. These standard test methods are utilized within the plastic pipe industry to assess the piping material's resistance to cracking under accelerated conditions of concentrated stress, aggressive chemical attack, and elevated temperature. According to ASTM D1693, 10 compression molded specimens of the PE material are prepared, deformed into a 180° U-bend, and submerged in an aggressive stress-cracking chemical such as Igepal CO630 (a strong detergent) at 100°C. The specimens are maintained at elevated temperature and the time to failure is recorded. Failure is defined as cracks that are visible on the surface of the specimens.

Because ASTM D1693 defines the time to the appearance of cracks on the surface of the material, it provides information about the material's resistance to the initiation of stress cracks. Modern PE pressure piping materials have been formulated and engineered to provide excellent resistance to the initiation of stress cracks. When tested in accordance with ASTM D1693, specimens commonly do not fail in thousands of hours. More recently, PE pressure piping materials have been developed to resist stress crack initiation to such an extent that they now cannot be adequately characterized by ASTM D1693. As a result, new tests have been developed that assess the slow crack growth resistance of the materials. Predominant among these tests is ASTM F1473, which like ASTM D1693 has been incorporated into ASTM D3350 as a classified slow crack growth resistance property.

ASTM F1473, the "PENT" test, has been particularly well researched as a method to assess the resistance of a PE compound to slow crack growth, the second stage of environmental stress cracking. Materials that do not fail under ASTM D1693 after thousands of hours are more effectively characterized under ASTM F1473.

Under ASTM F1473, specimens are prepared from compression-molded plaques of PE resin or taken from pipe. Extremely sharp razor notches are cut across the specimen to a specified depth of the specimen thickness. The specimen is placed in a constant temperature air oven at 80°C, and a constant tensile stress of 2.4 MPa (348 psi) is applied to the unnotched area. The time to specimen breakage is measured. It should be noted that elevated temperature air is known to be an aggressive, oxidizing environment for PE, especially under applied stress.

An empirical study of PE pressure piping materials compared ASTM F1473 performance to service life and concluded that a failure time of 12 hours under ASTM F1473 compared to a service history of 50 years¹¹. However, a minimum ASTM D3350 SCG cell classification value of 6, a minimum average failure time of 100 hours per ASTM F1473, is recommended for PE water pipes. This performance level provides a considerable margin against the potential for environmental stress-cracking failure in the field.

The final mode of pipe failure is Stage III or brittle-oxidative, which is the result of oxidative degradation of the polymer's material's properties. This type of failure is typically obtained under conditions of extreme laboratory testing. As a further precaution against Type III failure, the HDPE pipe industry has investigated the resistance of these products to failure under conditions of flowing potable water service. ASTM F2263¹² provides that pipe specimens are subjected to flowing water at specific conditions of temperature, pH, and chlorine content. These extreme test conditions are

used to further improve the capabilities of HDPE piping systems and their ultimate resistance to environmental stress cracking in potable water applications.

In summary, PE pressure piping materials used in AWWA pressure piping are exceptionally resistant to environmental stress crack initiation and to slow crack growth if a crack does initiate. ANSI/AWWA C906 requires PE materials that are highly resistant to environmental stress cracking and establishes product tests to ensure against crack initiation sites in the pipe ID. As such, PE pipe produced and labeled with the ANSI/AWWA C901/C906 designation indicates that the product has been manufactured from a material that has been tested and found to meet or surpass the requirements for resistance to slow crack growth in either of these standards. For further information regarding the evolution of resistance to slow crack growth in PE pipe, see the references at the end of this chapter¹³.

ENVIRONMENTAL CONSIDERATIONS

Weathering

Over time, ultraviolet (UV) radiation and oxygen may induce degradation in plastics that can adversely affect their physical and mechanical properties. To prevent this, various types of stabilizers and additives are compounded into a polymer to give it protection from these phenomena.

The primary UV stabilizer used in the PE pipe industry is carbon black, which is the most effective additive capable of inhibiting UV induced reactions. Carbon black is extremely stable when exposed to the outdoor elements for long periods of time and is relatively inexpensive compared to some of the more exotic colorant systems. The result is a piping system of uniform color that does not chalk, scale, or generate dust in response to extended periods of outdoor exposure.

PE pipe is generally formulated to resist ultraviolet (UV) degradation. Exposure to UV radiation leads to the formation of free radicals within the polymer matrix. These free radicals are then available to react with other molecules within the polymer, and the result can be a significant reduction in physical properties. The carbon black present in PE pipe acts as a primary UV absorber thus precluding the formation of free radicals. In this way, UV degradation is prevented, and the physical properties of the polymer are retained even after substantially long periods of exposure to the elements. Studies conducted by Bell Laboratories on the stability of carbon black containing PE used in wire and cable application have shown that these materials can sustain exposure to the elements over periods of 30 years plus with no appreciable change in the performance characteristics of the polymer¹⁴.

While carbon black is a very effective UV screen that provides maximum UV protection, the degree of protection it imparts may not be required for buried pipe applications. Generally, UV protection is only required for relatively short periods of time while the pipe is exposed to sunlight such as during storage or while in transit or in the process of handling during installation. As a result, alternate UV stabilization systems have been developed that have proven very effective and permit the use of colored, nonblack PE pipe. The reader is referred to the pipe manufacturer for information regarding the availability of these nonblack products.

Stabilization

Prolonged exposure to excessive heat can also initiate the generation of free radicals in a polymer. A chemical stabilizer system is typically added to the PE to prevent the generation of these free radicals. Generally, these stabilization systems are produced

from a combination of carbon black, FDA-approved antioxidants and heat stabilizers, or in the case of nonblack pipe, a series of FDA-approved heat stabilizers and antioxidants. These stabilization systems are designed and selected with the intention of providing long-term protection of the PE polymer from oxidation and thermal degradation. As noted, these additives are generally FDA approved and their suitability of use in potable water applications is determined in accordance with third party standards developed by a consortium that includes NSF International, American Water Works Association, Awwa Research Foundation, and other groups. The effectiveness of the stabilization system may be evaluated using differential scanning calorimetry (DSC) and/or the carbonyl index test. The DSC test measures the induction time to the onset of degradation and the temperature at which degradation begins. The carbonyl index test measures the degree of oxidative degradation by measuring the type and amount of carbonyl functional groups created on the surface of the polymer as a result of excessive exposure to heat or UV radiation.

PE pipe produced in accordance with ANSI/AWWA C906 must meet the requirements of ASTM D3350¹⁵. This industry recognized standard requires that the induction temperature for the onset of degradation must exceed 220°C.

Biological

Biological attack may be described as the degradation of the piping material caused by the action of organisms such as bacteria, fungi, insects, or rodents. PE has no nutritional value. It is considered inert in that it will neither support nor deter the growth or propagation of micro- or macro-organisms.

Numerous studies have been conducted over the years relative to the biological implications of PE pipe. These studies have revealed that insects or microorganisms pose no threat of damage or degradation to PE pipe. Some indication of rodent damage has been reported but most of this was related to placement of small diameter tubing in rodent infested areas. The resulting damage was attributed to the need for the rodent to maintain their teeth in good condition and the damage associated with gnawing on the profile was felt to be no greater with PE than with any other piping materials installed in these areas. Additional information is available from PPI Technical Report TR-11¹⁶.

LONG-TERM PROPERTIES

Long-Term Hydrostatic Strength

The pressure capability of PE pipe is based on an extrapolation of stress-rupture data over time. The extrapolation method predominantly used in North America is defined in ASTM D2837¹⁷. Using this protocol, stress-rupture data at a specific temperature is gathered over a 10,000 hour period. If the data meets certain distribution criteria, the data is extrapolated to 100,000 hours. The stress intercept that is extrapolated at 100,000 hours is referred to as the *long-term hydrostatic strength* (LTHS) of the material being evaluated. The LTHS will fall into one of a series of preferred stress ranges defined in ASTM D2837. The category into which the LTHS falls is referred to as the *hydrostatic design basis* (HDB) of the material. It is this value that is used to determine the pressure capability of a pipe under specified service conditions. The designer is referred to ASTM D2837 for a complete listing of the categories and stress ranges that are used to establish the HDB for thermoplastic materials. The HDB is used to determine the pressure capability of a specific pipe profile or DR

under certain conditions of stress. This pressure rating methodology is discussed in detail in Chapter 4.

The HDB for a material can be obtained at any of a variety of service temperatures. In fact, it is common practice to evaluate PE at the standard laboratory temperature of 73°F (23°C) and an elevated temperature of 140°F (60°C). Through a statistical analysis of the nature of both of the curves, information regarding the performance of the material under other service temperatures can be determined.

Information such as this is used by the Hydrostatic Stress Board (HSB) of the Plastics Pipe Institute (PPI) to issue recommendations for the HDB of thermoplastics materials that will be used to produce plastic pipe. These recommendations are reviewed and published periodically in PPI's TR-4¹⁸.

Fracture Mechanics

Fracture mechanics refers to the study of crack growth originating from flaws that may exist within a material or structure. Flaws may be the result of inhomogenities within a material, manufacturing inconsistencies, gouges, and scrapes that result from the handling or mishandling of the finished product or any other number of sources.

These flaws, whether microscopic or macroscopic in nature, act to intensify any nominal stress applied within the localized region. At some point, this intensified stress at the flaw will exceed the strength of the material and a small crack may develop. An initiated crack may subsequently grow and lead to failure of the part or component. Modern PE materials formulated specifically for pressure pipe applications are designed to resist the initiation of this slow crack growth phenomena even when subjected to millions of cycles of pressure transients.

The fracture resistance of a given structure or material will depend on the level of stress applied to it, the presence and size of any flaws in it, and the inherent resistance of the material to crack initiation and growth. Extensive research conducted on gas pipe indicates that modern PE resins designed for pressure piping applications are extremely resistant to slow crack growth¹⁹. The requirements of ANSI/AWWA C906 ensure that water pipe produced in accordance with this standard will demonstrate comparable levels of resistance to slow crack growth provided that the pipe system is designed, installed, and operated in accordance with the guidelines stated in subsequent chapters of this manual.

Fatigue

Each time a PE pipe is pressurized or subjected to hydraulic transients, its circumference expands and unrestrained length decreases in an elastic manner. For applications where the pressure is constant and below the pipe pressure rating, this small amount of expansion (strain) is not important and is not considered a design variable. However, strain does become important when the pipe undergoes higher, cyclic pressurization. There is a maximum critical strain limit, which once exceeded, permanently changes the characteristics of the pipe.

At higher strain levels, microcracks can develop within the PE matrix. Repeated straining that approaches the critical strain limit of the material can cause growth of the microcracks that may eventually propagate into a failure.

For modern PEs used in piping applications, the critical strain limit has been established to be 6 to 7 percent depending on the exact nature of the polymer. The typical PE pressure pipe undergoes a strain of 0.5 to 1.0 percent when placed in service, that is, a safety factor of at least 6 to 1. This is well below the critical strain limit for modern

PE pipe resins. Even cyclic pressure surges of up to 100 percent of the operating pressure of the PE water pipe system do not exceed the critical strain limit for these highly ductile materials.

To this end, Bowman and Marshall (et al.) have conducted extensive research on the fatigue resistance of modern PE pipe compounds^{20, 21}. Based on his research of combined creep and surge regimes at 80°C, Bowman concluded that butt-fused PE piping systems provide years of uncompromised service exceeding millions of surge cycles even under conditions of sustained pressurization. Marshall and his colleagues determined that today's tough PE pipe formulations can withstand sustained periods of high frequency surging (ranging from 1 to 50 cycles per hour) at magnitudes of up to 200 percent of the pipe's static pressure rating with no indication of fatigue and no reduction in long-term serviceability when properly installed. Research results such as these serve as the basis for the surge allowances stipulated in ANSI/AWWA C906.

INDUSTRY STANDARDS

Industry standards exist to establish the minimum level of performance for PE piping based on the physical properties resulting from the combined effect of the three fundamental polymer properties: density, molecular weight, and molecular weight distribution. Primary among these is ASTM D3350 and the various additional standards included by reference within ASTM D3350.

ASTM D3350 is a comprehensive classification standard that delineates seven key properties associated with piping performance. Ranges of performance for each of these properties are defined within this standard as well. The result is a matrix of piping related material properties defined by classification cells, which can be utilized to identify the particular PE compound used to manufacture pipe. Six properties and their respective cell limits are reproduced from ASTM D3350 in Table 1-3.

The seventh property, color and UV stabilizer, is identified by a letter, which follows the six cell classification numbers described in Table 1-3. The code letters for color and UV stabilizer are

- A—for natural
- B—for colored
- C—for black with minimum 2 percent carbon black
- D—for natural with UV stabilizers
- E—for colored with UV stabilizers

PE pipe compounds are typically black with a minimum of 2 percent carbon black, C, or colored with UV stabilizers, E.

By utilizing ASTM D3350, the pipe designer can reference a specific combination of six numbers and one letter to establish a minimum level of performance based on the properties referenced in the standard. Pipe produced in accordance with ANSI/AWWA C906 must be manufactured from PE material, which meets one of three cell classifications²¹ as defined by ASTM D3350. As noted in ANSI/AWWA C906, higher cell classes for some of the properties are allowed, but those for density and HDB are not. Considering the case for one of these cell classifications, 345464C, Table 1-4 presents an explanation of the minimum level of performance to be met.

By specifying a pipe produced from a feedstock with a cell classification of 345464C, as shown in Table 1-3, the designer has established the minimum level of performance for the polymer from which the pipe is produced. For example, in Table 1-4, a base resin density of 0.941 to 0.955 g/cc per ASTM D1505 is required. Base resin density is one of the key molecular parameters for PE in piping applications.

Further, the designer has specified a polymer with a melt index of less than 0.15 gr/10 min in accordance with ASTM D1238. Melt index is a relative indication of the

Table 1-3 ASTM D3350 cell classification limits

Property	Test Method	Test						
		0	1	2	3	4	5	6
1. Density, g/cm ³	D1505	—	0.910– 0.925	0.926– 0.940	0.941– 0.947	0.948– 0.955	>0.955	—
2. Melt index, g/10 min	D1238	—	>1.0	1.0 to 0.4	<0.4 to 0.15	<0.15	A	B
3. Flexural modulus, Mpa (psi)	D790	—	<138 (<20,000)	138<276 (20,000 to <40,000)	276<552 (40,000 to <80,000)	552<758 (80,000 to <110,000)	758<1,103 (110,000 to <160,000)	>1,103 (>160,000)
4. Tensile Strength at Yield, Mpa (psi)	D638	—	<15 (<2,200)	15<18 (2,200 to <2,600)	18<21 (2,600 to <3,000)	21<24 (3,000 to <3,500)	24<28 (3,500 to <4,000)	>28 (>4,000)
5. Slow crack growth resistance								
I. ESCR	D1693							
a. Test condition			A	B	C	C	—	—
b. Test duration, hr		—	48	24	192	600		
c. Failure, max., %			50	50	20	20		
II. PENT (hr)	F1473							
Molded plaque, 80°C, 2.4 Mpa, Notch depth per F14732, Table I			0.1	1	3	10	30	100
6. HDB, MPa (psi) @ 23°C	D2837	—	5.52 (800)	6.89 (1,000)	8.62 (1,250)	11.03 (1,600)	—	—

Table 1-4 Example of D3350 cell class specification

Property	ASTM Method	Cell Class Designation
Density	D1505	3
Melt index	D1238	4
Flexural modulus	D790	5
Tensile strength	D638	4
Slow crack growth resistance	F1473	6
HDB	D2837	4
Color and UV stabilizer code	D3350	C

molecular weight of the polymer, and the two are inversely related. That is, a lower melt index suggests a higher molecular weight. A higher molecular weight relates to an increase in certain physical properties as shown in Table 1-1.

The relative stiffness of the piping material as reflected in the flexural modulus is specified to be between 110,000 and 160,000 psi per ASTM D790 by the designation of a 5 in the third character position of the D3350 cell class designation.

By using the 345464C cell class designation, the short-term tensile yield strength of the polymer used to manufacture the pipe has been specified to be between 3,000 and

3,500 psi as shown in Table 1-3. Yield strength is determined in accordance with ASTM D638.

The ability of the pipe to resist slow crack growth is an important engineering design consideration. ASTM D3350 allows for the determination of slow crack resistance by either the D1693 (bent strip) method or the F1473 (PENT) method. Piping products produced from resins that maintain a slow crack growth cell classification of 4 have been successfully used for decades in potable water applications. However, recent advances in polymer technology provide for modern PE pipe resins that maintain cell classes of 5 and 6, which require testing in accordance with ASTM F1473, thus assuring the end user of even higher levels of technical performance as it relates to the slow crack growth resistance of modern PE pipe. A specification for modern PE piping systems that designates a material requirement of 345464C, D, or E identifies the highest level of resistance to slow crack growth.

The final numerical designation relates to the hydrostatic design basis of the material used to produce the pipe so specified. In this particular example, the designer has stipulated a material with a minimum hydrostatic design basis of 1,600 psi established in accordance with ASTM D2837. It is this value that is subsequently utilized to establish the pressure capability of the pipe based on the relationship between stress, wall thickness, and diameter.

The letter designation in the D3350 method of classification establishes a requirement for color and/or stabilization against the deleterious effects of UV light. In this particular case, the letter C refers to a material that must contain a minimum of 2 percent carbon black. The carbon black not only acts as a colorant but also as a primary UV stabilizer.

While ASTM D3350 provides for a significant number of combinations of cell classifications, not all combinations are commercially available. Additional information regarding the commercial availability of various cell class combinations may be obtained from the pipe producers and/or resin manufacturers. Additionally, ANSI/AWWA C901 and C906 refer to three specific minimum cell classifications, which may be used in potable water applications and, as such, the reader is referred to these standards for clarification on the cell class combinations, which are suitable for these installations.

PE is a thermoplastic material and may therefore be manufactured into a product, then ground into particles and remanufactured into another product. Once a product has been reduced to particles of an appropriate size, the material is called *rework* or *regrind*. Rework material for plastic pipe manufacturing is defined in ASTM F412.

ANSI/AWWA C901 and C906 allow for the use of rework material in the production of PE pipe with very specific limitations:

“Clean rework materials derived from the manufacturer’s own pipe or fitting product may be used by the same manufacturer for similar purposes provided that

- 1) The cell classification of the rework material is identical with the materials to which it will be added;
- 2) The rework material complies with all the applicable requirements of section 4.2 of this standard;
- 3) The finished products meet the requirements specified by the purchaser and comply with all requirements of this standard.”

Using regrind or rework material does not adversely affect the resulting pipe or pipe fittings provided the commonly accepted material handling procedures are

followed. These procedures ensure the cleanliness and segregation of the materials until they are incorporated in the product manufacturing process.

The requirement in ANSI/AWWA C901 and C906 for “clean rework materials derived from a manufacturer’s own pipe or fitting” prevents the use of PE material that has left the control of the original manufacturer, i.e., pipe products that were in service and were replaced.

CONCLUSION

The information contained in this chapter is provided to assist the reader in understanding some of the fundamental properties of PE. A basic understanding of these properties will assist the pipe designer in the effective use of these materials and serve to maximize the utility of the service into which they are ultimately placed. For further information concerning the engineering properties of PE piping, the reader is referred to a variety of sources including pipe manufacturer’s literature, additional publications of the PPI, and the references at the end of this chapter.

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