

Chapter 3

Material Properties

Scope

A principal objective of the following brief review of the nature of polyethylene (PE) piping materials, of their physical and chemical properties, and of their mechanical and engineering behavior, is to impart a basic understanding of the factors that lie behind the discussions and recommendations contained in this Handbook for the proper storage, handling, installation, design and operation of PE piping systems.

Also included in this Chapter is an Appendix that lists values for the more common engineering design properties of PE piping materials.

Introduction

A number of important performance advantages accounts for the widespread adoption of PE piping for so many pressure and non-pressure applications. A major one is PE's virtual freedom from attack by soils, and by ambient water and moisture. PE, being a non-conductor of electricity, is immune to the electrochemical based corrosion process that is induced by electrolytes such as salts, acids and bases. In addition, PE piping is not vulnerable to biological attack, and its smooth, non-stick inner surface results in low friction factors and exceptional resistance to fouling.

Another unique performance advantage is the flexibility of PE pipe. It allows for changes in direction with minimal use of fittings, facilitates installation, and makes it possible for piping up to about 6-inches in diameter to be offered in coils of longer lengths. A further one is strainability, a term denoting a capacity for high deformation without fracture. In response to earth loading a buried PE pipe can safely deflect and thereby gain additional and substantial support from the surrounding soil. So much so, that a properly installed PE pipe is capable of supporting earth fills and surface live loads that would fracture pipes that, although much stronger, can crack and fail at low strains. And, as proven by actual experience, PE pipe's high strainability makes it very resistive to seismic effects.

PE pipe and PE fittings can be joined to each other by thermal fusion processes which result in leak-proof bottle-tight joints that are as strong and as tough as the pipe itself. These advantages combine to make PE a preferred pipe for special applications, such as for horizontal directional drilling, for the renewal of old pipes by insertion, and for marine outfalls. For the first two named applications the butt-fusion process – which avoids the use of larger diameter couplings – enables installation to be conducted by pipe pulling and it permits the use of a larger diameter pipe.

Another recognized advantage of PE piping is its toughness. PE pipes, as well as the heat fusion joints in PE piping, greatly resist the propagation of an initial small failure into a large crack – a major reason for the overwhelming preference for PE piping for gas distribution applications. And, PE piping retains its toughness even at lower temperatures. In addition, PE piping exhibits very high fatigue resistance. Potential damage by repetitive variations in operating pressure (surges) is highly resisted.

Notwithstanding the above and various other advantages of PE piping, its successful design and application requires adequate recognition of its more complex stress/strain and stress/fracture behavior. PE piping does not exhibit the simple proportionality between stress and strain that is characteristic of metal pipes. And, its capacity to resist fracture is reduced as duration of loading is increased. In addition, these and its other mechanical properties exhibit a greater sensitivity to temperature and certain environments. Furthermore, the specific mechanical responses by a PE pipe can vary somewhat depending on the PE material from which it is made – mostly, depending on the nature of the PE polymer (e.g., its molecular weight, molecular weight distribution, degree of branching (density) but, also somewhat on the type and quantity of additives that are included in the piping composition. The particular behavior of the PE pipe that is selected for an application must be given adequate recognition for achieving an effective design and optimum quality of service. A brief explanation of the engineering behavior of PE and the listing of its more important properties is a major objective of this Chapter.

An additional objective of this Chapter is the presentation of values for the major properties that are used for material classification and piping design, and a brief description of the methods based on which these properties are determined.

PE Plastics

Plastics are solid materials that contain one or more polymeric substances which can be shaped by flow. Polymers, the basic ingredient of plastics, compose a broad class of materials that include natural and synthetic polymers. Nearly all plastics are made from the latter. In commercial practice, polymers are frequently designated as resins. For example, a PE pipe compound consists of PE resin combined with colorants, stabilizers, anti-oxidants or other ingredients required to protect and enhance properties during fabrication and service.

Plastics are divided into two basic groups, thermoplastics and thermosets, both of which are used to produce plastic pipe.

Thermoplastics include compositions of PE, polypropylene, and polyvinyl chloride (PVC). These can be re-melted upon the application of heat. The solid state of thermoplastics is the result of physical forces that immobilize polymer chains and prevent them from slipping past each other. When heat is applied, these forces weaken and allow the material to soften or melt. Upon cooling, the molecular chains stop slipping and are held firmly against each other in the solid state. Thermoplastics can be shaped during the molten phase of the resin and therefore can be extruded or molded into a variety of shapes, such as pipe, pipe fittings, flanges or valves.

Thermoset plastics are similar to thermoplastics prior to “curing,” a chemical reaction by which polymer chains are chemically bonded to each other by new cross-links. The curing is usually done during or right after the shaping of the final product. Cross-linking is the random bonding of molecules to each other to form a giant three-dimensional network. Thermoset resins form a permanent insoluble and infusible shape after the application of heat or a curing agent. They cannot be re-melted after they have been shaped and cured. This is the main difference between thermosets and thermoplastics. As heat is applied to a thermoset part, degradation occurs at a temperature lower than the melting point. The properties of thermosetting resins make it possible to combine these materials with reinforcements to form strong composites. Fiberglass is the most popular reinforcement, and fiberglass-reinforced pipe (FRP) is the most common form of thermoset-type pipe.

History of PE

The Imperial Chemical Company (ICI) in England first invented PE in 1933. The early polymerization processes used high-pressure (14,000 to 44,000 psi) autoclave reactors and temperatures of 200° to 600° F (93° to 316° C). The PE that came from these reactors was called “high pressure PE.” It was produced in a free radical chain reaction by combining ethylene gas under high pressure with peroxide or a trace amount of oxygen.

The original process was dangerous and expensive, so other safer and less expensive processes were developed. PE produced at low pressure was introduced in the 1950’s. These methods also afforded greater versatility in tailoring molecular structures through variations in catalysts, temperatures, and pressures.

Manufacture of PE

Polymers are large molecules formed by the polymerization (i.e. the chemical linking) of repeating small molecular units. To produce PE, the starting unit is ethylene, a colorless gas composed of two double-bonded carbon atoms and four hydrogen atoms (see Figure 1).

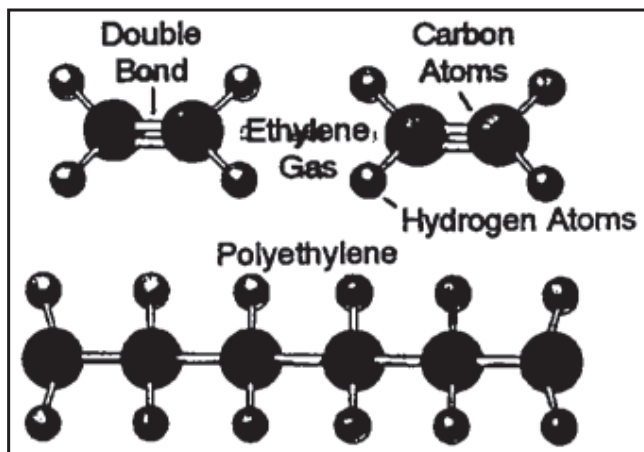


Figure 1 Manufacture of PE

There are currently three primary low-pressure methods for producing PE: gas-phase, solution and slurry (liquid phase). The polymerization of ethylene may take place with various types of catalysts, under varying conditions of pressure and temperature and in reactor systems of radically different design. Ethylene can also be copolymerized with small amounts of other monomers such as butene, propylene, hexene, and octene. This type of copolymerization results in small modifications in

chemical structure, which are reflected in certain differences in properties, such as density, ductility, hardness, etc. Resins that are produced without comonomer are called homopolymers.

Regardless of process type, the chemical process is the same. Under reaction conditions, the double bond between the carbon atoms is broken, allowing a bond to form with another carbon atom as shown in Figure 1. Thus, a single chain of PE is formed. This process is repeated until the reaction is terminated and the chain length is fixed. PE is made by the linking of thousands of monomeric units of ethylene.

Polymer Characteristics

PE resins can be described by three basic characteristics that greatly influence the processing and end-use properties: density, molecular weight and molecular weight distribution. The physical properties and processing characteristics of any PE resin require an understanding of the roles played by these three major parameters.

Density

The earliest production of PE was done using the high-pressure process which resulted in a product that contained considerable “side branching.” Side branching is the random bonding of short polymer chains to the main polymer chain. Since branched chains are unable to pack together very tightly, the resulting material had a relatively low density, which led to it being named low-density PE (LDPE).

As time passed and PEs of different degrees of branching were produced, there was a need for an industry standard that would classify the resin according to density. The American Society for Testing of Materials (ASTM) originally established the following classification system. It is a part of ASTM D1248, Standard Specification for Polyethylene Plastics Molding and Extrusion Materials^(2,5). This standard has since been replaced by ASTM D 3350; ASTM D 1248 is no longer applicable to PE piping materials.

Type	Density
I	0.910 - 0.925 (low)
II	0.926 - 0.940 (medium)
III	0.941 - 0.959 (high)
IV	0.960 and above (high, homopolymer)

Type I is a low-density resin produced mainly in high-pressure processes. Also contained within this range are the linear-low-density polyethylenes (LLDPE), which represent a recent development in the PE area using low-pressure processes.

Type II is a medium density resin produced either by low- or high-pressure processes.

Types III and IV are high-density polyethylenes. Type III materials are usually produced with a small amount of a comonomer (typically butene or hexene) that is used to control chain branching. Controlled branching results in improved performance in applications where certain types of stresses are involved. Type IV resins are referred to as homopolymers since only ethylene is used in the polymerization process, which results in least-branched and highest-possible-density material. Figure 2 depicts the various molecular structures associated with each type of PE.

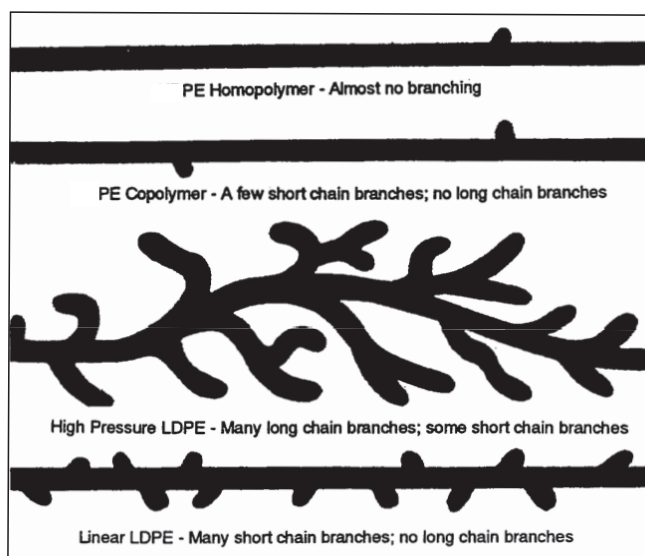


Figure 2 Chain Structure of PE

Crystallinity

The amount of side branching determines the density of the PE molecule. The more side branches, the lower the density. The packing phenomenon that occurs in PE can also be explained in terms of crystalline versus non-crystalline or amorphous regions as illustrated in Figure 3. When molecules pack together in tight formation, the intermolecular spacing is reduced.

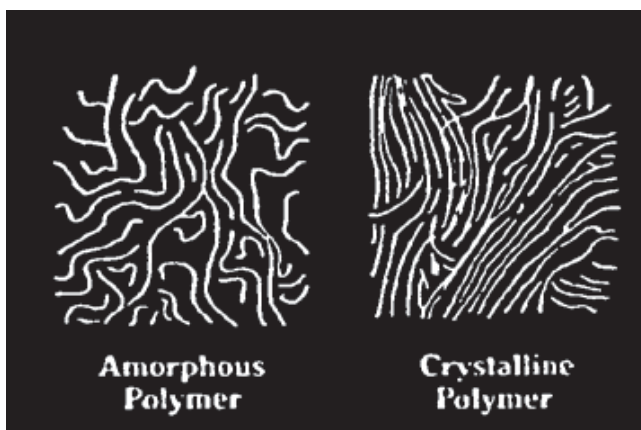
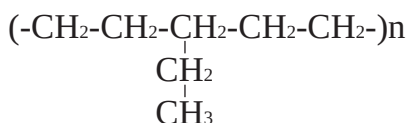


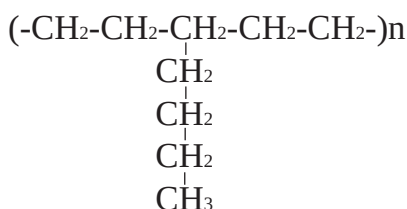
Figure 3 Crystallinity in PE

PE is one of a number of polymers in which portions of the polymer chain in certain regions align themselves in closely packed and very well ordered arrangements of polyhedral-shaped, microscopic crystals called spherulites. Other portions of the polymer chain lie in amorphous regions having no definite molecular arrangement. Since polyethylene contains both crystalline and amorphous regions, it is called a semicrystalline material. Certain grades of high density PE can consist of up to 90% crystalline regions compared to 40% for low density PE. Because of their closer packing, crystalline regions are denser than amorphous regions. Polymer density, therefore, reflects the degree of crystallinity.

As chain branches are added to a PE backbone through co-polymerization, the site and frequency of chain branches affect other aspects of the crystalline/ amorphous network. This includes the site and distribution of spherulites, as well as the nature of the intermediate network of molecules that are between spherulites. For example, using butene as co-monomer results in the following “ethyl” side chain structure⁽⁸⁾:



or using hexene results in this “butyl” side chain:



If two polymers were produced, one using butyl and the other hexene monomer, the polymer that contained the resultant butyl branches would have a lower density. Longer side branching reduces crystallinity and therefore lowers density. For high-density PE, the number of short chain branches is on the order of 3 to 4 side chains per 1,000 carbon atoms. It only takes a small amount of branching to affect the density.

Resin density influences a number of physical properties. Characteristics such as tensile yield strength and stiffness (flexural or tensile modulus) are increased as density is increased.

Molecular Weight

The size of a polymer molecule is represented by its molecular weight, which is the total of the atomic weights of all the atoms that make up the molecule. Molecular weight exerts a great influence on the processability and the final physical and mechanical properties of the polymer.

Molecular weight is controlled during the manufacturing process. The amount of length variation is usually determined by catalyst, conditions of polymerization, and type of process used. During the production of polyethylene, not all molecules grow to the same length. Since the polymer contains molecules of different lengths, the molecular weight is usually expressed as an average value.

There are various ways to express average molecular weight, but the most common is the number average (M_n) and weight average (M_w). The definitions of these terms are as follows:

M_n = Total weight of all molecules ÷ Total number of molecules

**M_w = (Total weight of each size) (respective weights) ÷
Total weight of all molecules**

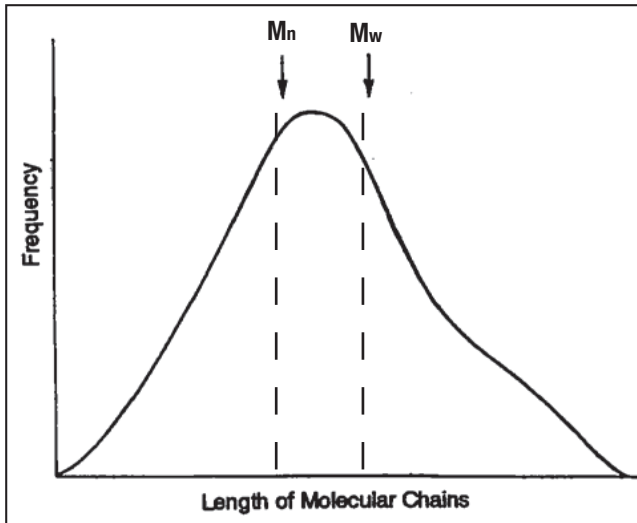


Figure 4 Typical Molecular Weight Distribution

Figure 4 illustrates the significance of these terms and includes other less frequently used terms for describing molecular weight.

Molecular weight is the main factor that determines the durability-related properties of a polymer. Long-term strength, toughness, ductility, and fatigue-endurance improve as the molecular weight increases. The current grades of highly durable materials result from the high molecular weight of the polymer.

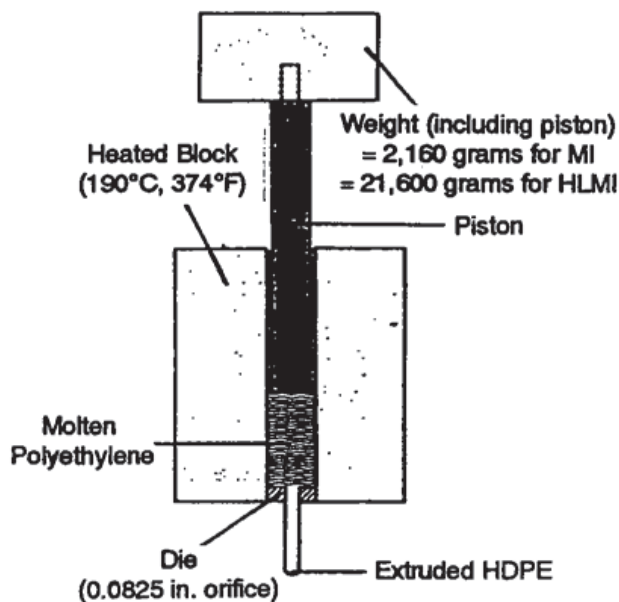


Figure 5 The Melt Flow Test (per ASTM D1238)

Molecular weight affects a polymer's melt viscosity or its ability to flow in the molten state. The standard method used to determine this "flowability" is the melt flow rate apparatus, which is shown in Figure 5. ASTM D1238, *Standard Test Method for Flow Rates of Thermoplastics by Extrusion Plastometer*⁽²⁾, is the industry standard for measuring the melt flow rate. The test apparatus measures the amount of material that passes through a certain size orifice in a given period of time when extruded at a predetermined temperature and under a specified weight. The melt flow rate is the measured weight of material that passes through the orifice in ten minutes.

The standard nomenclature for melt flow rate, as described in ASTM D1238, lists the test temperature and weight used. A typical designation is condition 190/2.16 that indicates the test was conducted at a temperature of 190°C while using a 2.16-kg weight on top of the piston. Other common weights include: 5 kg, 10 kg, 15 kg and 21.6 kg.

The term "melt index" (MI) is the melt flow rate when measured under a particular set of standard conditions – 190°C/2.16 kg. This term is commonly used throughout the polyethylene industry.

Melt flow rate is a rough guide to the molecular weight and processability of the polymer. This number is inversely related to molecular weight. Resins that have a low molecular weight flow through the orifice easily and are said to have a high melt flow rate. Longer chain length resins resist flow and have a low melt flow rate. The

melt flow rates of these very viscous (stiff) resins are very difficult to measure under the common conditions specified by this test. Therefore, another procedure is used where the weight is increased to 21.6 kg from the 2.16 kg weight used in the normal test procedure. This measurement is commonly referred to as the High Load Melt Index (HLMI) or 10X scale. There are other melt flow rate scales that use 5 kg, 10 kg or 15 kg weights.

There are various elaborate analytical techniques for determining molecular weight of a polymer. The melt flow rate gives a very quick, simple indication of the molecular weight. The more sophisticated methods include Gel Permeation Chromatography (GPC). The essence of GPC is to dissolve the polymer in a solvent and then inject the solution into a column (tubing). The column contains a porous packing material that retards the movements of the various polymer chains as they flow through the column under pressure. The time for the polymer to pass through the column depends upon the length of the particular polymer chain. Shorter chains take the longest time due to a greater number of possible pathways. Longer chain molecules will pass more quickly since they are retained in fewer pores. This method measures the distribution of the lengths of polymer chains along with the average molecular weight.

Effect of Molecular Weight Distribution on Properties

The distribution of different sized molecules in a polyethylene polymer typically follows the bell shaped normal distribution curve described by Gaussian probability theory. As with other populations, the bell shaped curve can reflect distributions ranging from narrow to broad. A polymer with a narrow molecular weight distribution (MWD) contains molecules that are nearly the same in molecular weight. It will crystallize at a faster, more uniform rate. This results in a part that will have less warpage.

A polymer that contains a broader range of chain lengths, from *short* to *long* is said to have a broad MWD. Resins with this type of distribution have good slow crack growth (SCG) resistance, good impact resistance and good processability.

Polymers can also have a bimodal shaped distribution curve which, as the name suggests, seem to depict a blend of two different polymer populations, each with its particular average and distribution. Resins having a bimodal MWD contain both very short and very long polyethylene molecules, giving the resin excellent physical properties while maintaining good processability. Figure 6 shows the difference in these various distributions.

The latest generation of high density PE pipe materials, known as high performance materials (e.g. PE 4710), are, for the most part, produced from bimodal resins. Pipe made from these materials are characterized by truly exceptional and unique resistance to slow crack growth (SCG), significantly improved long term performance, higher pressure ratings or increased flow capacity, and improved chemical resistance, all of which are achieved without compromising any of the other traditional benefits that are associated with the use of PE pipe.

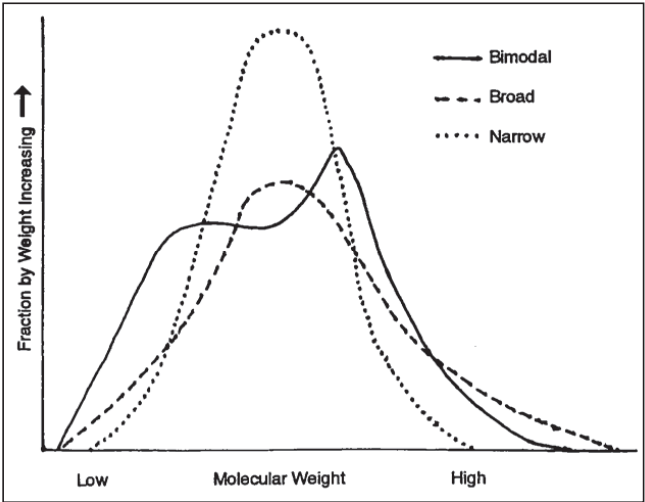


Figure 6 Molecular Weight Distribution

MWD is very dependent upon the type of process used to manufacture the particular polyethylene resin. For polymers of the same density and average molecular weight, their melt flow rates are relatively independent of MWD. Therefore, resins that have the same density and MI can have very different molecular weight distributions. The effects of density, molecular weight, and molecular weight distribution on physical properties are summarized in Table 1.

TABLE 1
Effects of Changes in Density, Melt Index, and Molecular Weight Distribution

Property	As Density Increases, Property	As Melt Index Increases, Property	As Molecular Wt. Distribution Broadens, Property
Tensile Strength (@ Yield)	Increases	Decreases	—
Stiffness	Increases	Decreases Slightly	Decreases Slightly
Impact Strength	Decreases	Decreases	Decreases
Low Temperature Brittleness	Increases	Increases	Decreases
Abrasion Resistance	Increases	Decreases	—
Hardness	Increases	Decreases Slightly	—
Softening Point	Increases	—	Increases
Stress Crack Resistance	Decreases	Decreases	Increases
Permeability	Decreases	Increases Slightly	—
Chemical Resistance	Increases	Decreases	—
Melt Strength	—	Decreases	Increases
Gloss	Increases	Increases	Decreases
Haze	Decreases	Decreases	—
Shrinkage	Increases	Decreases	Increases

PE Piping Materials

The Nature of PE Piping Materials

A PE piping material consists of a polyethylene polymer (commonly designated as the resin) to which has been added small quantities of colorants, stabilizers, anti-oxidants and other ingredients that enhance the properties of the material and that protect it during the manufacturing process, storage and service. PE piping materials are classified as thermoplastics because they soften and melt when sufficiently heated and harden when cooled, a process that is totally reversible and may be repeated. In contrast, thermosetting plastics become permanently hard when heat is applied.

Because PE is a thermoplastic, PE pipe and fittings can be fabricated by the simultaneous application of heat and pressure. And, in the field PE piping can be joined by means of thermal fusion processes by which matching surfaces are permanently fused when they are brought together at a temperature above their melting point.

PE is also classified as a semi-crystalline polymer. Such polymers (e.g., nylon, polypropylene, polytetrafluoroethylene), in contrast to those that are essentially amorphous (e.g., polystyrene, polyvinylchloride), have a sufficiently ordered structure so that substantial portions of their molecular chains are able to align closely to portions of adjoining molecular chains. In these regions of close molecular alignment crystallites are formed which are held together by secondary bonds. Outside these regions, the molecular alignment is much more random resulting in a

less orderly state, labeled as amorphous. In essence, semi-crystalline polymers are a blend of a two phases, crystalline and amorphous, in which the crystalline phase is substantial in population.

A beneficial consequence of PE's semi-crystalline nature is a very low glass transition temperature (T_g), the temperature below which a polymer behaves somewhat like a rigid glass and above which it behaves more like a rubbery solid. A significantly lower T_g endows a polymer with a greater capacity for toughness as exhibited by performance properties such as: a capacity to undergo larger deformations before experiencing irreversible structural damage; a large capacity for safely absorbing impact forces; and a high resistance to failure by shattering or rapid crack propagation. These performance aspects are discussed elsewhere in this Chapter. The T_g for PE piping materials is approximately -130°F (-90°C) compared to approximately 221°F (105°C) for polyvinyl chloride and 212°F (100°C) for polystyrene, both of which are examples of amorphous polymers that include little or no crystalline content.

In the case of amorphous polymers, their melting temperature, the temperature at which a transition occurs between the rubbery solid and the liquid states, is not much higher than their T_g . Also for amorphous polymers, the transition between a rubbery solid and a viscous liquid is not very emphatic. This contrasts with semi-crystalline polymers, for which this transition corresponds with the melting of all crystallites, and above which a highly viscous liquid state is reached. This more emphatic transition in PE between the semi-crystalline solid and highly viscous liquid states facilitates manufacture, fabrication and field joining because it allows for more efficient 'welding' to be conducted – when in a liquid state the polymer molecules are able to more effectively diffuse into each other and thereby, form a monolithic structure. In contrast, the melting point of amorphous polymers is less defined and, across this melting point there is not as definite a transition between a rubbery, or plastic state, and a liquid viscous state.

Structural Properties

PE Pipe Material Designation Code Identifies the Standard Classification of Essential Properties

Standards for PE piping define acceptable materials in accordance with a standard designation code. This code, which is explained in greater detail in Chapter 5, has been designed for the quick identification of the pipe material's principal structural and design properties. As this section deals with this subject, it is appropriate to first describe the link between the code designations and these principal properties. For this purpose, and as an example, the significance of one designation, PE4710, is next explained.

- The letters PE designate that it is a polyethylene piping material.
- The first digit, in this example the number 4, identifies the PE resin's density classification in accordance with ASTM D3350, Standard Specification for Polyethylene Plastic Pipe and Fittings Materials ⁽⁴⁾.

Certain properties, including stress/strain response, are dependent on a PE's crystalline content. An increase in this phase is reflected by an increase in density. An increase in density affects certain properties, for example an increase in tensile strength and stiffness. Also, a higher density results in changes to other properties. For this reason, the Table for Apparent Modulus that is included in the Appendix of this chapter lists values in accordance with the material's standard density classification. This ASTM standard classification can range from 2, the lowest value, to 4 the highest value.

- The second digit, in this example the number 7, identifies the material's standard classification for slow crack growth resistance – also, in accordance with ASTM D3350 – relating its capacity for resisting the initiation and propagation of slowly growing cracks when subjected to a sustained localized stress intensification.

The standard classification for current commercial grades is either 6 or 7. The 6 denotes very high resistance and the 7 even higher. The test method for determining quality of resistance to SCG is described later in this chapter.

- The third and fourth digits combined, the number 10 in this example, denote the material's recommended hydrostatic design stress (HDS) for water at 73°F (23°C), in units of 100psi. In this example the number 10 designates the HDS is 1,000psi.

There are two basic performance criteria based on which a recommended HDS is determined. The first is the material's long term hydrostatic strength (LTHS), a value that is required to comply with certain additional validation or substantiation requirements that are discussed later in this Chapter. The second is the material's quality of resistance to the initiation and growth of slowly growing cracks. An explanation of both of these criteria is included in this section. And, the standard method by which an LTHS is reduced into an HDS is explained in Chapter 5, "Standard Specifications, Test Methods and Codes for PE Piping Systems".

Stress/Strain Response and its Representation by Means of an Apparent Modulus

The potential range of the stress/strain response of a material is bounded by two extremes. At one extreme the response can be perfectly elastic; that is, in conformity to Hook's law whereby the magnitude of strain is always proportional to the magnitude of the applied stress. The resultant proportionality between stress and strain is labeled the modulus of elasticity. Elastic deformation is instantaneous, which means that total deformation (or strain) occurs at the instant the stress is applied.

Upon the release of the external stress the deformation is instantaneously and totally

recovered. This behavior is represented in Figure 7b as strain versus time for the instantaneous load-time curve depicted in Figure 7a. Under the modulus of elasticity concept, the stress/strain relationship is independent of duration of load application.

At the other extreme, under what is referred to as viscous behavior, deformation caused by the application of a stress is neither instantaneous nor proportional to the stress. Deformation is delayed and the rate and the final extent of deformation are dependent on the magnitude and the duration of the applied stress. Also, the deformation that occurs is not reversible after the stress is released. This response is depicted by Figure 7c.

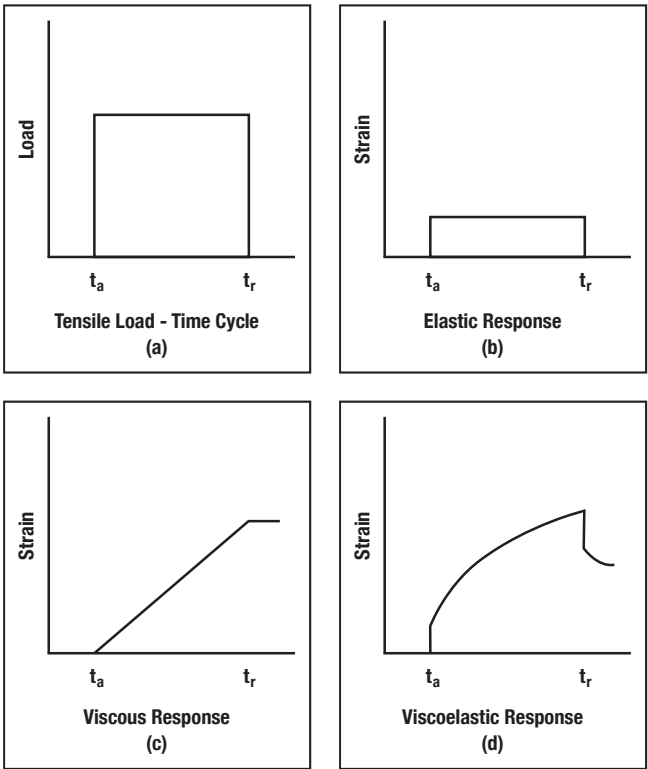


Figure 7 Strain Response (b-d) to a Load (a)

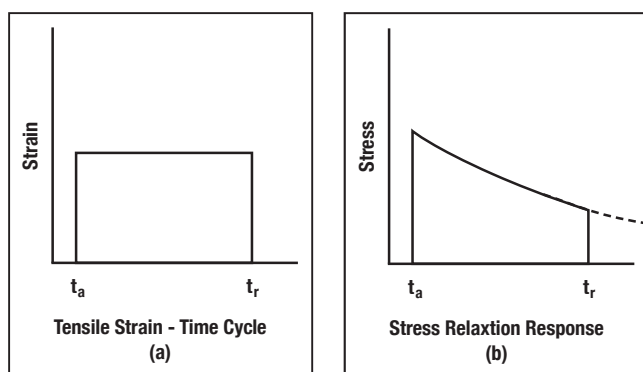


Figure 8 Stress Relaxation Response by a Viscoelastic Material

Viscoelastic behavior, which is depicted by Figure 7d, covers the intermediate region between these extremes. The imposition of a stress in the manner of Figure 7a results in a small instantaneous elastic strain that is then followed by a time-dependent strain. Upon removal of the stress there is a small elastic recovery of strain that is then followed by a time-dependent recovery. This time dependent recovery occurs more quickly for lower values of initial strain and more slowly for an initially larger strain. While the strain recovery may eventually be nearly total, there is almost always some remaining permanent deformation, which, again, is larger for an initially larger deformation.

Figure 7d illustrates viscoelastic response under the condition of constant tensile stress. However, if a strain is imposed and then kept constant, the initially required stress gradually decreases in the course of time. This reaction, which is illustrated by Figure 8, is called stress-relaxation. Stress relaxation is a beneficial response in situations where further deformation is either restrained or counteracted.

Models based on springs – which represent elastic response – and on dashpots –representing viscous response – have been developed to illustrate and to simulate the viscoelastic behavior of PE piping materials.^(11 12) A simple one, known as the Maxwell model⁽²⁹⁾, is shown on the right side of Figure 9. In this model the lone spring represent the elastic reaction, the parallel arrangement of spring and dashpot represents the viscoelastic reaction and, the dashpot represents the viscous reaction.

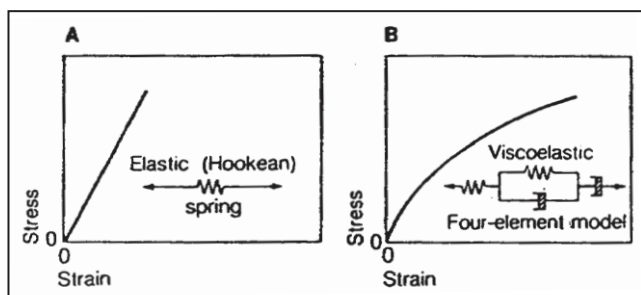


Figure 9 The Maxwell Model

A resultant stress/strain relationship for a viscoelastic/thermoplastic material is determined by a number of variables, principally the following:

1. The magnitude of the initial stress or strain (a larger stress or strain results in a larger viscous response)
2. The multi-axiality of the resultant stress (when a material is simultaneously pulled in more than one direction this inhibits its freedom to deform)
3. The duration of the sustained stress or of the sustained strain (increased duration results in a larger total response)
4. The temperature (it mostly affects the rate of the viscous response)
5. The environment (if an organic substance is adsorbed to some extent by PE, this may result in a plasticizing effect that mostly accelerates the viscous response – air and water are inert in this respect and they produce equivalent results)
6. Possible external restraints on the freedom to deform (e.g., the embedment around a buried pipe restricts free-creeping)

A frequently used method for evaluating the stress/strain response of PE piping materials is by means of tensile/creep tests that are conducted on test bars. In these tests, the specimens are subjected to a uni-axial stress and they are allowed to free-creep, meaning that their deformation is unrestrained. This combination of test parameters yields the maximum possible deformation under a certain sustained stress. When the logarithm of the strain (deformation) resulting from such tests is plotted against the logarithm of duration of loading it yields an essentially straight line for each level of sustained test stress. This behavior is illustrated by Figure 10. This essentially straight line behavior facilitates extrapolation of experimental results to longer durations of loading than covered by the data (the extrapolation is denoted by the dotted lines in Figure 10).

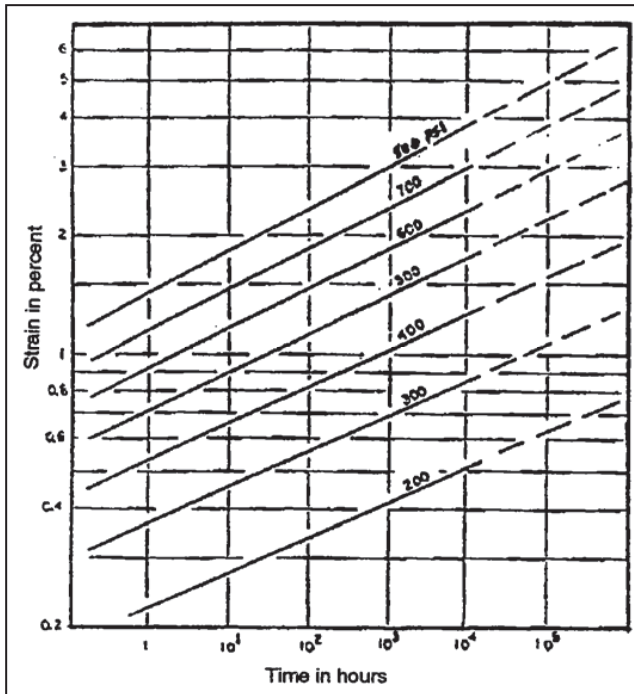


Figure 10 Typical Tensile Stress /Creep Response for a PE3XXX Piping Material When Subjected to a Sustained Uni-axial Tensile Stress, in Air at 73°F

Any point on a tensile/creep diagram, such as in Figure 10 gives a stress/strain ratio. To differentiate this ratio from the modulus of elasticity, which only applies to elastic behaving materials, it is designated as the apparent modulus under tension. For correct engineering use, a value of apparent modulus must identify the conditions under which that value has been established: the kind of stress (uni-axial versus bi- or multi-axial); the magnitude of the principal stress; the duration of stress application; the temperature; and, the test environment. Figure 11 illustrates the manner by which the apparent modulus of a PE3XXX material varies, at 73°F and in air, after different durations of sustained loading and in response to uni-axial stresses of different intensities.