

## Chapter 1

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# Engineering Properties of Polyethylene

## INTRODUCTION

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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

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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 D1238<sup>1</sup>. 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

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## 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*.

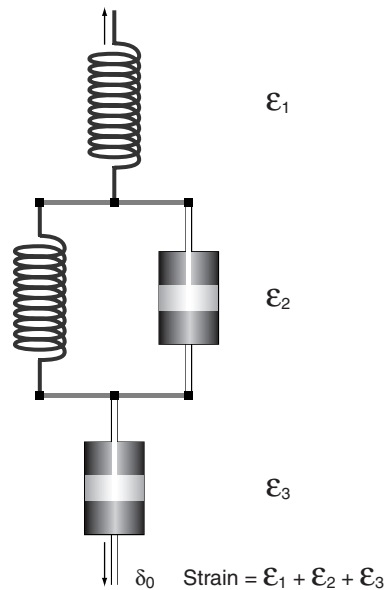


Figure 1-1 Traditional model of HDPE

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 D638<sup>2</sup>. 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

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