Chapter
1

History

and

Physical Chemistry

of

HDPE

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HISTORY AND PHYSICAL CHEMISTRY OF HDPE

History of HDPE and HDPE Pipe

At the very close of the 19th century, German chemist Hans von Pechmann noted a precipitate while working with a form of methane in ether. In 1900, German chemists Eugen Bamberger and Friedrich Tschirner identified this compound as polymethylene, a very close cousin to polyethylene. Thirty years later, a high-density residue was created by an American chemist at E.l. du Pont de Nemours & Company, Inc., Carl Shipp Marvel, by subjecting ethylene to a large amount of pressure.

Working with ethylene at high pressures, British chemists Eric Fawcett and Reginald Gibson created a solid form of polyethylene in 1935. Its first commercial application came during World War II, when the British used it to insulate radar cables. In 1953, Karl Ziegler of the Kaiser Wilhelm Institute (renamed the Max Planck Institute) and Erhard Holzkamp invented high-density polyethylene (HDPE). The process included the use of catalysts and low pressure, which is the basis for the formulation of many varieties of polyethylene compounds. Two years later, in 1955, HDPE was produced as pipe. For his successful invention of HDPE, Ziegler was awarded the 1963 Nobel Prize for Chemistry.

Today, plastic materials used for pipes are classed under thermosetting or thermoplastic resins. Plastic highway drainage pipes belong almost entirely to the thermoplastic group (most commonly, high-density polyethylene (HDPE), PVC and ABS). They exhibit attributes of toughness, flexibility, chemical resistance and non-conducting electrical properties. Thermoplastic highway drainage pipes have been used for highway drainage since the early 1970s. Since then, growing out of applications for agricultural drainage, more HDPE drainage pipes have been installed than all other plastic pipes combined. They are being used for storm sewers, perforated underdrains, storm drains, slope drains, cross drains and culverts.

Physical Chemistry and Mechanical Properties of HDPE

High-density polyethylene (HDPE)($0.941 \leq$ density < 0.965) is a thermoplastic material composed of carbon and hydrogen atoms joined together forming high molecular weight products as shown in Figure 1-1c. Methane gas (Figure 1-1a) is converted into ethylene (Figure 1-1b), then, with the application of heat and pressure, into polyethylene (Figure 1-1c). The polymer chain may be 500,000 to 1,000,000 carbon units long. Short and/or long side chain molecules exist with the polymer's long main chain molecules. The longer the main chain, the greater the number of

atoms, and consequently, the greater the molecular weight. The molecular weight, the molecular weight distribution and the amount of branching determine many of the mechanical and chemical properties of the end product.

Other common polyethylene (PE) materials are medium-density polyethylene (MDPE) (0.926 ≤ density < 0.940) used for low-pressure gas pipeline; low-density polyethylene (LDPE) (0.910 ≤ density < 0.925), typical for small-diameter water-distribution pipes: Linear low-density polyethylene (LLDPE), which retains much of the strength of HDPE and the flexibility of LDPE, has application for drainage pipes. Less common PE materials are ultra-high molecular weight polyethylene (UHMWPE) (density > 0.965) and very low density polyethylene (VLDPE) (density < 0.910). Other thermoplastic materials used for drainage pipes are polyvinyl chloride (PVC), polypropylene (PP), polybutylene (PB) and acrylonitrile-butadiene-styrene (ABS).

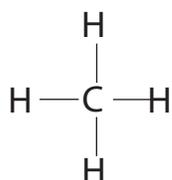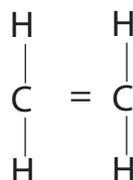## Figure 1-1a,b,c

Figure 1-1a: Methane   Figure 1-1b: Ethylene

Figure 1-1c: Polyethylene Molecular Chain

The property characteristics of polyethylene depend upon the arrangement of the molecular chains. The molecular chains, shown schematically in Figure 1-1c, are three-dimensional and lie in wavy planes. Not shown, but branching off the main chains, are side chains of varying lengths. The number, size and type of these side chains determine, in large part, the properties of density, stiffness, tensile strength, flexibility, hardness, brittleness, elongation, creep characteristics and melt viscosity that are the results of the manufacturing effort and can occur during service performance of polyethylene pipe.

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Polyethylene is characterized as a semi-crystalline polymer, made up of crystalline regions and amorphous regions. Crystalline regions are those of highly ordered, neatly folded, layered (in parallel) and densely packed molecular chains. These occur only when chains branching off the sides of the primary chains are small in number. Within crystalline regions, molecules have properties that are locally (within each crystal) directionally dependent. Where tangled molecular chains branching off the molecular trunk chains interfere with or inhibit the close and layered packing of the trunks, the random resulting arrangement is of lesser density, and termed amorphous. An abundance of closely packed polymer chains results in a tough material of moderate stiffness.

High-density polyethylene resin has a greater proportion of crystalline regions than low-density polyethylene. The size and size distribution of crystalline regions are determinants of the tensile strength and environmental stress crack resistance of the end product. HDPE, with fewer branches than MDPE or LDPE, has a greater proportion of crystals, which results in greater density and greater strength (see Figure 1-2). LDPE has a structure with both long and short molecular branches. With a lesser proportion of crystals than HDPE, it has greater flexibility but less strength. LLDPE structurally differs from LDPE in that the molecular trunk has shorter branches, which serve to inhibit the polymer chains becoming too closely packed. Hypothetically, a completely crystalline polyethylene would be too brittle to be functional and a completely amorphous polyethylene would be waxlike, much like paraffin. Upon heating, the ordered crystalline structure regresses to the disordered amorphous state; with cooling, the partially crystalline structure is recovered. This attribute permits thermal welding of polyethylene to polyethylene.

The melting point of polyethylene is defined as that temperature at which the plastic transitions to a completely amorphous state. In HDPE and other thermoplastic materials, the molecular chains are not cross-linked and such plastics will melt with the application of a sufficient amount of heat. With the application of heat, thermoplastic resins may be shaped, formed, molded or extruded. Thermosetting resins are composed of chemically cross-linked molecular chains, which set at the time the plastic is first formed; these resins will not melt, but rather disintegrate at a temperature lower than its melting point, when sufficient heat is added.

Figure 1-2

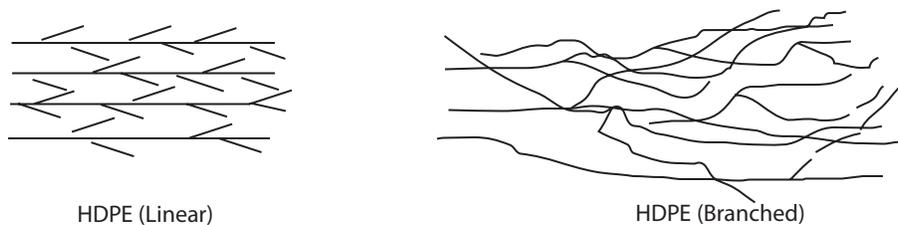HDPE (Linear)   HDPE (Branched)

Figure 1-2: Schematic of Linear and Branched Arrangements

During processing, elevated temperatures and energy associated with forming and shaping the polyethylene cause random orientations of molecules within the molten material to directionally align in the extruding orifice. At room temperatures, the ordered arrangement of the layered crystalline polyethylene molecules is maintained. Tie molecules link the crystalline and amorphous regions. When the capacities of the polymer chains are overwhelmed by tension, the polymer flows (alters its shape). Tensile forces (stresses) then initiate brittle fracture, evidenced by cracking. In HDPE this may occur at very high strain rates.

Once a crack is initiated, tensile forces (stresses), which were contained prior to the event of cracking, are released. These released tensile forces (stresses) are captured by the material at the leading tips of the crack, thereby greatly increasing the intensity of the stress field and the likelihood of continued cracking at that point and all points forward. The terms stress riser and stress intensity factor are used to identify and quantify the increase in the stress field at the tips of a crack. If these regions contain and adequately respond to this increased burden, then the cracks will not propagate; if they do not, crack propagation will result. This characterizes the mechanism of slow crack growth. Stress risers are proportional to the measure of stress. Cracks will not propagate in a stress-free environment or where the level of stress at the tip of a crack is at a sufficiently low threshold. When the tip of a propagating crack leaves a crystal, it enters the disordered, non-layered, more loosely packed, tangled molecules of the amorphous region where the energy associated with the stress field is partially dissipated as the tangled mass of molecules adjusts in time to the sustained forces.

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When polyethylene is pulled at low strain rates, in those areas where stretching has taken place, elongated rearrangement of the mass will be irreversible when molecular chains begin to slip by one another. Ultimate tensile strength occurs when the bonds between the molecular chains are fractured. The energy that would otherwise be stored in the system and which would otherwise be available to restore the region to its original geometry, is dissipated and unrecoverable with the event of the fracture. The new arrangement of molecules alters the stress/strain response of the remaining region. With increasing load and fewer bonds to resist, the material is less stiff and therefore takes less force to cause a unit of deformation. This phenomenon is noted on a stress-strain curve by an ever-decreasing slope as the curve bends increasingly to the right as the process continues. This is what defines strain softening, a characteristic of polyethylene and all materials that yield under increasing load. (The curved stress-strain curve of Figure 1-3 is an example of a strain softening material.) With sustained loads, the continuing deformation is defined plastic flow. If, at some point in the deformation process the deformation is maintained, the loads and resulting internal stresses relax. This process of adjustment is called stress relaxation.

Mechanical Properties and Cell Classifications

HDPE is a non-linear viscoelastic material with time-dependent properties. A thermoplastic pipe, serving as only one component of a pipe/soil composite structure, benefits by its attribute of stress relaxation wherein stresses (forces) are shed and transferred to the soil. Predictability of performance of a pipe in service (stress, strain and deformation responses, stability) requires knowledge of the mechanical properties of the HDPE resin and knowledge of the profile geometry.

ASTM D 3350 resin cell classifications provide the means for identification, close characterization and specification of material properties for polyethylene. Manufacturers of HDPE drainage pipes may choose higher cell classifications than the minimums required by these specifications in order to optimize competing economic and performance constraints of production, handling and service.

Density, molecular weight and molecular weight distribution dominate the resin properties that influence the manufacture of the polyethylene pipe and the subsequent performance of the pipe. Table 1-1 lists cell classification properties and the ASTM specification governing the laboratory procedure that defines and determines each. (Note that melt index (MI) is inversely related to molecular weight.) Note that cell classifications for density and molecular weight are included in Table 1-1; molecular weight distribution (MWD) is not.

Table 1-1

CELL CLASSIFICATIONS (SEE ASTM D 3350)			
Property	ASTM Specification	Classification	Classification Requirement
Density	ASTM D 1505 – Test Method for Density of Plastics by the Density-Gradient Technique	3	0.941-0.955 gm/cm3
Melt index (MI)	ASTM D 1238 – Test Method for Flow Rates of Thermoplastics by Extrusion Plastometer	3	$0.4 > MI \geq 0.15$
Flexural modulus (E_f)	ASTM D 790 – Test Method for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials	5	$758 \leq E_f < 1103$ MPa $110{,}000 \leq E_f < 160{,}000$ psi
Tensile strength (f_t)	ASTM D 638 – Test Method for Tensile Properties of Plastics	4	$21 \leq ft < 24$ MPa $3000 \leq f_t < 3500$ psi
Slow crack growth resistance Environmental stress crack resistance (ESCR)	ASTM D 1693 – Test Method for for Environmental Stress-Cracking of Ethylene Plastics	2	test condition B, 24 hr duration 50% failure (max)
Hydrostatic Strength Classification Hydrostatic Design Basis (HDB)	ASTM D 2837 – Obtaining Hydrostatic Design Basis for Thermoplastic Pipe Materials	0	(not pressure rated)
Color (C)	(not specified by ASTM)	C	$2\% \leq C \leq 5\%$

Molecular Weight Distribution

The distribution of different sized molecules in a polyethylene polymer typically follows the bell shaped normal distribution curve described by the Gaussian probability theory. As with other populations, the bell shaped curve can reflect distributions ranging from narrow to broad. A polymer containing a broad range of chain lengths is said to have a broad molecular weight distribution (MWD). Resins with this type of distribution have good Environmental Stress Crack Resistance (ESCR), good impact resistance and good processability.

A polymer with a narrow MWD contains molecules that are nearly the same in molecular weight. It will crystallize at a faster, more uniform rate. This results in a product that will hold its shape.

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.

MWD is 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 melt index (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 1-2.

Table 1-2

	EFFECTS OF CHANGES IN DENSITY, MELT INDEX AND MOLECULAR WEIGHT DISTRIBUTION		
Property	As Density Increases, Property:	As Melt Index Increases, Property:	As Molecular Weight Distribution Broadens, Property:
Tensile Strength (At 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	Decreases	Decreases	Increases

Density

The density of polyethylene is a measure of the proportion of crystals within its mass. Crystals, a result of the layering and close packing of polyethylene molecules, are denser than the tangled, disordered arrangement of molecules in the amorphous regions. Copolymers are often used to create and control the formation of side branches. Homopolymers, with densities of 0.960 and above, are produced without copolymers and experience very little branching. To reduce the density, butene, hexene or octene are added to make a copolymer. Butene will add branches two carbon units long; hexene, four carbon units long; and octene, six carbon units long. The greater the length of the branched carbon chains, the lower the final density. ASTM D 3350 classifies polyethylene by density as follows: high-density polyethylene (HDPE) (0.941 ≤ density < 0.965), low-density polyethylene (LDPE) (0.910 ≤ density < 0.925), medium-density polyethylene (MDPE) (0.926 ≤ density <

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0.940). Less commonly employed PE materials are homopolymers (density > 0.965) and very low density polyethylene (VLDPE, density < 0.910). Flexural stiffness and tensile strength increase with density; the result is increasing brittleness, and decreasing toughness and stress crack resistance.

Melt Index

The melt flow rate measures the viscosity of the polyethylene resin in its molten state. It is a parameter related to the average molecular weight of the resin chains of polymer extruded through a standard size orifice under specified conditions of pressure and temperature in a ten-minute period of time. The greater the lengths of molecules, the greater the molecular weight and the greater the difficulty in extruding the resin through the standard orifice. The result: resins of greater viscosity as measured by a lower melt flow rate. When the test is conducted with pressure delivered by a standard load caused by a 47.6 lb (21.6 kg) weight at a temperature of 374°F (190°C), the resulting melt flow rate is termed the melt index (MI). The greater the viscosity, the lower the melt index value.

A lower MI (higher average molecular weight) is predictive of greater tensile strength, toughness and greater stress crack resistance. However, the lower the MI, the greater the energy required, at any extrusion temperature, to extrude polyethylene resin.

The average molecular weight, as measured by the MI, does not identify the range of chain lengths within the molecules; the molecular weight distribution (MWD) does. Polyethylene polymers of the same MI and the same density may have very different properties if the molecular weight distributions (MWD) are different. A polymer with a narrow MWD will crystallize more rapidly and with greater uniformity, resulting in less warpage and greater fidelity to the intended geometry. A polymer with broad MWD may have better stress crack resistance, impact resistance and ease of processing.

Flexural Modulus

The flexural modulus (E_f) is a material stiffness that is, in part, predictive of a structure or a structural element's resistance to bending under the application of loads. When combined with the geometric stiffness (a function of the moment of inertia and other geometric properties), the composite stiffness is termed the bending stiffness. The greater the bending stiffness, the greater the bending resistance and, other things being equal, the greater the bending stresses. For flexible pipe, the material modulus (E) is a composite of the material's flexural stiffness (E_f) and ring compression stiffness (E_c). Current design practice assumes equivalence for working values E_f and E_c.

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Non-linear stress/strain curves of HDPE, and the modular values derived therefrom, are sensitive to rates of load application and are generally 'linear' up to approximately 2% strain. Stress and strain are determined at the point of maximum bending on a simply supported test beam caused by a centrally applied load. The slope of the line drawn between points of zero strain and 2% strain on a stress/strain curve typically defines the flexural modulus. Because of the stress relaxation attribute of HDPE, the less rapid the loading and the longer the duration of load application, the flatter the early slope of the stress/strain curve and the lower the estimate of flexural modulus; hence the need for a carefully defined (see ASTM D 790) rate of load application. (See Figure 1-3.)
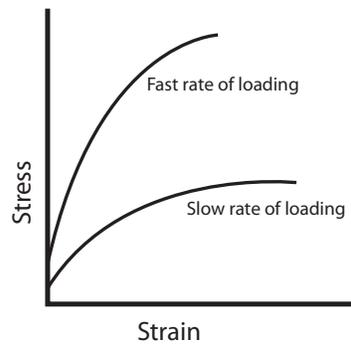
Figure 1-3

Figure 1-3: Curves of Stress v Strain (immediately after loading)

For HDPE pipes, the minimum pipe stiffness requirements set by specification determines, in part, the amount of material required, the cost of which dominates the cost of the finished pipe delivered to the job site. The characteristics of the stress/strain curve and the associated values of stress, strain and pipe stiffness are sensitive to the rates of application of load and displacement.

Stiffness requirements for pipes of any material may be met by material adjustments to the modulus of elasticity, geometric adjustments to the moment of inertia, or both. Profile pipe walls, easily shaped in HDPE by extrusion and/or vacuum forming, are designed to increase the wall's moment of inertia above that which would be the case for a solid wall pipe of the same material content, thereby enabling an optimization of cross-sectional area. The flexural modulus increases with density for a given melt index. See Table 1.2 for the effects of changes in density and melt index on the more general properties of HDPE.

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Tensile Strength

The point at which a stress causes a material to deform beyond its elastic region (permanent deformation) is called the tensile strength at yield. When stressed below the yield point, an elastic material recovers all the energy that went into its deformation. Recovery is possible for polyethylene when the crystals are subjected to low strain levels and maintain their integrity. A formulation of greater density (higher fraction of crystals, lower melt index) is predictive of greater tensile strength and increasing brittleness.

The force required to break the test sample is called the ultimate strength or the tensile strength at break. The strength is calculated by dividing the force (at yield or break) by the original cross-sectional area. ASTM D 638, Standard Test Method for Tensile Properties of Plastics, is used to determine the tensile properties of polyethylene pipe resins. Test specimens are usually shaped as a flat "dog bone", but specimens can also be rod-shaped or tubular per ASTM D 638. During the tensile test, polyethylene, which is a ductile material, exhibits a cold drawing phenomenon once the yield strength is exceeded. The test sample develops a "neck down" region where the molecules begin to align themselves in the direction of the applied load. This strain-induced orientation causes the material to become stiffer in the axial direction while the transverse direction (90° to the axial direction) strength is lower. The stretching or elongation for materials such as polyethylene can be ten times the original gauge length of the sample (1000% elongation). Failure occurs when the molecules reach their breaking strain or when test sample defects, such as edge nicks, begin to grow and cause failure. Fibrillation, the stretching and tearing of the polymer structure, usually occurs just prior to rupture.

Tensile or compressive elastic deformations of a test specimen along a longitudinal axis excite respective inward or outward deformations parallel to a transverse axis normal to the first. Poission's ratio is the ratio of lateral strain to longitudinal strain. When tested according to ASTM E 132, Standard Test Method for Poisson's Ratio at Room Temperature, Poisson's ratio for polyethylene is between 0.40 and 0.45.

Environmental Stress Crack Resisitance (ESCR)

Under certain conditions of temperature and stress in the presence of certain chemicals, polyethylene may begin to crack sooner than it would at the same temperature and stress in the absence of those chemicals. This phenomenon is called environmental stress cracking (ESC).

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Stress cracking agents for polyethylene tend to be polar materials such as alcohols, detergents (wetting agents), halogens and aromatics. The property of a material to resist ESC is called environmental stress crack resistance, or simply ESCR. The mechanism is not fully understood, but failures from ESC tend to be due to the development of cracks in areas of tensile stress which slowly grow and propagate over time. Stress cracking may be avoided by using appropriate resin formulations of stress crack resistant materials; appropriate geometric designs and manufacturing controls that prevent the occurrence of severe stress risers; and by limiting stresses and strains during pipe installation.

There are over 40 different ESCR test methods used to determine the chemical resistance of various materials. The standard test currently used in the polyethylene industry is the bent-strip test. It is also called the "Bell Test," since it was developed during the 1950's for wire and cable coatings for the telephone industry. ASTM D 1693, Standard Test Method for Environmental Stress Cracking of Ethylene,Plastics describes the test method used to determine the ESCR value for polyethylene. Ten small compression-molded specimens are notched and bent and then placed into a holder. The holder is immersed into a tube of a surfactant, typically one such as Igepal CO-630 at 212°F (100°C) and 100% concentration, and the time to failure is noted. The results are reported using the notation Fxx, where xx is the percentage of samples that have failed. For example, the statement F20=500 hours means that 20% of the samples have failed within 0 to 500 hours.

This test was developed when the time to failure was less than 10 hours. Excellent stress crack resistance of modern resins, coupled with stress relaxation in the pre-bent samples results in a test method wherein few failures occur. The efficacy of the test diminishes after a few hundred hours. This test is currently used mainly as a quality assurance test rather than providing definitive rankings of pipe performance.

Notched Constant Ligament Stress (NCLS)

Disadvantages of the ESCR test method are overcome with the Notched Constant Tensile Load (NCTL) test as described in ASTM D 5397. Because ASTM D 5397 is intended for geosynthetic materials using membranes as the specimen, a new test method was developed for piping materials – the Notched Constant Ligament Stress (NCLS) test. In this test method, HDPE resin is compression molded into a plaque. Dumbbell samples are machined from the plaque and notched in the midsection. Samples are placed in an elevated temperature bath containing a wetting agent for acceleration. The sample is then subjected to a constant ligament stress until a brittle failure occurs from slow crack growth. This is now an ASTM test method, F 2136.

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HDPE – A Material of Choice

Metal, plastic, concrete and clay make up most of the materials used for the manufacture of drainage pipes. Metal pipes may be steel, ductile iron or aluminum; concrete pipes may be steel-reinforced, earth-reinforced, non-reinforced, precast or cast-in-place; and plastic pipes may be of thermosetting resins (e.g., glass-reinforced epoxy or polyurethane) or thermoplastic resins (e.g., HDPE, PVC, polypropylene or ABS (acrylonitrile-butadiene-styrene)). The material longest in use is vitrified clay; the newest materials are plastic. Some pipes are built with a combination of materials; corrugated steel pipes lined and/or coated and/or paved (inverts) with plastic, bituminous or concrete materials. Durability (mostly, resistance to chemical and electro-chemical corrosion and abrasion), surety of structural performance over time, integrity of joints, surety of hydraulic performance (as pipe ages), ease of construction, availability and life cycle costs dominate the choice of pipe material(s).

Highway drainage facilities are often subject to hostile effluents and embedment soils. Concrete pipe is subject to chemical attack when in the environments of low pH (acids) and/or soluble salts (sulfates and chlorides) in drainage waters and neighboring soils. Sulfates, mainly those of sodium, calcium, potassium and magnesium, are found in many locations in the states of the northern Great Plains, in the alkali soils of western and southwestern arid regions, and in seawater. Uncoated (or otherwise unprotected) galvanized steel pipes are degraded in environments of low pH and low resistivity of soil or water. Permissible levels of pH vary by jurisdiction; a range of soil or water of $6.0 < pH < 9.5$ is generally accepted. Unlike pipes of concrete, steel, aluminum and iron, thermoplastic and vitrified clay pipes do not corrode or otherwise degrade in these environments; expensive maintenance is not required. Unlike metal pipes and steel reinforcement of concrete pipes, thermoplastic and vitrified clay pipes are non-conductors; cathodic protection is not required to prevent degradation due to galvanic corrosion at locations of low soil resistivity or in the vicinity of stray electrical direct currents. Polyethylene is often used to line and encase metal pipes thereby offering barrier protection from aggressive soils or stray electrical currents leading to galvanic corrosion. HDPE offers a range of $1.5 < pH < 14$.

Accidental highway spillage of high concentrations of some organically based chemicals, such as crude oils and their derivatives (solvents, gasoline, kerosene) or concentrated acids and bases, may cause swelling and softening of thermoplastic materials if sustained over long periods (measured in months). Of the four most common drainage pipes of thermoplastic materials (ABS, PVC, polypropylene, and HDPE), resistance to these aggressive chemicals is in the order noted; ABS the least resistive, HDPE is the most resistive.

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Polyester and epoxy thermosetting resin pipes, reinforced with continuous windings of glass filaments, primarily intended for sanitary sewers, were found to be corrosive in the presence of available hydrogen ion (present in acids and water). Penetration to the glass/resin interface may result in debonding of the glass reinforcement and wicking along the glass/resin interface. Thermosetting resin pipes reinforced with randomly oriented chopped fibers of short lengths have succeeded these pipes.

The chemical inertness of HDPE and the flexible "trampoline" response of the long chain molecules of HDPE result in a highly corrosion-resistant material. HDPE pipe is most often favored for transporting slurries containing highly abrasive mine tailings. Abrasion of metal, bituminous and concrete protective coatings of metal and concrete pipes (a function of the square of the flow velocity) leave these pipes vulnerable to accelerated erosion after penetration to the bare pipe material.

For the same conditions of embedment, the more flexible the pipe the lesser the proportion of overburden load attracted to the pipe. The attribute of stress relaxation of HDPE pipes (and thermoplastic pipes in general), which is greater than any relaxation of the embedding soil, assures that overburden loads and stresses within the pipe walls will decrease with time. The result is that a significant proportion of loads initially resisted by a flexible pipe will be transferred to the soil of the pipe/soil composite structure; the opposite is true for rigid pipes. Furthermore, the ability of buried flexible pipes to alter their shapes from circles to ellipses is exactly what transforms much of what would be bending stresses (which include tensile stresses) into membrane ring compression stresses. For the same conditions of embedment, rigid pipes (which lack the ability to comply with alteration of shape) respond with greater tensile stresses than flexible pipes and, in the case of concrete pipes, require steel reinforcement to manage these tensile stresses. HDPE pipes, properly embedded in a competent soil mass, result in a formidable soil/pipe composite structure that is almost entirely in the favored ring compression.

Favorable and commonly accepted roughness values of Manning's 'n' of 0.010 - 0.013 make smooth-lined corrugated HDPE a favorable choice for the transport of drainage waters. Velocity of flow is insensitive to changes in pipe shape due to service loads. The non-stick surface of HDPE resists scaling and pitting, and therefore does not require a design with a less favorable Manning's 'n' to accommodate future conditions.

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Additional Considerations

Crack Resistance:

Weak molecular bonds, perpendicular to the densely packed layered molecules of polyethylene crystals, tie adjacent molecules. In response to tensile stresses, cracks may form and propagate parallel to these layers by rupturing these weak bonds. Less dense and disordered arrangements of molecules in amorphous regions are more resistant to crack propagation than the layered molecules in crystals. For polyethylene resins of the same molecular weight, the lesser the density, the greater the resistance to stress cracking. The greater the proportion of crystals, the greater the density and brittleness of the resin. Density alone, however, is an inadequate predictor of stress crack resistance.

All common materials, extruded or otherwise shaped or formed at elevated processing temperatures, shrink during cooling. Residual stresses, which result, combine with those stresses resisting externally applied loads. In processes where stretching after forming takes place result in mechanical properties parallel to the direction of stretch different than those oriented perpendicular to the direction of stretch. At low rates of strain, should cracking of these orthotropic materials occur, they are likely to be parallel to the direction of stretch.

A more general purpose of ASTM D 1693, the test for ESCR, is prediction of the performance of ethylene resins subjected to environments such as soaps, wetting agents, oils, detergents or other materials likely to be stored or marketed in containers. This test is likely to assure proper material formulation (inclusive of post-consumer recycled resins) and to minimize contaminant inclusions.

Compression

The response of a buried flexible pipe is dominated by compression. Note in Table 1-1 there is no cell classification for compression. For purposes of design and for small strains (less than 2%), the compression modulus is taken to be of equal magnitude as the elastic tensile modulus. At greater stress levels, compression strain is less than the tensile strain. HDPE in compression does not tear or crack; stability for thin elements is a design consideration.

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Notes