Part I of a Two-Part Article

THE CHARACTERIZATION OF POLYETHYLENE MATERIALS AND THEIR SUITABILITY FOR USE IN LONG-TERM SERVICE

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Introduction

Polyethylene (PE) is a very versatile and widely used plastic. It is used in blow molded food bottles, blow molded household and industrial chemical bottles, automotive gas tanks, molded housewares, injection molded food containers, molded crates, cases, and pallets, as well as geomembranes, pond liners and pipe and fittings. Many of the end uses in which PE is employed are short-term packaging applications, where the service life of the product is measured in days or weeks. In contrast, geomembranes, liners, pipe, fittings or other long-term durable applications could have intended service lives of fifty years, one hundred years, or longer.

The characterization of various PE materials can be accomplished by the use of short-term testing, long-term testing, and accelerated testing. Such tests allow estimation of projected service lives of up to fifty years and beyond. It is important to understand the purpose of these tests as well as their limitations in order to accurately assess the suitability of such materials for longer-term service.

There are three basic properties of PE materials which are measured by short-term testing that are useful to assess processing and end-use properties. These are density or crystallinity, melt index and molecular weight distribution.

Density

The American Society for Testing and Materials (ASTM International)[1] has identified three major classifications based on density values for polyethylene materials. They are the following: Type I materials (0.910 to 0.925 g/cc), Type II materials (0.926 to 0.940 g/cc); Type III materials (0.941 to 0.965 g/cc). Type I materials are low-density (LDPE) and linear low-density polyethylene (LLDPE). Type II materials are medium density copolymer polyethylene (MDPE). Type III materials are high-density polyethylene (HDPE). Type III materials include both homopolymer polyethylene and copolymers of polyethylene with other alpha-olefin monomers (e.g. butene, hexene, or octene).

In homopolymer polyethylenes, the polymer chains are packed very closely together and form regular, repeating microstructures. Thus the density and degree of crystalline structure are higher. The introduction of co-monomers into the polymer chain causes the creation of short chain branches, which stick out of the polymer backbone and disrupt the regular packing of the polymer chains. This reduces the crystallinity and also the density of these materials. Homopolymer HDPE materials offer the highest mechanical strength properties because the polymer molecules are packed more regularly and more closely together.

ASTM D3350, “Standard Specification for Polyethylene Plastics Pipe and Fittings Materials,” identifies four classifications of polyethylenes based on density: Cell class 1, which is densities of 0.925 and lower; Cell class 2, which includes densities

>0.925 to 0.940; Cell class 3, which includes densities of >0.940 to 0.955; and Cell class 4, which includes materials with densities >0.955.

Melt Index

ASTM test method D1238, "Test Method for Melt Flow Rates of Thermoplastics by Extrusion Plastometer," provides a method for measuring the flow properties of polyethylene materials in the molten state. This test, which is more commonly referred to as melt index, measures the amount of material, in grams, which passes from an orifice of a set diameter due to the application of a set force in a set time period (ten minutes). The melt index number provides a rough estimate of the average molecular weight and processability of a particular polyethylene material. Materials having relatively short average polymer chain lengths will flow through the orifice more easily and the resulting Melt Index will have a higher value. Conversely materials with higher average polymer chain lengths (higher average molecular weights) will not flow as easily and will have lower melt index values.

Molecular Weight Distribution

Polyethylene polymer chains are not all the same length or the same mass. A particular sample of polyethylene will have a large number of molecular chains and there will be a large variation in their lengths and thus in their masses. Molecular weight distribution is used to define the statistical groupings of these various lengths of polymer chains. When most of the polymer chains are of approximately the same length and thus similar molecular weight, the distribution is said to be narrow. When there is a large variation in the lengths of the chains, the distribution is said to be broad.

Effects of Density, Melt Index and Molecular Weight Distribution on HDPE Properties

The effects of changes in the density, molecular weight (melt index) and molecular weight distribution (MWD) on the physical properties of polyethylene materials are shown in Table 1.

In an attempt to avoid premature cracking of the pipe, AASHTO M294 limits the material

Table 1: Effects of Changes in Density, Melt Index and Molecular Weight Distribution (MWD) on Various Properties

Property of HDPE	**As Density Increases, Crystallinity Increases and The Property:**	**As Melt Index Increases, Average Molecular Weight Decreases and The Property:**	**As MWD Broadens, The Property:**
Tensile strength (at yield)	Increases	Decreases	-
Stiffness	Increases	Decreases slightly	Decreases
Impact Strength	Decreases	Decreases	Decreases
Low Temperature Brittleness	Increases	Increases	Decreases
Abrasion Resistance	Increases	Decreases	-
Softening Point	Increases	-	Increases
Stress Crack Resistance	Decreases	Decreases	-
Permeability	Decreases	Increases slightly	-
Chemical Resistance	-	Decreases	-

density to .955 gm/cc and requires a melt index of 3.

SHORT-TERM PROPERTIES

Tensile Properties

Short-term tensile properties of polyethylene materials are commonly determined using a constant speed testing apparatus. The tensile testing results are shown in the form of force and deformation data or stress-strain curves. Test specimens are specified as to their dimensions and preparation procedures (ASTM D638 "Standard Test Method for Tensile Properties of Plastics"). These tests are normally done at room temperatures. A thermoplastic material will deform when a force is applied to it. The amount of deformation per unit length is termed the strain and the force per cross sectional area is termed the stress. At very low stress levels, strain is proportional to stress and is reversible. The material deforms but will recover its original shape if the stress is removed. The Modulus of Elasticity (or Young's Modulus) is the ratio between stress and strain in this reversible region. The strain is referred to as the elastic strain since it is reversible also. At higher stress levels, strain is no longer directly proportional to stress and it is not reversible when the stress is removed. The material begins to deform such that the original dimensions are not recoverable if the stress is removed. This strain is described as plastic strain. The point at which a stress causes a material to deform beyond its elastic region is termed the tensile strength at yield. The force required to break the test sample is called the ultimate strength or the tensile strength at break. The speed at which the test is conducted will affect the elastic modulus. At slow speeds the polymer molecules have sufficient time to disentangle, which will lower the stress needed to deform the material and will lower the modulus. Conversely, at higher crosshead speeds on the testing equipment, the molecular entanglement requires a higher stress (force) for deformation and hence results in a higher modulus value. As this indicates, it is necessary to know the exact testing condition by which test data are developed. Slight changes in condition can drastically alter the test values. Also, test data may not correlate closely with field requirements.

Flexural Properties

The flexural strength of a material is the maximum stress in the outer fiber of a test specimen at rupture. The test is done with a specimen supported at each end with a load applied at the center of a sample bar. The distortion of the sample is measured as the load is increased. If the specimen does not break, as is usually the case with polyethylene, then the amount of stress is reported at a specified level of strain (usually 2% or 5%). Flexural strength is related to the density and to a lesser extent to the molecular weight. As the density increases, the material becomes stiffer since the molecules do not have as much space to move around one another. The entanglement of the polymer molecules also resists these movements as the molecular weight increases and thus increases the stiffness of the material. Since most thermoplastic materials do not break under this test, the true flexural strength of these materials cannot be determined. Typically, the stress at 2% strain is used to calculate the flexural modulus. ASTM D790, "Standard Test Method for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials" is used to determine this property.

[1] ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959
[2] The Plastics Pipe Institute, 1825 Connecticut Avenue, NW Suite 680, Washington, D.C. 20009, www.plasticpipe.org
[3] American Association of State and Highway Transportation Officials, 444 N. Capitol St., NW Washington, DC 20001
[4] ASTM Standardization News, October 2001

SYNOPSIS AND COMMENTARY

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Dr. Walsh is an expert in the area of plastic piping materials, and understands the resin requirements needed to achieve a particular strength and durability balance in plastic pipe. Many Civil Engineers, and those who specify drainage pipe, have had very little if any education in plastics. In this summer issue of Concrete Pipe News and the conclusion of his article in the Fall Concrete Pipe News publication Dr. Walsh provides insight into the engineering properties that often get overlooked in the flashy brochures given to specifiers.

In the first half of his article, Dr. Walsh takes us through the three basic short-term properties of PE materials; density, melt index, and weight distribution. A close look at Table 1 reveals that improvements in short-term properties are often detrimental to the pipe in the long term. An increase in material density results in a more brittle pipe that has less crack resistance. Corrugated High Density Polyethylene pipe uses its corrugations to lessen the amount of material while still maintaining a high moment of inertia in the pipe wall. While HDPE drainage pipe manufacturers find benefits in using higher density resin, such as a pipe that can use less material and still maintain its stiffness, the end user may experience problems with the product in the future. Also, because HDPE drainage pipe experiences a constant load over a long period of time and HDPE's tensile strength is tested in the lab over a short period of time, future inspection of the installed product may be warranted. If nothing else, Dr. Walsh's descriptions of the pipe material properties proves that although HDPE pipe is highly installation sensitive, even a proper installation does not necessarily guarantee a quality product in the future if the material properties are not appropriate.

The second part of Dr. Walsh's article will focus on the long-term material properties and service issues with HDPE pipe materials. We hope that you will save this summer issue of *Concrete Pipe News* and put it together with the fall issue when it arrives so that if you ever consider specifying HDPE drainage pipe you will have the complete story on what you need to know today to have a quality installation tomorrow.

Dr. Walsh is president of Walsh Consulting Services Company, Houston, Texas. Prior to starting the firm in 1993, Dr. Walsh was executive director of the Plastic Pipe Institute. As part of the Society of the Plastic Industry, Inc., Dr. Walsh created and managed marketing programs for the development of polyethylene pipe markets in North America. During his career, he has served on numerous government agencies and regulatory bodies. Dr. Walsh is a recognized expert in the areas of plastic piping materials, testing and long-term durability. He has a Doctor of Philosophy in Chemistry from Rensselaer Polytechnic Institute and a Bachelors of Science degree from Boston College. Dr. Walsh can be reached at (281) 493-2344, email: t.s.walsh@earthlink.net.