1.1 Introduction

Since its scientific discovery in 1933, polyethylene (PE) has grown to become one of the world's most widely used and recognized thermoplastic materials. The versatility of this unique plastic material is demonstrated by the diversity of its use and applications. The original application of PE was as a substitute for rubber in the fabrication of electrical insulation during World War II. Modern PE resins are highly-engineered for more rigorous applications such as pressure-rated gas and water pipes, landfill membranes, automotive fuel tanks, and other demanding applications.

The use of PE as a piping material first occurred in the mid-1950s. In North America, its original use was in industrial applications, followed by rural water distribution, and then oil field production where a flexible, tough and lightweight piping product was needed to better serve the rapidly-developing oil and gas production industry. The success of PE pipe in these installations quickly led to its use in other demanding pipe applications, including stormwater drainage.

The first corrugated PE pipe commercially-produced in the United States was made in Middletown, Delaware, on July 3, 1967. This 4-in. (100 mm) diameter annularly-corrugated extruded pipe was produced to compete in the agricultural drainage market against 12-in. (300 mm) long, 4-in. (100 mm) diameter clay or concrete tile, which dominated the market at that time. Corrugated PE pipe proved to be easier and less expensive to install because of its longer lay lengths.

Since its inception in 1966, the corrugated plastic pipe (CPP) industry has grown dramatically from its initial introduction for use as agricultural drainage tile to storm and land drainage industry in North America, exceeding 1-billion dollars annually.

During this same growth period, available diameters have expanded from a 4-in. (100 mm) pipe to a pipe diameter range of 2-in. (50 mm) through 60-in. (1500 mm). Markets where CPP is used have changed from predominantly agricultural to housing, commercial development,

Plastics Pipe Institute | 105 Decker Court, Suite 825 | Irving TX, 75062 |469-499-1044 |www.plasticpipe.org

transportation, mining, industry, forestry, storm sewer, sanitary sewer, turf drainage, and stormwater treatment. This growth in market size and applications is a testament to the viability and versatility of corrugated plastic pipe.

1.2 Features and Benefits

When selecting pipe materials, designers, owners and contractors specify materials that provide reliable, long-term service durability, and cost-effectiveness. Corrugated high-density polyethylene (HDPE) and polypropylene (PP) pipes, herein collectively called Corrugated Plastic Pipe (CPP), are versatile materials and have ideal characteristics for use in underground drainage applications. Some of the many attributes for CPP include the following:

- CPP is one of the most inert drainage pipe materials available. Its chemical and abrasion resistance, along with the additives that make it resistant to ultraviolet degradation, result in an unrivaled design service life.
- In addition, CPP has a low carbon footprint, making it a sustainable solution for drainage that is further enhanced when produced with recycled resins. More information on the material properties, durability, and service life of CPP can be found in Chapter 2 on History and Physical Chemistry and Chapter 8 on Durability.
- The CPP manufacturing processes are environmentally-responsible and minimize impact to the environment. More information on the manufacturing process for CPP can be found in Chapter 3 on Manufacturing.
- Because of its versatility and innovative manufacturing processes, the availability of pipe and fittings products and the uses of CPP continue to expand. Chapter 4 on Products and Applications highlights the expanded pipe and fitting products, available joints, and variety of applications where CPP is utilized today.
- With its smooth interior liner, dual-wall CPP provides an efficient means of drainage conveyance. With a Manning's roughness coefficient of 0.012, dual-wall CPP is hydraulically efficient and

in some cases can result in the use of smaller diameters than some of the other drainage pipe materials. Chapter 5 on Hydrology provides engineering guidance for determining drainage pipe needs and Chapter 6 on Hydraulics provides guidance on the flow characteristics offered by CPP.

- When properly installed, CPP meets or exceeds the requirements for the most demanding load applications, such as heavy highway, railroad, deep fill, landfill, and mining. The performance of CPP under these demanding load conditions has been documented in numerous case studies over the years. Additionally, CPP can be designed using the thorough and conservative engineering methods used for highway construction; namely, the load and resistance factor design (LRFD) methodology. A detailed description of how this structural design method can be applied to CPP is found in Chapter 7 on Structural Design.
- CPP is light-weight, and easy to transport and install. This ease of handling and simple joint assembly contributes to the low installation costs for CPP. Proper installation is important for the performance of any buried pipe. Chapter 9 on Installation & Construction Inspection provides detailed guidance for the proper assembly and installation of CPP and describes the various post-installation inspection methods that are available.
- Because of its superior durability, CPP will remain in service for many, many years after installation. Its smooth interior reduces the accumulation of sediment and the longer lay-lengths of CPP reduces the number of joints needed. These are two common maintenance concerns for other types of drainage pipe materials. The versatility of CPP makes pipe extensions or repairs very easy. More information on common inspection, maintenance, and repairs that may be necessary for a CPP drainage system can be found in Chapter 10 on In-Service Inspection, Maintenance & Repair.

All of these attributes, combined with competitive initial costs, make CPP a wise material choice for drainage pipe projects. Low initial material cost, ease and speed of installation, extended service life, and lower environmental impact make the life cycle cost of utilizing CPP for drainage applications the lowest available. Allowing for competition on projects among pipe materials has been proven to reduce the average installation costs for the construction of drainage infrastructure. More information on the economics of using CPP can be found in Chapter 11 on Engineering Economics.

1.3 Materials

The materials used for the corrugated pipe market are primarily HDPE and PP.

While there are many applications for corrugated HDPE and PP pipes, they generally fall into two categories: (1) land drainage, and (2) culverts and sewers. Within the category of corrugated HDPE pipe, there are various material standards how HDPE should be designed for a variety of applications. HDPE pipe used in land drainage applications has been incorporating recycled resins for decades. Since 2018, corrugated HDPE pipes manufactured with recycled resins have been permitted in public applications.

Land drainage pipe applications are typically located outside of the public right-of-way (ROW). Culvert and storm sewer pipes are primarily used in public, municipal, or DOT ROW. Specific characteristics of the materials used to manufacture CPP are included in published specifications for a variety of products and applications shown in Appendix 1. These standards substantially define the critical material properties for the intended applications for the pipe.

1.4 Key Research Milestones

The use of CPP has been researched significantly over the years. Several of those research efforts are described throughout this Handbook. Research has been initiated and conducted by a variety of entities, including manufacturers, academia, and governmental agencies like AASHTO and State DOTs. As a result, a significant amount of independent research data is available to support the expanded use of CPP. The following sections summarize some of the research efforts that have been conducted. These summaries are organized into categories that reflect each technical area addressed by the research.

Plastics Pipe Institute | 105 Decker Court, Suite 825 | Irving TX, 75062
|469-499-1044 |www.plasticpipe.org

1.4.1 Performance Under Loads

"Analysis of the Performance of a Buried High-Density Polyethylene Pipe." Written by Naila Hashash and Ernest Selig, University of Massachusetts, and published in Structural Performance of Flexible Pipes, edited by Sargand, Mitchell, and Hurd, October 1990, pp. 95 - 103.

> In 1988, the Pennsylvania DOT began a study to evaluate the behavior of corrugated polyethylene pipe backfilled with crushed stone at a buried depth of 100 ft (30.5m). This document reports the status of the pipe condition 722 days after its installation and summarizes the in-service properties based on instrumentation data. The measured vertical deflection was 4.6% and the horizontal deflection was 0.6%. Much of the deflection measured was due to a slight (1.6%) circumferential shortening in the pipe. This amount of deflection is well within the generally accepted limit of 7.5%. Soil arching was found to reduce the load on the pipe by 77%, which shows that the soil column load is a very conservative method to estimate this load component.

"Field Performance of Corrugated Polyethylene Pipe." Written by John Hurd, Ohio Department of Transportation, and published in Public Works, October 1987.

> This article summarizes the results of a field study conducted in 1985 on 172 corrugated PE pipe culvert installations. These installations represented real-world applications where backfill procedures may or may not have been conducted in accordance with standard Ohio DOT recommendations. The primary findings related to structural integrity of the pipe were that shallow cover, even with heavy truck traffic, did not appear to cause significant amounts of deflection. In addition, the deflection which was measured appeared to be due to its installation conditions.

"Laboratory Test of Buried Pipe in Hoop Compression." Written by Ernest Selig, Leonard DiFrancesco, and Timothy McGrath, and published in Buried Plastic Pipe Technology, 1994, pp. 119 - 132.

The project involved developing an apparatus which could subject a pipe to purely compressive forces. A pressure of 55 psi (379 kPa) was reached, at which point equipment problems were found to develop. The authors indicated that this pressure was the equivalent of 100 feet (30.5m) of cover based on other tests they had performed. At this pressure, the pipe also experienced a 3% circumferential shortening, which resulted in a significant beneficial soil arching.

"Pipe Deflections - A Redeemable Asset." Written by Dr. Lester Gabriel and published in Structural Performance of Flexible Pipes, edited by Sargand, Mitchell, and Hurd, October 1990, pp. 1 - 6.

This paper provides a simple description of the role of deflection in a properly-performing flexible pipe. It explains that deflection is not a liability but rather a behavior that forces the backfill material to take on a disproportionate amount of load. Deflection allows flexible pipe to be installed in applications with significant buried depths.

"Structural Performance of Three-Foot Corrugated Polyethylene Pipe Buried Under High Soil Cover." Written by Reynold Watkins and published in Structural Performance of Flexible Pipes, edited by Sargand, Mitchell, and Hurd, October 1990, pp. 105 - 107.

A 3-ft (900mm) diameter corrugated PE pipe was tested in a load cell to determine if it performed as well as the smaller diameter pipes. The author recognized the effects of stress relaxation. The report concluded that corrugated PE pipes with 3-ft (900 mm) diameters appear to structurally perform under high soil cover favorably, provided that a good granular pipe zone backfill is carefully placed and compacted. This finding was consistent with the backfill and material recommendations set forth in previous pipe installations.

"Time-Dependent Deflection of Thermoplastic Pipes Under Deep Burial." Written by Shad Sargand, Glenn Hazen, Kevin White, and Alan Moran. Published in Transportation Research Record: Journal of the

Transportation Research Board, January 2001.

The focus of this study was to observe the deflection performance of six thermoplastic pipes during burial and under actual field conditions (over the long term). The six different thermoplastic pipes were located under 40 ft (12.2 m) of cover using either Ohio DOT 304 crushed limestone or ODOT 310 river sand materials for backfill. Each pipe was instrumented with displacement potentiometers that measured deflection in the vertical and horizontal directions along with circumferential shortening. The results from the study indicated that the amount of deflections stabilized within two months after the completion of construction.

"Evaluation of Corrugated HDPE Pipes Manufactured with Recycled Content in Commuter Rail Applications." Written by Michael Pluimer, PhD. PhD Dissertation at Villanova University's College of Engineering, published on Proquest 2016.

This research project involved a 3-year study comparing the performance of corrugated HDPE pipes manufactured with recycled materials to those manufactured with virgin materials relative to slow crack growth due to both fatigue and creep. Pipes were installed with just 2 ft. (0.5 m) of cover underneath a commuter railroad in Philadelphia, and the results showed no significant difference in performance between the pipes manufactured with virgin and recycled materials. A service life model was developed for pipes manufactured with recycled materials.

1.4.2 Service Life Performance

National Cooperative Highway Research Program (NCHRP) Report 429, HDPE Pipe: Recommended Material Specifications and Design Requirements.

This project investigated pipe failures and the slow crack growth failure mechanism. Materials specifications were recommended to minimize cracking potential. These recommendations were accepted by the AASHTO Committee on Materials and are currently part of the AASHTO M 294 standard.

"A Service Life Assessment of Corrugated HDPE Pipe." Written by Michael Pluimer and published in the Journal of ASTM International, West Conshohocken, PA 2011.

This paper presented a method for determining the service life of corrugated HDPE pipes by utilizing and modifying some methods employed by the pressure pipe industry. The paper demonstrated 100-year service life for corrugated HDPE pipes manufactured with virgin materials in typical installed conditions.

"AASHTO R 93: Standard Practice for the Service Life Determination of Corrugated HDPE Pipes Manufactured with Recycled Content."

This standard practice details a procedure for determining the service life of corrugated HDPE pipes containing recycled materials based on the Un-notched Constant Ligament Stress (UCLS) test published as ASTM F3181. The standard practice was developed by Michael Pluimer, PhD and Rick Thomas and published in NCHRP Report 870.

1.4.3 Design and Analysis

"Short-term Versus Long-term Pipe Ring Stiffness in the Design of Buried Plastic Sewer Pipes." Written by Lars-Eric Janson and published in Pipeline Design and Installation, proceedings from the International Conference sponsored by the Pipeline Planning Committee of the Pipeline Division of the American Society of Civil Engineers, March 1990, pp. 160 -167.

This report describes the viscoelastic behavior of polyethylene. The author suggested the use of short-term properties when the pipe is backfilled in friction soils or in firm silty/clayey soils.

"Stress Relaxation Characteristics of the HDPE Pipe-Soil System." Written by Larry Petroff and published in Pipeline Design and Installation, proceedings from the International Conference sponsored

Plastics Pipe Institute | 105 Decker Court, Suite 825 | Irving TX, 75062 |469-499-1044 |www.plasticpipe.org

by the Pipeline Planning Committee of the Pipeline Division of the American Society of Civil Engineers, March 1990, pp. 280-293.

> This report discusses the viscoelastic nature of polyethylene and addresses both creep and stress relaxation behaviors. The study reported that 80% of the total deflection that a pipe will experience throughout its life will occur within the first 30 days. The study also indicated that the highest stresses developed in polyethylene pipe buried in a compacted granular material occur shortly after installation and then relax soon thereafter.

"Stiffness of HDPE Pipe in Ring Bending." Written by Timothy McGrath, Ernest Selig, and Leonard DiFrancesco, and published in Buried Plastic Pipe Technology- 2nd Volume, 1994, pp. 195 - 205.

> This project was conducted to determine whether or how the modulus of elasticity of HDPE pipe changes over time. The HDPE pipe was deflected and held in position to generate a stress/strain curve. Although the results appeared to indicate that the material was losing strength over time, the application of repeated incremental loads caused the pipe to respond with its short-term modulus, indicating no loss of strength had occurred.

"Proposed AASHTO Structural Design Properties for Corrugated Polypropylene Storm Sewer Pipe." Written by Brent Bass, Timothy McGrath, and Bill Vanhoose. Transportation Research Record n 2310 p 129-136.

> This paper presents the test methods and sampling conventions required to arrive at structural design properties, as well as test results for four polypropylene resins commercially available in the United States. The paper also uses these test results as the basis for proposed structural design properties for polypropylene storm sewer pipe for adoption into the AASHTO Load and Resistance Factor Design (LRFD) Bridge Design Specifications.

"Performance of Polypropylene Corrugated Pipe in North America." Written by John M. Kurdziel, P.E. ASCE Pipelines Conference 2015,

Plastics Pipe Institute | 105 Decker Court, Suite 825 | Irving TX, 75062 |469-499-1044 |www.plasticpipe.org

Baltimore, MD.

The focus of this research paper was to highlight the development of standards covering the performance benefits of polypropylene pipe in gravity flow storm and sanitary applications.

NCHRP Report 438 – Recommended LRFD Specifications for Plastic Pipe and Culverts – by Timothy McGrath, PhD and Vincent Sagan, Published by the National Academy of Sciences Transportation Research Board, Washington, DC, 2000.

This project developed the methodology that incorporated thermoplastic pipe into Section 12 of the AASHTO LRFD design standards.

NCHRP Report 619 – Modernize and Upgrade CANDE for Analysis and LRFD Design of Buried Structures – by Michael Katona, PhD, Timothy McGrath, PhD, and Mark Mlynarski, Published by the National Academy of Sciences Transportation Research Board, Washington, DC, 2008.

This project upgraded and simplified the CANDE program and incorporated the AASHTO LRFD Section 12 changes that affect plastic pipes.

NCHRP Report 631 – Updated Test and Design Methods for Thermoplastic Drainage Pipe – by Timothy McGrath, PhD, Grace Hsuan, PhD, and Ian Moore, PhD, Published by the National Academy of Sciences Transportation Research Board, Washington, DC, 2008.

This project made extensive recommendations for how to improve the testing of plastic pipes. It also provided recommended modifications for existing design methods, many of which have been adopted by AASHTO.

NCHRP Report 647 – Recommended Design Specifications for Live Load Distribution to Buried Structures – by Lee Peterson and Timothy McGrath, PhD, Published by the National Academy of Sciences Transportation Research Board, Washington, DC, 2010.

This project improved the predictions for live load distribution over all types of buried structures and provided improved design procedures for all pipe types.

1.4.4. Use of Recycled Resins

NCHRP Report 696 – Performance of Corrugated Pipe Manufactured with Recycled Polyethylene Content - by Richard Thomas and David Cuttino, Published by the National Academy of Sciences Transportation Research Board, Washington, DC, 2008.

With the considerable interest in utilizing recycled plastic in products of all types including pipe, this project generated laboratory test data on a broad range of recycled polyethylene blends. Recommendations were provided for test requirements and contaminant limits. Since the project did not include any pipe tests in the ground, a follow-up project was initiated to verify the results and recommendations from this project.

NCHRP Report 870 – Field Performance of Corrugated CPP Manufactured with Recycled Content – by Michael Pluimer, PhD, Joel Sprague, Richard Thomas, Leslie McCarthy, PhD, Andrea Welker, PhD, Shad Sargand, PhD, and Kevin White,, Published by the National Academy of Sciences Transportation Research Board, Washington, DC, 2008.

This was a follow-up study to NCHRP Report 696 and was completed in 2017. It established the first performance-based standard for corrugated HDPE based on design service life. Results from this research included the incorporation of recycled resins into AASHTO M 294. It also developed a new AASHTO Standard Practice to determine the service life of corrugated HDPE pipes manufactured with recycled materials, which was published by AASHTO as AASHTO R 93 in 2019.

Plastics Pipe Institute | 105 Decker Court, Suite 825 | Irving TX, 75062 |469-499-1044 |www.plasticpipe.org

1.4.5. Hydraulic Performance

Innovative Drainage Pipe – American Society of Civil Engineers, Utah State University, 1989.

In this test program, the Utah State Water Research Laboratory evaluated nine different pipes supplied by three separate manufacturers. The pipe diameters studied were 12, 15 and 18 inches (300, 375, and 450 mm). The test sections consisted of a minimum of 100 pipe diameters. The tests were conducted at full pipe flow with velocities ranging from three to 12 feet (0.9 to 3.6 cm) per second. The researchers also measured the interior roughness of the test pipes. The report includes a summary of the Manning's "n" value data for testing done at a velocity of five feet (1.5 cm) per second.

Changes in Hydraulic Roughness Coefficients for Circumferentially Strained M294 Pipe, Utah State University, August 2005.

The objective of this test program was to quantify the increase in hydraulic roughness due to circumferential pipe wall strain over a range of conditions that might be encountered in field. The testing for Manning's "n" values that had previously been completed was done in the absence of external circumferential loads on the pipe. For this test program, 200 feet (61 cm) of 24-in. (9.5 cm) diameter pipe was installed. The circumferential stresses and resulting strains were achieved by girdling the entire test section with adjustable flat steel bands. The tightness of the bands could be adjusted to achieve different strain conditions.

Roughness Coefficient Testing for Large Diameter High Density Polyethylene Pipe, Colorado State University, January 2009.

Previous Manning's "n" testing had concentrated on smooth interior HDPE pipes with relatively small diameters (24 in. (600 mm) or less) under full flow conditions. In order to have a complete set of Manning's "n" coefficient data, a test program was designed and

Plastics Pipe Institute | 105 Decker Court, Suite 825 | Irving TX, 75062
|469-499-1044 |www.plasticpipe.org

executed to quantify the Manning's "n" coefficient for a 36-in. (900 mm) diameter HDPE. The test apparatus consisted of 120 feet (37 m) of pipe installed within a flume with a width of eight feet (2.4 m).

1.5. A Firm Foundation for the Ideal Drainage Pipe

This is just a taste of the extensive research performed over the years to validate corrugated HDPE and PP as a viable culvert, drainage pipe, and storm sewer conveyance materials. Additional research is available from the industry, from AASHTO and Departments of Transportation, and from individual CPP manufacturers. Together they demonstrate that CPP is the most researched pipe of all the commonly used drainage pipe materials. The following chapters build upon this foundational research and provide practical guidance for understanding, selecting, designing, installing, and maintaining CPP for culvert, drainage, and storm sewer systems. The research and guidance provided, combined with the numerous benefits and performance capabilities, make CPP the ideal choice for gravity flow drainage applications.

Plastics Pipe Institute | 105 Decker Court, Suite 825 | Irving TX, 75062
|469-499-1044 |www.plasticpipe.org