EPA/600/R-14/251 | January 2014 | www2.epa.gov/water-research

EPA
United States
Environmental Protection
Agency

National Database Structure for Life Cycle Performance Assessment of Water and Wastewater Rehabilitation Technologies (Retrospective Evaluation)

Office of Research and Development
Water Supply and Water Resources Division

EPA/600/R-14/251
August 2014

National Database Structure for Life Cycle Performance Assessment of Water and Wastewater Rehabilitation Technologies (Retrospective Evaluation)

by

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Contract No. EP-C-11-038
Task Order No. 1

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ABSTRACT

This report builds upon a previous pilot study to document the in-service performance of trenchless pipe rehabilitation techniques. The use of pipe rehabilitation and trenchless pipe replacement technologies has increased over the past 30 to 40 years and represents an increasing proportion of the approximately $25 billion annual expenditure on the operation and maintenance of the nation's water and wastewater infrastructure. This report describes the establishment of a database to house performance evaluation data for rehabilitation technologies used in the water and wastewater sectors, carries out additional retrospective evaluations of cured-in-place-pipe (CIPP) rehabilitation projects and begins the evaluation of several fold-and-form, deform-reform, and sliplining projects. The new retrospective data for CIPP and the testing of the other rehabilitation technologies are described in detail. The CIPP data are combined with the pilot study data for an overall assessment of the current status of CIPP life cycle performance. The potential uses of the database for data mining of key trends are demonstrated based upon the CIPP technology performance data. The examination of CIPP liners with up to 34 years in service and other rehabilitation technologies with up to 19 years of service has shown that all of the rehabilitation technologies are showing little evidence of deterioration in service. The test results for 18 CIPP samples from nine cities across North America indicate that properly designed and installed CIPP liners should meet and likely exceed the typical 50-year expected design life. For the fold-and-form, deform-reform, and sliplining projects, there are only two to three samples per rehabilitation technology and hence less can be said about overall performance. Nevertheless, all of the samples tested still met the material property requirements at installations after 14 to 19 years of service. In summary, this provides an excellent prognosis for the rehabilitation technologies on which the nation is depending.

ACKNOWLEDGMENTS

This report has been prepared with input from the research team, which includes Battelle and the Trenchless Technology Center (TTC) at Louisiana Tech University. The technical direction and coordination for this project was provided by Dr. Ariamalar Selvakumar of EPA. The project team would like to acknowledge several key contributors to this report in addition to the authors listed on the title page. The project would not have been possible without the cooperation of the representatives of the various cities and agencies that assisted in identifying appropriate sample locations and retrieving samples for the study. These include: Mark Gehrke and Wayne Querry from the City of Denver; Siri Fernando and Albert Kwan, City of Edmonton; Jason Iken, Greg Johnson, Joshua Kosmicki and Joe Smith, City of Houston; Roger Hanas and John Morgan, City of Indianapolis; Rod Lovett and Ini Roberts, Miami-Dade Water and Sewer Department; Greg Ballard, Hal Balthrop, Robby Ervin, Glenn Mizell and Paul Stonecipher, City of Nashville; Dino Ng, City of New York; Jim Frantz, Ken Gardner, and Kelly Hamill, City of Northbrook, IL; Chris Macey (AECOM) and Kas Zurek, City of Winnipeg. The city and contractor crews who carefully excavated and/or cut samples are also to be thanked – excellent samples were retrieved that safely made the journey to the TTC and Battelle laboratories for further study. These include: Tim Carroll (TLCarroll Consulting Enterprises) and Bill King (Levi Contractors) in Denver; Alex Sharpe (Insituform) in Indianapolis; Steve Cudd in Miami-Dade; Charlie Parker (Metro Wastewater) in Nashville; Gene Camali (En-Tech) in New York. Thanks also go to Joe Barsoom, former Director of the Sewer Division for the City and County of Denver, who assisted in the setup of the evaluations in Denver. Others providing input to the project were: Richard Aillet, Bobby Booze, Craig Christians, Marc Flatt, Roy Hughes, Dan Kvasnicka, Susan Marino, Ali Mustapha, James Redmond, Jorge Rivero, Dan Shjandemaar, Kirk Skogen, James Theiler, Craig Weinland, and Eric Wharton. The authors would also like to acknowledge research team participants who attended the sample retrievals and conducted the laboratory testing. These include: Yu Yan, Tylor Baus, Ben Curry, Jake Pierce, Don Reuter, and Ryan Stowe. The programmers for the database include Hrudaya Nath Kommareddy and Rajesh Kandepu. Finally, the authors would like to thank Mr. Phil Zahrredine of Office of Wastewater Management and Dr. Robert Brown of Urban Watershed Management Branch for their timely review of the research report.

EXECUTIVE SUMMARY

This report builds upon a previous pilot study to document the in-service performance of trenchless pipe rehabilitation techniques (EPA, 2012). Use of pipe rehabilitation and trenchless pipe replacement technologies has increased over the past 30 to 40 years and represents an increasing proportion of the approximately $25 billion annual expenditure on the operation and maintenance of the nation's water and wastewater infrastructure (EPA, 2002). Despite the massive public investment represented by the use of these technologies, little formal and quantitative evaluation has been conducted on whether they are performing as expected and whether rehabilitation is indeed cost-effective compared to replacement.

The major reasons for an interest in a retrospective evaluation of pipe rehabilitation systems are:

- The biggest data gap in asset management for pipeline systems involving rehabilitation is prediction of the remaining asset life for the existing pipe and how long rehabilitation techniques can extend that life. Municipalities have expressed a strong desire for data on the current condition of previously installed systems to validate or correct the assumptions made at the time of rehabilitation.
- Since several of the major pipe lining techniques have now been in use for at least 15 years (some over 30 years in the U.S. and over 40 years internationally), it is a good time to undertake such an investigation to assess whether the originally planned lifetime (typically assumed to be 50 years) is reasonable based on the current condition of the liner.

It is not within the scope of this report to propose a new method to assess the longevity of pipe rehabilitation liners and it is considered that the current level of data collected is insufficient to provide an experimental basis for such a prediction that could cover the wide range of installation and use parameters to which U.S. sewers are subjected. However, the data do provide important feedback on the current condition of some of the older installations associated with each technology evaluated.

The initial project described in the previous report focused on CIPP liners because they were the first trenchless liners (other than conventional slipliners) to be used in pipe rehabilitation and because they hold the largest market share within relining technologies. The pilot testing used CIPP samples from both large and small diameter sewers in two cities (EPA, 2012).

The current work takes up two of the recommendations from the prior work: to develop a database structure for the exchange of performance information on rehabilitation technologies and to collect a wider sample of physical test data and performance data on such technologies. In the current work, the physical evaluation was extended to the use of CIPP in additional cities. A total of 13 new CIPP samples from seven cities were added to the five CIPP samples from two cities tested in the pilot study. The 18 CIPP liner samples from both the current and the pilot study mostly ranged in age from 17 to 34 years, while two younger liners (5 and 9 years) were also included. Samples of other types of rehabilitation liners (two polyvinyl chloride [PVC] fold-and-form liners, three high density polyethylene [HDPE] deform-reform liners, and two polyethylene slipliners) were also collected and tested.

Testing of the various liners over both projects included thickness, annular gap, ovality, specific gravity, porosity, flexural strength, flexural modulus, tensile strength, tensile modulus, surface hardness, glass transition temperature, Raman spectroscopy, environmental stress crack resistance and pipe stiffness as appropriate to the liner type and condition.

CIPP Rehabilitation Evaluation

The CIPP liners have specified minimum values for flexural modulus and flexural strength in American Society for Testing and Materials (ASTM) F1216 and hence these are typically considered the key test parameters for CIPP. The average flexural modulus values from each site for the new CIPP samples retrieved ranged from 237,264 pounds per square inch (psi) to 477,609 psi. The mean and standard deviation for the flexural modulus from all the new samples in the current study was 330,825 psi and 70,060 psi, respectively. Two out of the 13 average flexural modulus values fell below the ASTM requirement of 250,000 psi, but there is no indication that these low values represent deterioration of the liner as opposed to a poor liner quality in the as-installed liner.

The flexural strength values for the new CIPP samples ranged from 4,469 psi to 8,592 psi. The mean and standard deviation of flexural strength from all the new samples in the current study was 6,682 psi and 1,211 psi, respectively. Only one of the average flexural strength values fell below the ASTM as-installed requirement of 4,500 psi.

The strength and modulus values for all CIPP liners from both the current study and the pilot study are plotted against the age of the liners in this report, but there is no obvious trend with age. This observation is reinforced by a literature review (including two studies from the UK and Denmark involving "retrieved" samples of the actual liner installation), in which the results show no consistent pattern of change with age with some results increasing by modest amounts and others decreasing by modest amounts. There are other data in the literature where installation sample tests are available for comparison, but these samples do not have the same installation conditions as samples from the liner installed within the host pipe.

The value of specific gravity and surface hardness for predicting the values of mechanical test parameters was explored using the table of average values from each site and the full dataset of all test data. Despite significant scatter in most of the relationships explored (only two of all the linear regressions plotted had R^2 correlation values above 0.50), there are visible trends of increasing flexural modulus, flexural strength and tensile modulus with increasing specific gravity. There was, however, only a minor increase of tensile strength observed with increasing specific gravity. A small increase in the Shore D hardness of the inner and outer liner surfaces with increasing flexural modulus values was also seen. The inner hardness showed a more pronounced relationship, but the scatter was large and the R^2 values both very low.

A Web site has been created where the full database of retrospective test data is available for interested parties to download so that users can carry out their own analyses of the data collected. Data are available by sample or as aggregated data across all of the samples for a particular liner type. A number of example plots using the Web site graphing functions are given in the main body of the report. The use of the database to examine other potential relationships is explored in the report for the CIPP samples which currently have more sites represented.

As part of the current project, a literature review was conducted to gain other insights and data from similar studies being reported worldwide. This added to the information collected in an "international scan" conducted in the pilot study. A number of cities worldwide have carried out some form of evaluation of rehabilitation technology performance, but test data from such evaluations often are not included in the literature. Overall, the experiences reported worldwide indicate that CIPP rehabilitation is considered a reliable technique with a good track record. However, as a site-constructed lining process, a number of defects can occur at the time of installation and these should be minimized.

The overarching conclusions from the study of the retrospective samples of CIPP lining are as follows:

- The CIPP-lined sewers examined are holding up very well after their current in-service exposures of 5 years to 34 years.
- While some defects were noted in the samples or the associated closed-circuit television (CCTV) inspections, it is believed that most of these defects were created at the time of installation and do not represent a degradation of the liner with time.
- In general, lining of a sewer pipe is only carried out when the existing host pipe has experienced significant defects. For the sites studied, the CIPP lining has stabilized that deterioration and is providing a continued service life for the pipe – and has done so without the need for excavating and replacing the line from the surface.
- While the current dataset does not allow conclusions to be made about the average expected lifetime of CIPP liners, it does appear that the original design life of 50 years expected by most municipalities will be met and that much longer lifetimes can be achieved.

The above conclusions are not meant to imply that no CIPP liners will fail or have performance issues. A number of quality/performance issues have been noted in this study and references are also provided in the report to other studies that have assessed installation defects. These should be addressed in designs, specifications and quality assurance/quality control (QA/QC) procedures to ensure that high quality liners are installed.

Evaluation of Other Rehabilitation Technologies

The non-CIPP liners evaluated in this study comprised two PVC fold-and-form liners with 14 and 15 years of service, three HDPE deform-reform liners with 15 to 19 years of service, and two polyethylene slipliners. One of the slipliners had 18 years of service and the other had an unknown installation date, but is believed to be of a similar or older age. No test data from the time of installation were available for any of the liner types.

For the PVC fold-and-form liners, the key parameters for evaluation are in terms of tensile strength, tensile modulus, flexural strength and flexural modulus. For the HDPE deform-reform and polyethylene slipliners, the key parameters for evaluation are in terms of density, flexural modulus, tensile strength and environmental stress crack resistance (ESCR).

The average tensile strengths for the fold-and-form liners were 5,418 psi and 5,914 psi compared to the as-installed required tensile strength from ASTM F1867 of 3,600 psi. The average (short-term) tensile moduli for the fold-and-form liners were 288,335 and 314,873 psi compared to the minimum required in ASTM F1867 of 155,000 psi. The average flexural strengths for the fold-and-form liners were 7,791 psi and 8,581 psi compared to the as-installed required flexural strength from ASTM F1867 of 4,100 psi. The average (short-term) flexural moduli for the fold-and-form liners were 273,471 and 279,551 psi compared to the minimum required in ASTM F1867 of 145,000 psi. Both the tensile and flexural liner properties after 14 and 15 years of service are well in excess of the required values at the time of installation.

The average tensile strengths for the deform-reform liners ranged from 2,975 psi to 3,053 psi compared to the minimum permissible values at installation of 2,600 psi for PE3408. The average (short-term) tensile moduli ranged from 142,479 psi to 162,567 psi, but there is no corresponding requirement in the standard. The average flexural strengths for the deform-reform liners ranged from 3,133 psi to 3,364 psi, but again there is no corresponding requirement in the standard. The average (short-term) flexural moduli ranged from 103,646 psi to 108,816 psi compared to the minimum value of 80,000 psi for PE3408. Hence, the retrospective test values exceeded the as-installed requirements after 15 to 19 years of service.

The average tensile strengths for the slipliners were 2,979 psi and 3,098 psi compared to the minimum permissible values at installation of 2,600 psi for PE3408. The average (short-term) tensile moduli were 137,875 psi and 147,875 psi, but there is no corresponding requirement in the standard. The average flexural strengths for the slipliners were 3,152 psi and 3,174 psi, but again there is no corresponding requirement in the standard. The average (short-term) flexural moduli were 100,636 psi and 101,881 psi compared to 80,000 psi for PE3408. As for the deform-reform HDPE liners, the installation test parameters are all still satisfied at the current length of service.

The results of the other evaluation tests conducted on these liner types are provided in the report, but did not indicate any distress or deterioration of these types of liners. Neither the fold-and-form nor the deform-reform liners are currently marketed in the U.S. and sliplining is not often used in smaller diameter sewers. This disappearance from the U.S. marketplace reflects both competitive pressures in the marketplace and the tendency of both the fold-and-form and deform-reform liners to not be locked into position longitudinally after installation (causing potential misalignment of lateral openings cut in the liner). However, in terms of the retrospective evaluation of liner condition, these types of liners are all performing well.

Future Research Activities

The following future research activities are recommended to further the current work to make the conclusions more robust and to extend this type of study to other infrastructure systems.

- Continue to collect and test samples from additional sewerage systems in North America and encourage municipalities and agencies to use opportunities where rehabilitated sections of pipes or manholes are to be uncovered to include such collection and testing in their work.
- Extend the range of non-CIPP rehabilitation/renewal systems that are investigated for sewer systems.
- Apply a similar methodology to gain an understanding of the performance of rehabilitation systems for pressure pipes – both water distribution systems and sewer force mains.
- Expand the database by adding new data as they become available and encourage municipalities to add their own test data to the database through administrative access procedures with appropriate data vetting.
- Expand the qualitative technology performance information to provide much broader insights into the issues experienced with a rehabilitation technology and the overall level of satisfaction with the technology.

Overall Summary

The examination of CIPP liners with up to 34 years in service and other rehabilitation technologies with up to 19 years of service has shown that all of the rehabilitation technologies are showing little evidence of deterioration in service. The test results for 18 CIPP samples from nine cities across North America indicate that properly designed and installed CIPP liners should meet and likely exceed the typical 50-year design life that is expected. For the fold-and-form, deform-reform, and sliplining projects, there are only two to three samples per rehabilitation technology and hence less can be said about overall performance. Nevertheless, all of the samples tested still met the material property requirements at installation after 14 to 19 years of service. In summary, this provides an excellent prognosis for the rehabilitation technologies on which the nation is depending.

CONTENTS

APPENDICES

FIGURES

TABLES

ABBREVIATIONS AND ACRONYMS

2-D	two-dimensional
3-D	three-dimensional
ASTM	American Society for Testing and Materials
CCTV	closed-circuit television
CIPP	cured-in-place pipe
DR	standard dimension ratio for a pipe (= outside diameter ÷ thickness)
D-R	deform-reform method of pipe rehabilitation using HDPE
DSC	differential scanning calorimetry
EPA	U.S. Environmental Protection Agency
EPAD	elevated pressure application device
ESCR	environmental stress crack resistance
F&F	fold-and-form method of pipe rehabilitation using PVC
HDPE	high density polyethylene
I/I	infiltration and inflow
IKT	Institut für Unterirdische Infrastruktur GmbH (Institute for Underground Infrastructure)
ISTT	International Society for Trenchless Technology
LVDT	linear variable displacement transducer
MSE	mean squared error
NASTT	North American Society for Trenchless Technology
NDT	non-destructive testing
NRMRL	National Risk Management Research Laboratory
PE	polyethylene
psi	pounds per square inch
PUB	Public Utilities Board (Singapore)
PVC	polyvinyl chloride
QA	quality assurance
QAPP	Quality Assurance Protocol Plan
QC	quality control
RPD	relative percent difference
Tg	glass transition temperature
TO	task order
TTC	Trenchless Technology Center
UTM	Universal Testing Machine
UV	ultraviolet

1 INTRODUCTION

This report presents the results of continued work to understand and document the performance of pipe rehabilitation technologies. The project has been funded by the U.S. Environmental Protection Agency (EPA) as part of a broader initiative to study and support technology development for the rehabilitation of water distribution and wastewater collection systems. Use of trenchless pipe rehabilitation and pipe replacement technologies has increased over the past 30 to 40 years and represents an increasing proportion of the approximately $25 billion annual expenditure on the operation and maintenance of the nation's water and wastewater infrastructure (EPA, 2002). Prior to this initiative and despite the massive public investment represented by the use of these technologies, little formal and quantitative evaluation in the U.S. has been conducted on whether or not the pipes were performing as expected and if rehabilitation was indeed cost-effective compared to replacement. An initial pilot study was funded under EPA's Aging Water Infrastructure Research Program for the development of a sample recovery and testing protocol together with the recovery and extensive testing of four samples of cured-in-place pipe (CIPP) liners from two participating cities (EPA, 2012). This research expanded upon the initial efforts by: collecting more CIPP samples, collecting retrospective evaluation samples for additional rehabilitation technologies (e.g., other than CIPP), and developing the structure for a national database on the performance of trenchless rehabilitation technologies. This report presents the results from building a database to document the performance of rehabilitation technologies on a national basis including additional CIPP liner testing, testing of three other types of rehabilitation technologies (sliplining, fold-and-form, and deform-reform), and a review of the overall experiences with sewer rehabilitation technologies.

This research was conducted for the EPA National Risk Management Research Laboratory (NRMRL) under Task Order (TO) No. 01 titled *Field Demonstration and Retrospective Evaluation of Rehabilitation Technologies for Wastewater Collection and Water Distribution Systems* of the Scientific, Technical, Research, Engineering, and Modeling Support II (STREAMS II) Contract No. EP-C-11-038. The research team for the retrospective evaluation was a collaborative effort between Battelle and the Trenchless Technology Center (TTC) at Louisiana Tech University. TTC carried out the liner testing and developed the database and data mining approaches.

1.1 Objective of This Study

The objective of this study was to create a database of performance results for technologies used in the rehabilitation of gravity sewers, along with the means for interpreting the results through data mining techniques. This objective has included extending the number of sites contributing physical testing data from older in-service liner technologies and capturing broader qualitative data from the agencies that participated in the study.

1.2 Long-Term Goals of the Initiative

As discussed in the prior report, the major reasons for interest in a retrospective evaluation of pipe rehabilitation systems are that:

- The biggest data gap in asset management for pipeline systems involving rehabilitation is prediction of the remaining asset life for the existing pipe and how long rehabilitation techniques can extend that life. Municipalities have expressed a strong desire for data on the current condition of previously installed systems to validate or correct the assumptions made at the time of rehabilitation.

- Since several of the major pipe lining techniques have now been in use for at least 15 years (some over 30 years in the U.S. and over 40 years internationally), it is a good time to undertake such an investigation to assess whether the originally planned lifetime (typically assumed to be 50 years) is reasonable based on the current condition of the liner.
- A valuable outcome would be to address one of the largest unknowns in terms of decision-making for engineers carrying out life cycle cost/benefit evaluations.

This type of evaluation can provide answers to the question "How long can I extend the life of the asset if I rehabilitate it instead of replacing it?" but can also start to fill one of the biggest gaps in knowledge about rehabilitation technologies that exists today – their expected lifetimes under a variety of installation and service conditions. Evaluating rehabilitation technologies that have already been in service for a significant length of time can provide data that could be used immediately by other municipalities (e.g., what properties/defects are critical; what accelerates deterioration) and can establish benchmarks for vendors against which they can improve their products (i.e., it could become a driver for achieving excellence).

1.3 Prior Work in This Initiative

The initial pilot study described in an earlier report (EPA, 2012) focused on CIPP liners because they were the first trenchless liners (other than conventional slipliners) to be used in pipe rehabilitation and because they hold the largest market share within relining technologies. The pilot testing used CIPP samples from both large and small diameter sewers in two cities: Denver, CO and Columbus, OH. For the small diameter (8 in.) sewers in each city, a 6 ft section of pipe and liner was exhumed. For the larger diameter sewers (36 to 48 in. diameter), CIPP liner samples were cut from the interior of the pipe and the liner was patched in situ.

The pilot study report provided a detailed description of the CIPP process, its use in the U.S. and an international scan of the approaches to sewer rehabilitation in other cities worldwide. The development of the sample retrieval and testing protocols used for the retrospective study was also described. Testing on the liners included thickness, annular gap, ovality, density, specific gravity, porosity, flexural strength, flexural modulus, tensile strength, tensile modulus, surface hardness, glass transition temperature, and Raman spectroscopy. In addition, environmental data were gathered as appropriate to each retrieval process including: external soil conditions and internal waste stream pH. The findings from the testing were presented in detail in the report and a short overall summary of the pilot study findings and the information gathered from the international scan is given below (EPA, 2012).

The pilot study activities also produced several review reports on the state of technology for water and wastewater rehabilitation (EPA, 2009, 2010, 2013).

1.3.1 Evaluation of Samples from Denver and Columbus. All of the samples retrieved from the four locations involved in the pilot study testing were in excellent condition after being in use for 25 years, 23 years, 21 years, and 5 years, respectively. Three of these liners had already been in service for approximately half of their originally expected service life. Two samples had a flexural modulus value that was lower than the originally specified value, but this could not be tied directly to deterioration of the liner over time. In the case of the Denver 48-in. downstream liner, in particular, it appeared likely that the poor physical test properties may have resulted from variability within the liner rather than a change over time. Some indication of a softening of the interior surface of the liner that was exposed most to the waste stream (interior invert and spring lines) relative to the interior crown location and that of the exterior surface of the liner was noted in surface hardness testing. However, it is not yet possible to isolate any effect on the resin liner itself from the hydrolysis of the handling layer that was originally present on the inside surface of the CIPP liner. For newer CIPP liners, a different handling/inner layer with greater durability is used, but it is still a softer material than the CIPP resin itself.

In Denver, a few specific defects were noted at different locations in closed-circuit television (CCTV) inspections of nearly 5,800 ft of CIPP liners installed at the same time as the retrieved sample. Most of these were related to poor practices in cutting or reinstating lateral connections and only three appeared potentially unrelated to lateral reinstatement issues. These were a local liner bulge, a separation of the liner from the wall of the pipe, and a local tear in the liner.

Overall, there was no reason to anticipate that the liners evaluated in the pilot study would not last for their intended lifetime of 50 years and perhaps well beyond.

1.3.2 Follow-on Work Recommended in the Pilot Study Report. Given the insights provided by the pilot studies in Denver and Columbus, an expansion of the retrospective evaluation study was recommended to create a broader national database that would help to better define the expected life of sewer rehabilitation technologies. Specifically, it was recommended that the pilot studies and retrospective evaluation program be extended to cover the following activities:

- Additional CIPP sample retrieval in other cities with a wider variety of site and sewage flow characteristics.
- Pilot studies of other sewer rehabilitation technologies, focusing initially on those with the greatest number of years of service. As with the current CIPP study, the pilot study would seek to identify the most useful quantitative tests that could be used to evaluate performance, degradation, and expected remaining life.
- A broader review of the locally interpreted data from cities participating in the study on their experiences with rehabilitation technologies.
- An effort to encourage sewer agencies to keep as-installed material test data for later comparison with follow-up testing. This should include working with the most widely used database and asset management systems to make sure that such information can readily be incorporated and identified using their software.
- Adaptation, development, and/or calibration of non-destructive testing (NDT) methods, plus similar efforts for material test methods that could use small physical samples that are easily retrieved robotically from inside the pipe and for which the damage could be easily repaired. Several quantitative liner characterization tests that could be expected to be developed for robotic deployment within sewer mainlines of 8-in. diameter and larger have been identified as part of this project.

The current work takes up two of the recommendations from the prior work: to develop a database structure for the sharing of performance information on rehabilitation technologies and to collect a wider sample of physical test data and experiential data on such technologies. The results of the pilot study testing and the findings of related studies by others are considered, along with the new evaluations in Section 5 of this report.

1.3.3 Related U.S. and International Efforts. A comprehensive literature review was conducted to summarize information from recent studies of CIPP technology performance. In addition, the international scan undertaken in the pilot study provided some insight into the experiences of a wide range of utilities that have embarked on significant CIPP rehabilitation programs over past decades. The purpose was to assess internationally-based utilities' views on the effectiveness of CIPP rehabilitation and to document any efforts to evaluate and/or monitor the installed quality of their CIPP installations over the long term. The information collected pointed to a number of efforts being made internationally to evaluate the performance of CIPP rehabilitation of gravity sewers in the UK, France, Germany, Singapore, Australia, Japan, and Canada. Information identified relative to CIPP performance and longevity is summarized in Section 4, which addresses key findings from recent studies and this research.

1.4 Organization of the Report

The remainder of the report is organized into the following sections:

- **Section 2 Database Development.** Section 2 describes development of the database for retrospective evaluation data, its user interface, and data mining approaches.
- **Section 3 Rehabilitation Methods and the Retrospective Evaluation Process.** Section 3 introduces the CIPP process and gives an overview of other rehabilitation technologies. The retrospective evaluation process for the collection and testing of physical samples of CIPP liners and other rehabilitation technologies is described.
- **Section 4 Related Studies of CIPP Performance.** Section 4 identifies and summarizes information from related recent studies of CIPP quality control (QC) and in-service performance that have been reported in the literature.
- **Section 5 Summary Results and Common Threads.** Section 5 provides an integrated discussion of the long-term performance of CIPP and the other rehabilitation technologies from all of the information collected by the study to date. It also illustrates potential uses of the database by exploring the CIPP data relationships.
- **Section 6 Conclusions and Recommendations.** Section 6 provides the conclusions from the current work and recommendations for the focus of ongoing studies.

2 DATABASE DEVELOPMENT

2.1 Database Need and Value

This section describes the creation of a database to assemble the test results from the retrospective evaluation study for sewer rehabilitation technologies. A review of insights and data visualizations that can come from the database are presented in Section 5.3 of this report.

The pilot study on retrospective evaluation (EPA, 2012) and the continued evaluation work described in this report have highlighted the importance of understanding the performance of rehabilitation technologies that have been installed over the past 30 plus years. In order to be able to analyze the data being collected (either individually by municipality or across sites) and make it as useful as possible to cities and industries working to improve performance, there needs to be a structure for organizing the data, analyzing the data in different ways, and inputting new data as more are collected. The database developed in this phase of the project provides a platform for such analyses and allows for potential correlations to be explored across any of the test data collected for the liners.

2.2 Database Location and Accessibility

The database is currently being maintained and housed on a TTC server. It is accessible through the following Web link: http://138.47.78.37/Retrospective. The database has been made available online through a Web site constructed using *Microsoft ASP.Net technology* with *C#.Net* and the database software is *MYSQL*. Provisions have been made for both user login and administrative login accounts. In addition, a registration option is also available for new users. The user is asked to provide the following information to register: *Name*, *Organization*, and *Role*. The user also provides their e-mail address, proposed user name, and password. An automated e-mail will then follow from the Administrator to the new user once a request for the opening of an account has been received. Once accepted by the administrator, users are asked to provide their user name and password to access the site. Administrative access is open to the database development and maintenance team only with limited access granted to agencies that are able to contribute data.

2.3 Database Overview

After successful login, the user will be directed to the home page where a brief description of the project is given. As shown in Figure 2-1, the Web site housing the database consists of the following Web pages:

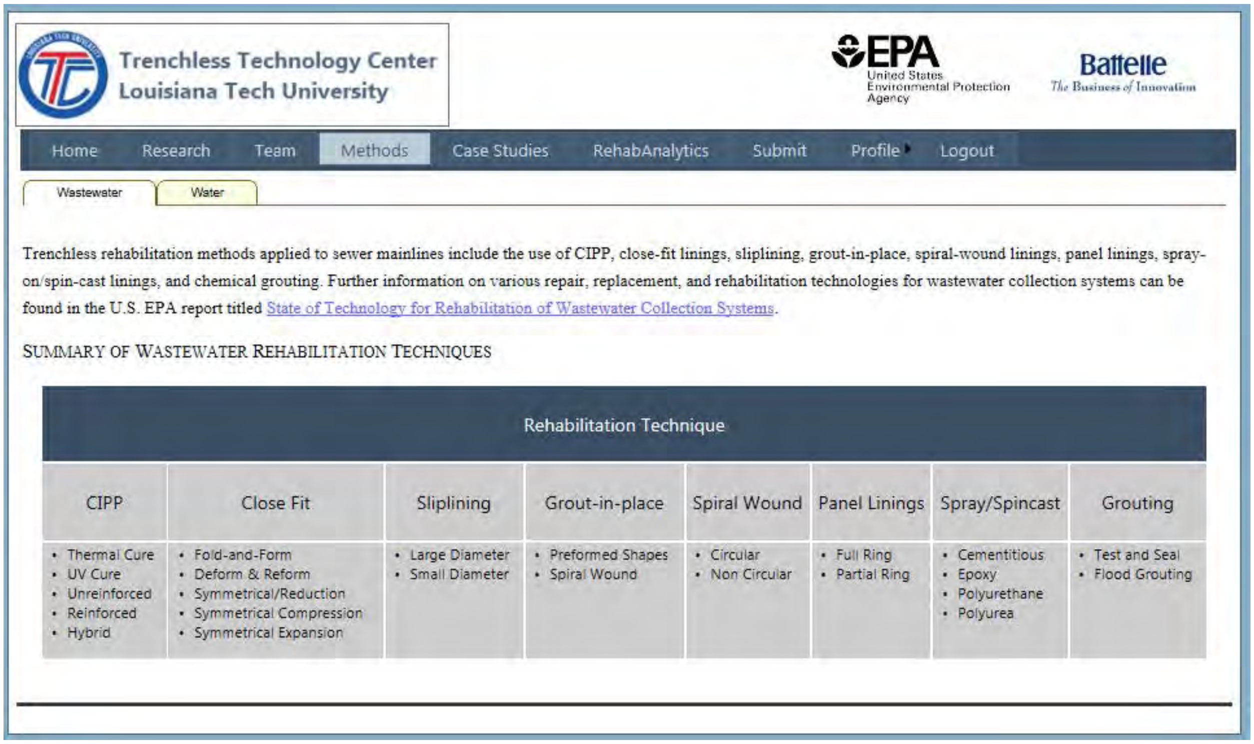
- Home Page,
- Research Page,
- Team Page,
- Methods Page,
- Case Studies Page,
- RehabAnalytics,
- Submit, and
- Account Profile/Login.

Figure 2-1. Home Page of the Database Web Site

Under the *Research* Web page, the overall research objectives for the retrospective study are explained, along with information about the database. The participants on the research team from Battelle Memorial Institute and the TTC, Louisiana Tech University are presented under the *Team* Web page, along with acknowledgments of the participating cities.

Separate tabs for *Water* and *Wastewater* technologies are provided under the *Methods* Web Page (see Figure 2-2). Under the *Wastewater* tab, the various sewer rehabilitation methods included are outlined and links are provided to the specific case studies providing data for each of the four rehabilitation methods – CIPP, deform-reform, fold-and-form, and sliplining – that are a part of the database structure. The *Water* rehabilitation technology tab is provided for the potential extension of the database to include the rehabilitation of water distribution systems.

Retrospective evaluation specimens were collected from different physical locations across North America. In the *Case Studies* tab, access to information and data about the rehabilitation case studies is provided (see Figure 2-3). The data related to each sample were labelled following the naming scheme "Name of the City – Diameter of the Host Pipe – Year of Installation." For example, NYC-15-1989 stands for the test results for the CIPP liner sample installed in a 15-in. diameter sewer line in 1989 from New York City. From this Web page, the user can select a rehabilitation method and download the testing data into a Microsoft® Excel format for review and analysis. The user can select a specific case study to review or select to download all of the data for a particular rehabilitation method. The data downloaded are all of the available raw data.



Rehabilitation Technique							
CIPP	Close Fit	Sliplining	Grout-in-place	Spiral Wound	Panel Linings	Spray/Spincast	Grouting
• Thermal Cure • UV Cure • Unreinforced • Reinforced • Hybrid	• Fold-and-Form • Deform & Reform • Symmetrical/Reduction • Symmetrical Compression • Symmetrical Expansion	• Large Diameter • Small Diameter	• Preformed Shapes • Spiral Wound	• Circular • Non Circular	• Full Ring • Partial Ring	• Cementitious • Epoxy • Polyurethane • Polyurea	• Test and Seal • Flood Grouting

Figure 2-2. Rehabilitation Technology Methods Included in the Database

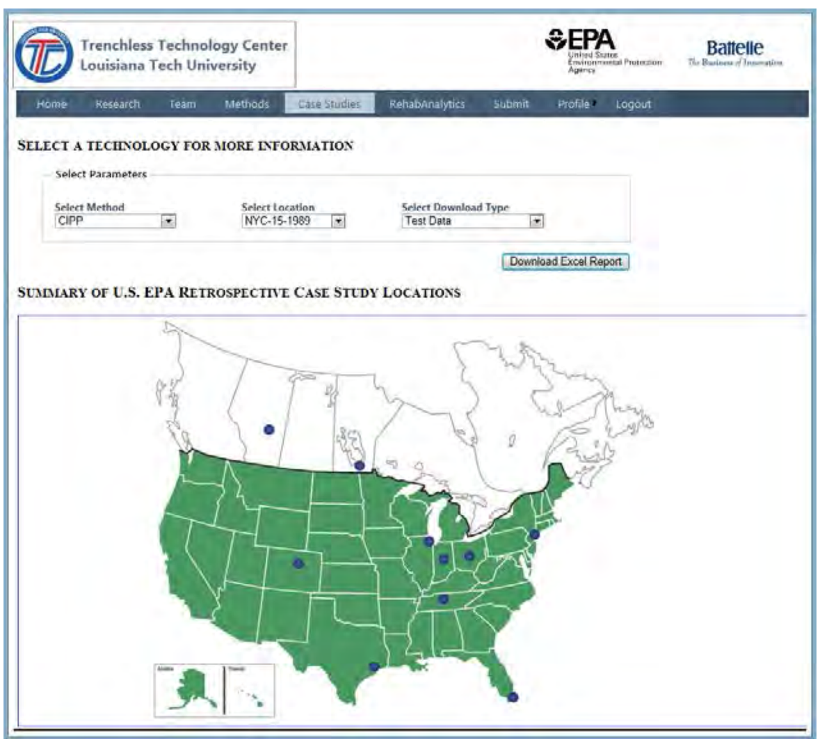


Figure 2-3. Retrospective Case Studies Included in the Database

The *RehabAnalytics* Web page provides direct access to plot and view the data within the database utilizing data mining techniques. Three options are provided to compare different parameters obtained from the test results performed on the exhumed samples. The *RehabAnalytics* is currently designed to plot values for a single technology (e.g., CIPP, deform-reform, fold-and-form, or sliplining). Plots can be generated for a single sample location and/or across all of the sampling locations for a given technology. The types of plots that can be generated by the user with *RehabAnalytics* include the following:

- Mean value plots for a single parameter across all samples;
- Two-dimensional (2-D) scatter plots for the visualization of trends and relationships between two parameters at a time for a single sample or for multiple samples; and
- Three-dimensional (3-D) plots for further visualization of relationships between three parameters at a time.

From the *Mean Values Plot* tab, the user can compare the mean test results for one parameter across all of the exhumed samples for a given technology. Figure 2-4 shows an example plot of the mean values of flexural strength for the CIPP samples. Figure 2-5 shows an example 2-D plot indicating an increasing trend of flexural strength when compared to the tensile strength for CIPP samples. For the 2-D plots, there is also an optional curve fitting function to assist in analyzing trends in the data. Additional example 2-D plots are presented in Section 5.3.

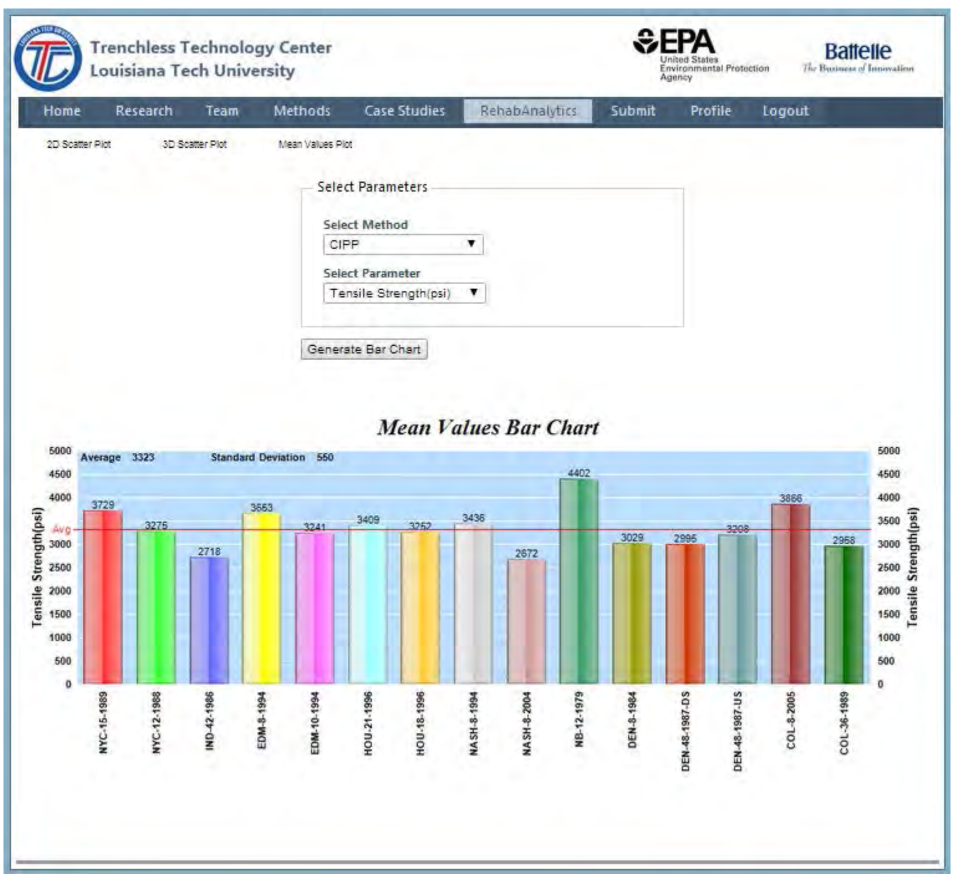


Figure 2-4. RehabAnalytics Mean Value Plot for Flexural Strength of CIPP Samples

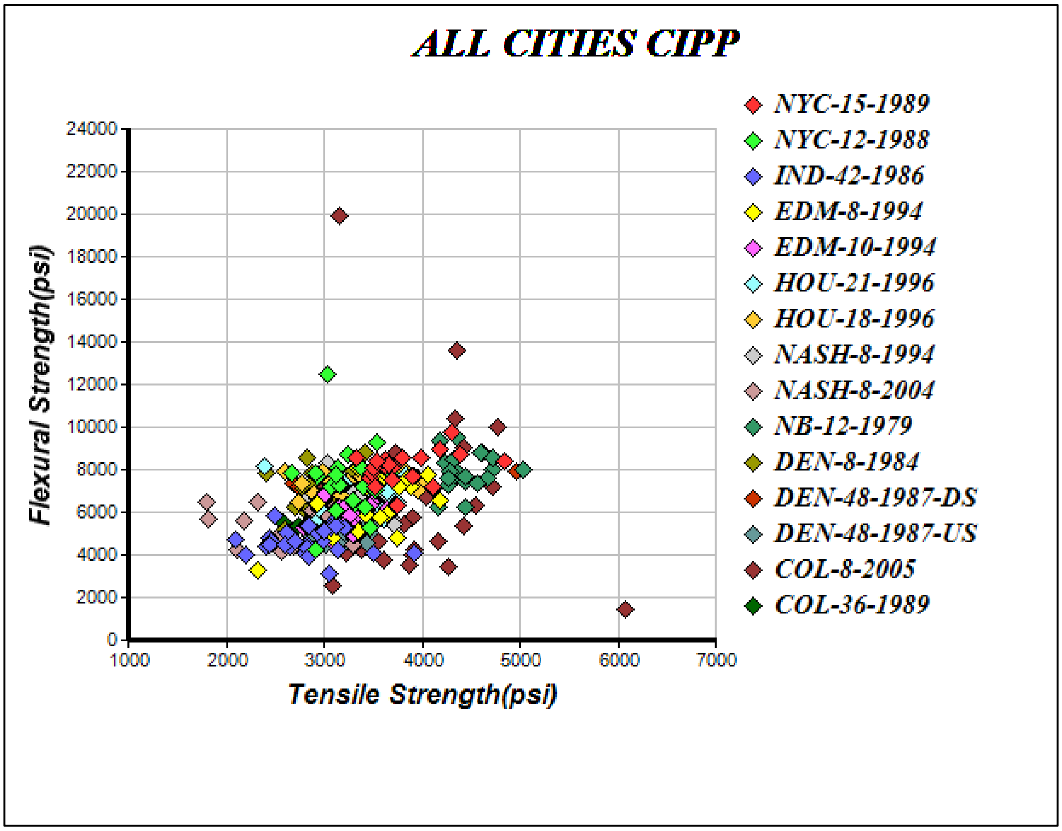


Figure 2-5. RehabAnalytics 2-D Plot of CIPP Flexural Strength versus Tensile Strength

The Web page also makes provision for updating of the database and the uploading of new data into the database, but this function is not accessible to the public. Information provided on the home page invites agencies that wish to contribute data to contact the database administrator so that the type and quality of the data available can be assessed before the data are accepted for inclusion in the database. Once the approval is given, the data contributor can receive a special administrative access to upload the contributed data and its supporting information.

2.4 Database Content

The structure of the database has been targeted towards making the retrospective evaluation test result data on rehabilitation technologies available for analysis by the user and industry communities. Table 2-1 shows the key test parameters currently incorporated into the database for CIPP samples and the planned testing parameters for the additional technologies including deform-reform, fold-and-form, and sliplining. The full database is comprised of two types of information: site background information (Table 2-2) and testing results data (Table 2-3). Site background information about the host pipe and its location, liner, and agency are considered as firm and not likely to be updated. As the sample retrieval and associated data collection work progressed, it became clear that many municipalities do not have complete historic information on the rehabilitation technologies used, specifications at the time of installation, or follow-up evaluations providing any problems identified. Therefore, the site background information listed in Table 2-2 is provided to the extent available from each participant. The test data in the database as listed in Table 2-3 are always listed in an updatable format so that new test results can be incorporated by the administrator as required.

Table 2-1. Retrospective Test Parameters in the Database

Method	Test	Pipe Rehabilitation Method			
		CIPP	F&F PVC	D/R HDPE	Sliplining
ASTM D2122	Thickness	*	*	*	*
ASTM D638	Tensile Strength	*	*	*	*
	Tensile Modulus	*	*	*	*
ASTM D790	Flexural Strength	*	*	*	*
	Flexural Modulus	*	*	*	*
ASTM D792	Apparent Specific Gravity	*	*	*	*
ASTM D2240	Durometer (Shore D) Hardness	*	*	*	*

* Currently included

Table 2-2. Site Background Information Listed in the Database

Firm Parameters	
Agency Assessment Data	**Site Sample Data (continued)**
Agency	Host Pipe Shape
System Type	Host Pipe Diameter
System Length (miles)	Host Pipe Depth
Technology Used	Visual Observations
Technology Length (ft)	Sample Photo
Date First Used	CIPP Type
Frequency of Installation Issues	Liner Design Thickness (mm)
Severity of Installation Issues	Liner Installer
Description of Installation Issues	Tube Manufacturer
Frequency of Long-Term Performance Issues	Tube Material Type
Severity of Long-Term Performance Issues	Tube Material Construction
Description of Long-Term Performance Issues	Sealing Layer Type
Overall Assessment of Long-Term Cost-Benefit Value	Sealing Layer Thickness (in.)
Site Sample Data	Resin Supplier
Rehabilitation Type	Resin Type
Date of Rehabilitation	Resin Trade Name
Approximate Age	Primary Catalyst
Date Collected	Secondary Catalyst
Host Pipe Location	Soil Analysis

Host Pipe Material	

Table 2-3. Updatable Test Data for Particular Samples

Updatable Parameters	
Thickness	Apparent Specific Gravity
Pipe Inside Diameter	Environmental Stress Cracking
Pipe Outside Diameter	Durometer (Shore) Hardness
Density/Porosity	Pipe Stiffness
Tensile Strength	Glass Transition Temperature
Tensile Modulus	Short-Term Liner Buckling Strength
Flexural Strength	Pipe Ovality
Flexural Modulus	Environmental Service Conditions

The main sample test data included are thickness (ASTM D2122), flexural modulus and flexural strength (ASTM D790), tensile modulus and tensile strength (ASTM D638), apparent specific gravity (ASTM D792), and hardness (ASTM D2240). Also included in the database are other specific tests that can aid in the understanding of liner performance and degradation. The procedures for the collection of the main sample test data are provided in Appendix A, along with the specific test protocols followed for the collection of the field samples and their subsequent evaluation and testing.

2.5 Data Interpretation

One of the purposes of assembling the database is to allow for the investigation of correlations among the testing parameters and also in relation to host pipe and service conditions. In order to chart testing results on a 2-D plot, it is necessary to have a value on the "X" axis paired to a matching value on the "Y" axis. However, each test as described above may involve a different number of measurements for replicate specimens from a single sample. For example, the tensile strength testing method (ASTM D638) calls for at least five specimens to be tested for each sample, while for the apparent specific gravity/density (ASTM D792) up to 20 specimens were tested for each sample. This results in an unequal number of measurements for a given sample. Therefore, a dataset with 15 tensile strength values and 20 specific gravity results would result in 15 "paired" results that could be plotted and five "unpaired" specific gravity results that could not be plotted or plotted on one of the axes. While this does not affect the ability to plot the mean values of the data, it does affect the ability to create scatter plots from the raw data for each sample.

To mitigate the unequal number of measurements, additional tests were run above the prescribed minimum values in the ASTM methods (e.g., up to 15 replicates of ASTM D638 and D790 were run versus only five replicates). However, unequal numbers of measurements still exist. A statistical approach was developed to generate estimated or "synthetic" data for plotting purposes only. In this approach, the tensile modulus, bending modulus, bending strength, and hardness were assumed to be functions of density. It was assumed that the relationships between the specimen's density and its tensile modulus, bending modulus, bending strength, and hardness are proportional. The resulting synthetic data would have the same linear relationship to density as the observed data. The data synthesized using this statistical approach are only used for the viewing of trends in the data within the *RehabAnalytics* plotting functions. The statistical approach uses an ordinary least squares regression model. The natural logarithm of each measurement is the independent variable and the natural logarithm of density is the dependent variable as follows:

$$\ln(measurement_i) = \alpha + \beta \ln(density_i) + \varepsilon_i$$

where α is intercept, β is slope, *measurement* is any of the measurements with unpaired values (tensile modulus, bending modulus, bending strength, and hardness) and ε_i is the error associated with the linear model for the ith measurement. The model is fit to the paired observations. The "unpaired" observations are assumed to be distributed at random. Once the linear model is fit, the (natural logarithm) predicted values based on the model are calculated for both the paired and unpaired measurements. Next, the prediction variance associated with each of the measurement predictions is calculated according to:

$$s_{pred}^2 = MSE\left[1 + \frac{1}{n} + \frac{(X_h - \bar{X})^2}{\sum(X_i - \bar{X})^2}\right]$$

which is the prediction variance associated with ordinary least squares regression modeling.

Mean squared error (MSE) of the model is:

$$MSE = \frac{1}{n-2}\sum(observed - predicted)^2$$

where *n* is the number of paired observations used to fit the linear model. A random number from a standard normal distribution with the calculated prediction variance is generated to represent noise in the prediction. The statistical approach uses the Box-Muller transform to generate independent, normally distributed random numbers. The noise was added to the natural logarithm predicted value and then transformed back to the original scale.

To provide an illustration of this statistical transformation process, a specific example is described below. The step-by-step calculation for this example is shown in Table 2-4 and continued in Table 2-5. In this example, 15 tensile modulus values (Table 2-4, Column 2, Tensile Modulus) and 20 density values (Table 2-4, Column 1, Density) are considered related to the NYC-15-1989 sample. In this example it is assumed that the five largest tensile modulus values are unpaired; however, in the algorithm for the database the unpaired values are assumed to be distributed at random. The following steps describe the statistical procedure:

- The magnitudes of the tensile modulus values are in a range 10^4 higher when compared to the density values. Therefore, the 15 available tensile modulus values and the 20 available density values were represented by their natural logarithms (Table 2-4, Columns 4 and 3).
- Next, the intercept (alpha) and slope (beta) of a plot of the 15 available pairs of tensile modulus versus density values were calculated using linear regression. A linear equation was obtained using the calculated intercept and slope values.
- All density values, including the five "unpaired" density values (i.e., those without corresponding tensile modulus values), were then plugged into the equation and predicted values of the natural logarithm of the tensile modulus were calculated (Table 2-4, Column 7, Predicted ln[Tensile Modulus]).
- The errors of the predicted values for the available 15 tensile modulus values were computed (Table 2-5, Column 1, Error) and the mean squared error (Table 2-5, Column 3, MSE) of the tensile modulus values was calculated.
- The mean of the natural logarithms of the 15 corresponding available density values was calculated (Table 2-5, Column 4, Mean[ln{Density}]) and was used along with the MSE to

calculate the variance associated with the prediction of the five "additional" tensile modulus values (Table 2-5, Column 5, Prediction Variance).

- Finally, the noise of the density values corresponding to the five "additional" tensile modulus values was calculated using the Box Muller transformation (Table 2-5, Column 6, Noise) based on which the final value of each "synthetic" tensile modulus value was estimated (Table 2-5, Column 7, Synthetic Tensile Modulus) and used as synthetic data by *RehabAnalytics* to prepare a plot.

Table 2-4. Synthesis of Additional Tensile Modulus Values for Plotting Purposes (Part 1)

Density, pcf	Tensile Modulus, psi	ln(Density)	ln(Tensile Modulus)	Constant in the Model Equation*		Predicted ln(Tensile Modulus)
78.64	462521	4.3649	13.0444			13.2224
82.1	605810	4.4079	13.3143	Alpha	13.58289	13.2189
81.52	532143	4.4008	13.1847	Beta	-0.08258	13.2195
80.47	558672	4.3879	13.2333			13.2205
80.82	533626	4.3922	13.1875			13.2202
80.16	533729	4.3840	13.1876			13.2209
80.89	732320	4.3931	13.5040			13.2201
80.81	535320	4.3921	13.1906			13.2202
80.08	567942	4.3830	13.2498			13.2209
79.03	577666	4.3698	13.2668			13.2220
81.6	537092	4.4018	13.1939			13.2194
84.08	495523	4.4318	13.1134			13.2169
83.25	511923	4.4218	13.1459			13.2177
82.3	584860	4.4104	13.2791			13.2187
80.33	542363	4.3861	13.2037			13.2207
83.12	No Value	4.4203				13.2179
83.79	No Value	4.4283				13.2172
81.21	No Value	4.3970				13.2198
82.31	No Value	4.4105				13.2187
83.85	No Value	4.4290				13.2171

*Model Equation: ln(Tensile Modulus) = alpha + beta*ln(Density); pcf = pound per cubic foot

Table 2-5. Synthesis of Additional Tensile Modulus Values for Plotting Purposes (Part 2)

Error	Squared Error	MSE	Mean (ln[Density])	Prediction Variance	Noise	Synthetic Tensile Modulus
-0.178	0.0317	0.0115	4.3952			
0.095	0.0091					
-0.035	0.0012					
0.013	0.0002					
-0.033	0.0011					
-0.033	0.0011					
0.284	0.0806					
-0.030	0.0009					
0.029	0.0008					
0.045	0.0020					
-0.025	0.0006					
-0.104	0.0107					
-0.072	0.0052					
0.060	0.0037					
-0.017	0.0003					
				0.013835	0.0172	559668.16
				0.015024	0.2248	688320.43
				0.012242	0.1649	649966.78
				0.012829	-0.0822	507093.66
				0.015145	0.1195	619477.04

The "synthetic" values generated by this process are shown in Figure 2-6.

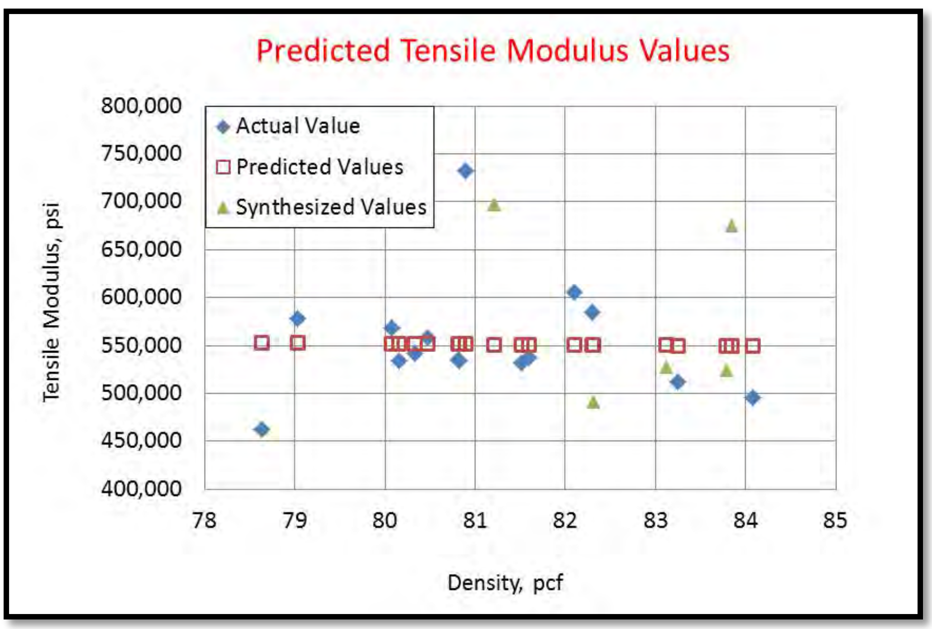


Figure 2-6. Raw and Synthetically-Generated Tensile Modulus Values

Within *RehabAnalytics*, the user can then decide whether or not to utilize this statistical approach by selecting “0,” “50,” “100,” or “500” for the number of synthetic values to be generated (see Figure 2-7). For each set of synthetic values generated, the positions of the unpaired values within the distribution of the data are randomly selected. The “0” mentioned in the dropdown box (see Figure 2-7) indicates that no synthetic values are generated and only “paired” values are plotted. A comparison of “0” synthetic value and “100” synthetic values for HOU-21-1996 is shown in Figure 2-8. Both plots indicate the increasing trend of flexural strength when compared to the tensile strength. It is expected that this synthetic data addition process yields more understandable and consistent visualization of the data in the database, but the user also has the option to download the raw data and use this to create their own plots from the database.

Figure 2-7. RehabAnalytics Generation of Synthesized Values in the Database

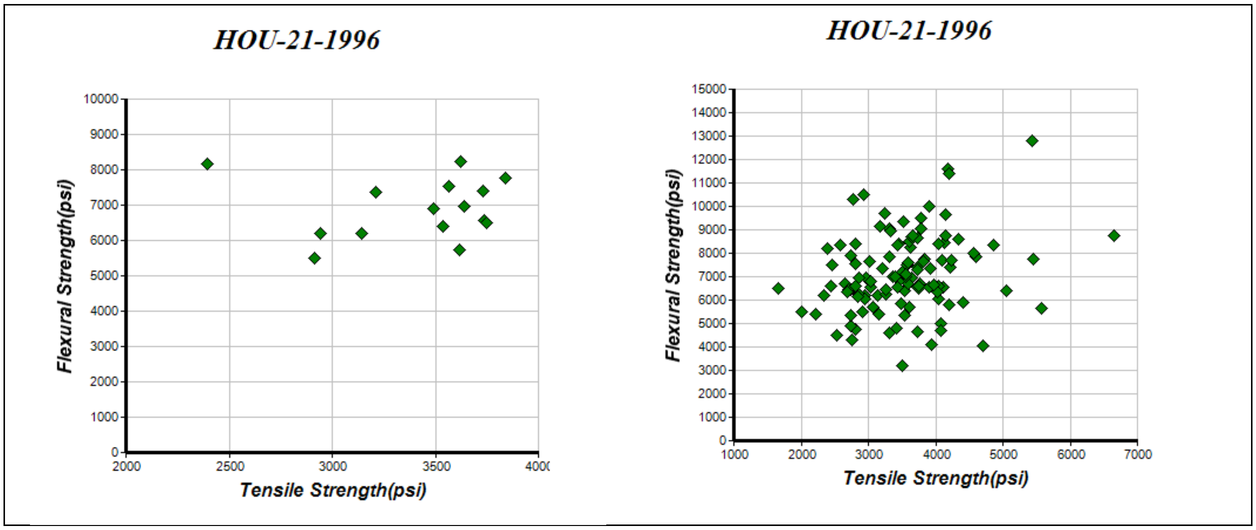


Figure 2-8. No Synthetic Values (left) and 100 Synthetic Values (right) for HOU-21-1996

2.6 Data Mining and Future Applications

The data from the retrospective study were then used in generating plots of interest for further review and analysis. The potential of the current database to identify relationships among the test parameters is explored in Section 5.3 of this report. Recommendations for future work in expanding the database are provided in Section 6.

3 REHABILITATION METHODS AND THE RETROSPECTIVE EVALUATION PROCESS

This section provides a brief introduction to the common methods used for the trenchless rehabilitation of sewer and water systems in North America followed by a description of the approach used to evaluate the performance of selected rehabilitation technologies that had been in service for a significant portion of their anticipated service life. The discussion of both the methods and their testing is divided into "CIPP rehabilitation" and "other rehabilitation technologies" because of the dominant position of CIPP technologies for rehabilitation of sewer systems in the U.S.

3.1 Cured-in-Place Pipe Rehabilitation

This section provides background on the CIPP lining process and describes the protocols used to retrieve and test the retrospective CIPP samples. A detailed description of CIPP lining technology, its variants, design issues and test parameters can be found in the pilot study report (EPA, 2012).

The main focus of the initial retrospective evaluation in both the pilot study and this ongoing work was chosen to be CIPP liners used in gravity sewer systems. This choice was made on the basis of the extensive current use of this technology in the U.S. market. Apart from sliplining, CIPP was the earliest trenchless relining technology used in the U.S. and has liners that have been in service for up to 38 years in the U.S. and up to 43 years in the UK.

CIPP lining involves the impregnation of a liner fabric with a resin either in a factory setting or on site. The saturated fabric contained within one or more sealing layers is then introduced into the host pipe that is to be rehabilitated. Once the liner is in place, it is cured using either heat or ultraviolet (UV) light, depending on the formulation of the resin used. The resulting cured liner provides a close-fit, high-strength lining to the host pipe and is typically designed to extend the life of the host pipe by a minimum of 50 years. Figure 3-1 highlights the main variants in CIPP technologies available today based on tube construction, method of installation, curing method, and type of resin.

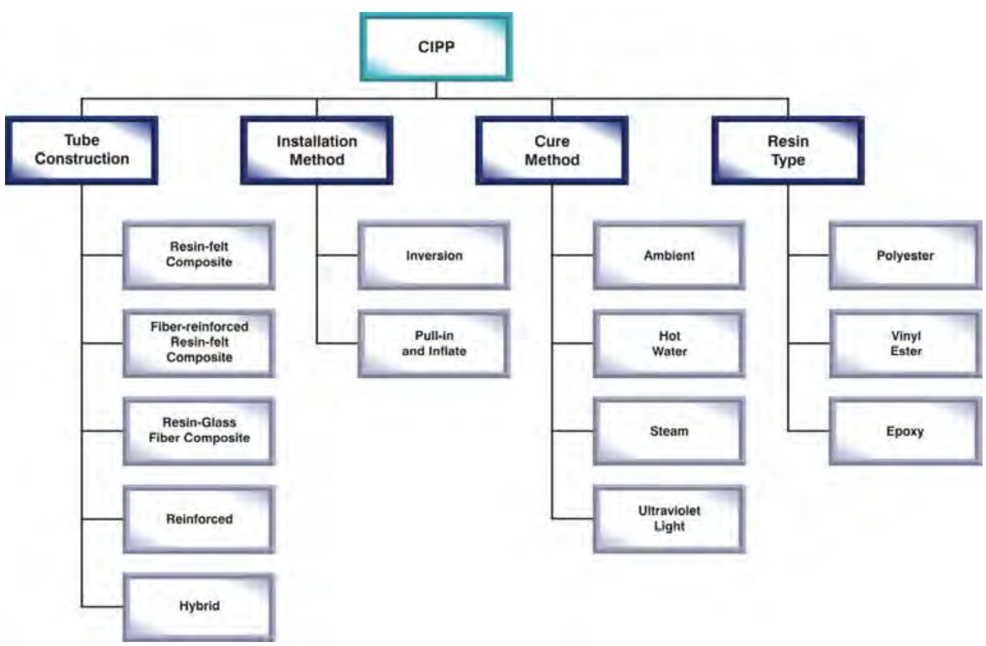


Figure 3-1. Summary of Common CIPP Technologies

The early CIPP product was a needled felt tube, impregnated with polyester resin that was typically inverted into a sewer through a manhole and cured using hot water. This product is still used for gravity sewers. The first known municipal use of a CIPP lining occurred in 1971 in the relining of a 230-ft (70 m) length of the Marsh Lane Sewer in Hackney, East London. This 100-year old brick egg-shaped sewer had dimensions of 3.85 ft × 2 ft (1,175 mm × 610 mm). It should be noted that this first installation was actually a pull-in-and-inflate liner. Inversion was not possible until coated felt was used in 1973 (EPA, 2012).

3.1.1 Pipe Rehabilitation Process Using CIPP. A CIPP project involves a variety of investigative, planning and execution phases. Once a liner has been identified as needing rehabilitation or replacement, the characteristics of the liner and the problems experienced will determine if the CIPP process is a suitable candidate. CIPP is generally available in diameters of 4 to 120 in., depending (especially in the larger diameters) on the supplier's and contractor's capabilities and experience. Guidance on this type of decision can be found in the literature on rehabilitation technologies and from manufacturers and suppliers. Software to support the method selection process also has been developed and a review of such software development can be found in Matthews et al. (2011 and 2012).

Prior to the relining work, the existing host pipe will be carefully examined (typically using a CCTV camera inspection) and any necessary additional measurements (such as pipe diameter) collected. Data on pipe depth, soil type and groundwater conditions will also be gathered.

Based on these data, the following major design parameters would be determined for the use of CIPP in gravity flow sewers:

- Accurate measurements of the internal diameter of the host pipe and any variations in diameter along individual sections of pipe to be relined.
- Any ovality in cross-section dimensions for the host pipe (more than 10% ovality is typically not considered suitable for relining with CIPP because of greatly increased thickness requirements for the liner).
- Whether the host pipe is considered structurally sound (i.e., the lining is not required to support the surrounding soil loading). If the pipe is not considered structurally sound, then additional data regarding the potential soil loading are required including the effect of any traffic loadings on the pipe/liner system.
- The depth of the pipe below the groundwater level (the maximum depth is often used when the groundwater depth varies). This water pressure acts on the outside of the liner through the defects present in the host pipe. The liner thickness is calculated to provide an adequate safety factor against local buckling of the liner under the external water pressure.
- The presence of particular environmental parameters that may affect the liner design and its longevity. Such factors may include the aggressiveness of the groundwater or waste stream within the pipe (e.g. pH or presence of hydrocarbons), the presence of high or low temperatures that may affect curing and/or the apparent creep modulus over the liner lifetime, abrasive internal flows, etc.

The key ASTM standards pertaining to different types of CIPP liner installation are shown in Table 3-1. The structural requirements of the liner are designed for all of the standards using the procedures specified in ASTM F1216. This is based primarily on a formula for the buckling of thin liners restrained within a host pipe. Since a CIPP liner is a thermoset plastic material, it exhibits creep displacements over time under constant load and hence its resistance to buckling over long loading periods is much less than its short-term buckling resistance. This is accounted for in the F-1216 design approach by using an estimate of the effective modulus of deformation of the liner over the planned design life of the rehabilitation. This effective modulus value typically is established by using extended (often 10,000 hour) creep and/or buckling tests for the liner/liner material. The measured values are then extrapolated to the typical 50-year design life values. Much research has been carried out and many papers written on the analysis of long-term buckling in such liners and are referenced in the pilot study report (EPA, 2012).

Table 3-1. Key ASTM Standards Covering CIPP Installations

ASTM F1216	Standard Practice for Rehabilitation of Existing Pipelines and Conduits by the Inversion and Curing of a Resin-Impregnated Tube
ASTM F1743	Standard Practice for Rehabilitation of Existing Pipelines and Conduits by Pulled-in-Place Installation of Cured-in-Place Thermosetting Resin Pipe (CIPP)
ASTM F2019	Standard Practice for Rehabilitation of Existing Pipelines and Conduits by the Pulled in Place Installation of Glass Reinforced Plastic Cured-in-Place Thermosetting Resin Pipe (CIPP)
ASTM F2599	Standard Practice for The Sectional Repair of Damaged Pipe By Means of An Inverted Cured-In-Place Liner

The required thickness of the liner depends on the effective long-term modulus of the liner, its Poisson's ratio, its mean diameter, its ovality and the chosen safety factor, in addition to the external loading conditions provided by the groundwater pressure and/or external soil/traffic loadings. An important factor in the ASTM buckling equation is a correction factor (K) for the degree of buckling restraint provided by the close fit of the liner within the host pipe. However, in typical designs only a single fixed value (K = 7.0) is used for this parameter. Where special environmental conditions such as aggressiveness of groundwater or internal flows and/or temperatures outside the normal range are encountered, the resins used and the design thickness may be adjusted to account for these differences.

In most cases, the application of the ASTM F1216 equations results in a conservative design for the required thickness of the liner (Zhao et al., 2005). Conservatism can occur for a variety of reasons, e.g., because the groundwater loading used for design is seldom at the assumed value, because only a limited section of the pipe has the ovality assumed in the design, because the contractor chooses to exceed the minimum required value of liner modulus to make sure of product acceptance, and/or because the buckling restraint factor is conservative for the application considered. Such conservatism may provide a cushion against unacceptable performance in failure modes not considered explicitly in the design process, e.g. local imperfections in the shape of the host pipe, and accommodate liner flaws that are not identified by the quality assurance (QA) or QC procedures, e.g. locally weak or porous areas of the liner.

Once the liner materials, liner cross-section, curing method and installation procedure have been decided, the project execution can occur. Most CIPP liners are impregnated with resin ("wet out") in a factory setting. A vacuum impregnation process is typically used to allow the resin to flow more easily into the liner fabric and to more fully saturate it. Prior to 2001, this vacuum impregnation process was covered by a patent and, hence, other CIPP lining companies often used modified procedures to work around the patent. After wet out and during transport to the site, thermally-cured liners are kept in refrigerated storage or in a chilled condition to avoid premature curing of the liner.

Small diameter liners (e.g., for sewer laterals) and very large liners may be wet out at the site. For small liners, this may be for convenience and is facilitated by the relative ease of handling a small diameter liner during wetting out. For large diameter liners, the large liner thickness coupled with the large host pipe diameter means that the lay-flat liner becomes too heavy or too wide to transport when wet out. However, on-site wet out puts an extra burden on QC for the impregnation process.

When the impregnated liner is ready, it is introduced into the host pipe to be relined. This can be done by inversion of the liner along the host pipe using water or air pressure or by pulling the liner into place and then inflating it to a close fit using water or air (see Figure 3-2).

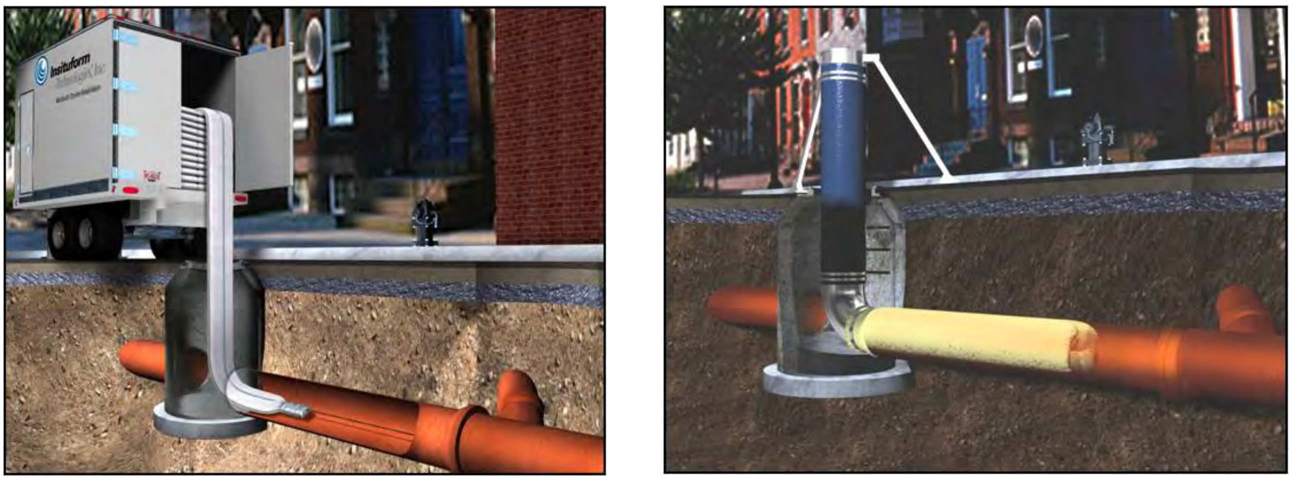


Figure 3-2. CIPP Installation Options: Liner Pull-in (left) and Liner Inversion (right) (Courtesy Insituform Technologies, Inc.)

Once the uncured liner is in place and held tightly against the host pipe, the liner is cured using hot water, steam or UV light, causing the liner resin to become a cross-linked and solid liner material. The curing procedures (time and temperature curves for thermal curing and UV light intensity and advance rate for UV curing) are important in making sure that the full thickness of the liner becomes properly cured and that thermal or other stresses are not introduced into the liner in a partially cured state.

Following the full curing of the liner and removal of any accessory installation materials, the restoration of lateral connections can be carried out. These are typically simply restored by cutting openings at the lateral connection. A dimpling of the liner can aid in the identification of the position of the connection, but such dimpling is less identifiable in liners with higher strength fabrics. If the CIPP liner has a significant annular space and if the connection is not grouted or sealed to the sewer lateral, then this connection can be a source of continued infiltration into the mainline sewer.

3.2 Steps for the Retrospective Study of CIPP Liners

The retrospective testing for CIPP liners in the current study generally followed the progression of activities in the pilot study as outlined below:

- The most effective evaluation tests from the pilot study were chosen to evaluate the current condition of a CIPP liner and provide information on its potential longevity.

- Approval of the liner test protocol by EPA was received through review and approval of the STREAMS TO 1 Quality Assurance Project Plan (QAPP) titled *Retrospective Evaluation of Cured-in-Place Pipe Liners* (Battelle, 2012a).
- The proposed liner evaluation protocol and its expected benefits were discussed with interested municipalities.
- Municipalities identified previously installed CIPP liners with as many years of service as possible.
- Detailed discussions were held with the interested municipalities regarding the division of responsibilities and costs for the field retrieval of samples.
- Once the sites were agreed upon, the detailed planning of the sample retrieval was undertaken, the field work carried out, and the test sections/samples shipped to the TTC for testing.
- The test data for each site were collected and evaluated. Comparisons with the pilot study data and the qualitative evaluations of CIPP lining performance were made.
- The data were included in the newly formulated database structure.

Under the current work, samples from 13 CIPP liners from seven cities were obtained and tested. One additional sample was defective (NY sample 1). Its retrieval and condition is described in Appendix B but the sample was not subjected to detailed testing and is not included in the overall sample count. This was in addition to the samples from five CIPP liners from two cities that were obtained in the pilot study as discussed in Section 1.3. The summary results of the pilot study testing are compared with the test results obtained in this research phase in Section 5.

3.3 Testing and Measurement Protocols for CIPP Liners

The testing and measurement protocols used are described in Appendix A. The parameters to be measured included visual inspection, environmental service conditions, annular gap, liner thickness, ovality, specific gravity, tensile strength/modulus, flexural strength/modulus, surface hardness, glass transition temperature, and porosity. ASTM testing standards were followed according to the parameter being measured. Where ASTM standards were not available (e.g. visual inspection, annular gap, liner thickness, ovality and environmental service conditions), the procedures used, numbers of measurements, specimen photos, etc. are provided either in Appendix A or B. The following principal ASTM test standards were used in the laboratory testing of the current retrospective samples (a full list of ASTM Standards mentioned in the report is provided in Appendix E): specific gravity (ASTM D792), tensile properties (ASTM D638), flexural properties (ASTM D790), hardness (ASTM D2240) and glass transition temperature (ASTM D1356). The testing parameters also depended on the size of the sample retrieved. For example, ovality and buckling tests were only applicable to whole pipe samples collected from small diameter pipes. In some cases, due to the sample retrieval process, the site conditions or the host pipe/liner condition, it was not possible to collect all of the data for all of the samples. The specific information collected for each sample is provided with the discussion for each test location in Appendix B. This appendix describes the data collection, analyses, and project documentation in accordance with EPA NRMRL's QAPP Requirements for Applied Research Projects (EPA, 2008) and the project-specific QAPPs (Battelle, 2012a; 2012b; and 2013).

3.4 Overview of Other Rehabilitation Technologies

3.4.1 Wastewater. As shown in Figure 3-3, a variety of trenchless rehabilitation methods have been or can be applied to sewer mainlines including the use of CIPP linings, close-fit linings, grout-in-place, spiral-wound linings, panel linings, spray-on/spin-cast linings, and chemical grouting. Pipe repair (e.g., repair sleeves or short CIPP liners) and pipe replacement methods (e.g., sliplining and pipe bursting) can also be carried out using trenchless technology approaches. These all represent an alternative to the traditional dig and replace method of sewer renewal. Further information on these various repair, replacement, and rehabilitation technologies can be found in companion EPA reports (EPA, 2009, 2010). The 2010 report (EPA, 2010) also contains datasheets for most of the products/technologies available in the U.S. Both reports are available for free download from the EPA Aging Water Systems website (URLs are provided in the reference section at the end of this report). The test results for the retrospective pilot study of fold-and-form (polyvinyl chloride [PVC]) lining, deform-reform (high density polyethylene [HDPE]) lining, and sliplining are also included in this report.

Wastewater collection systems also may include pressure sewers (force mains) to convey sewage when gravity flow is not the preferred option. Rehabilitation technologies for pressure sewers have more in common with the rehabilitation technologies used in water distribution systems than those used only for non-pressure sewerage applications. While they are a potential future target for retrospective evaluation, they are not included in the current phase of the research.

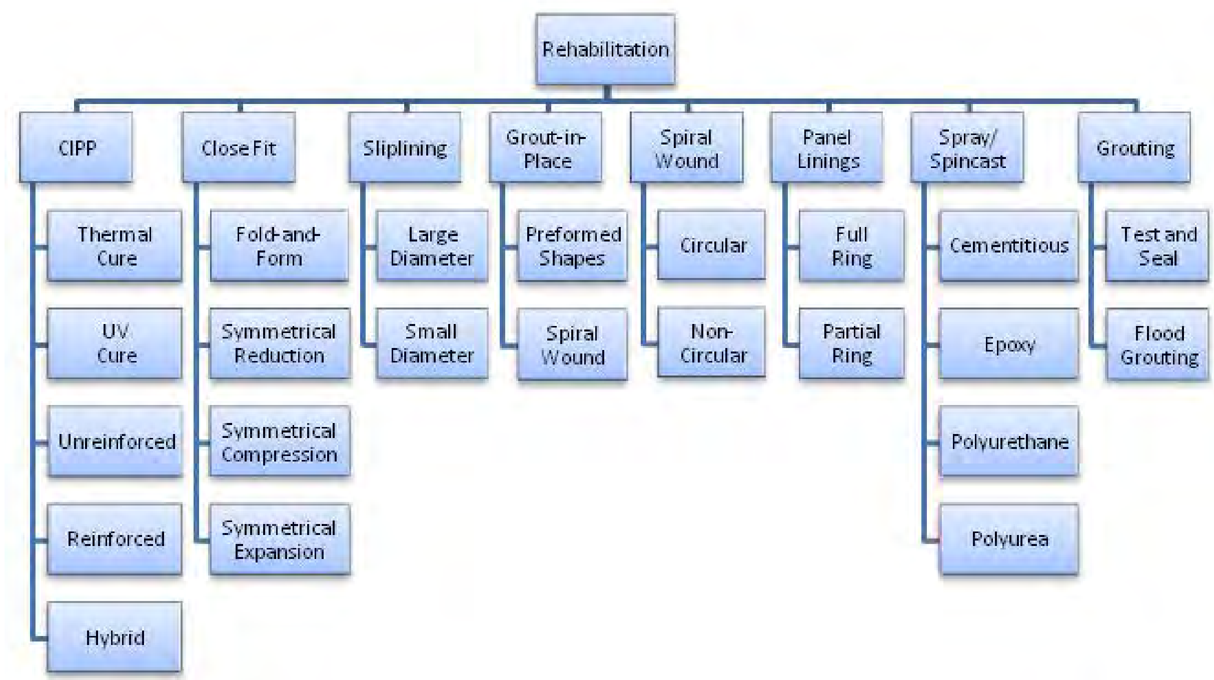


Figure 3-3. Summary of Trenchless Sewer Rehabilitation Technologies

3.4.2 Water. Trenchless rehabilitation methods for water mains are shown in Figure 3-4 and include the use of spray-on-lining, sliplining, CIPP, inserted hose lining, and close-fit lining systems (EPA, 2013). Trenchless rehabilitation for water mains typically relies upon the existing pipe becoming part of the renewal work. If the rehabilitation is to provide only corrosion protection, or the existing pipe is only partially deteriorated, then the remaining structural strength of the existing pipe can be incorporated into the fabric of the completed system. For fully deteriorated water mains, the existing pipe acts merely as a right-of-way or a platform for the installation of a fully structural liner that must be designed to carry all of the imposed internal and external loadings. Sliplining, which can be considered a replacement method because a completely new line is inserted inside the old line, also is included for further consideration in a future retrospective study of water main renewal. Other repair and replacement methods (e.g., pipe bursting) are available, but are not considered as candidates for a future retrospective study at this time.

Trenchless water main rehabilitation using spray or spincast linings was the earliest form of water main rehabilitation, but the principal use of these linings has been to provide corrosion protection or taste control within the water main. Structural spray or spincast linings that have the capability to resist internal pressures, while spanning defects within the host pipe, are a later development. Fully structural sprayed linings have only been tried in the U.S. in the last few years.

Sliplining has been used for renewing pressure pipes for many years (particularly in the gas industry), but since it often requires increased system pressures to compensate for the loss of pipe diameter, it has some limitations on its use.

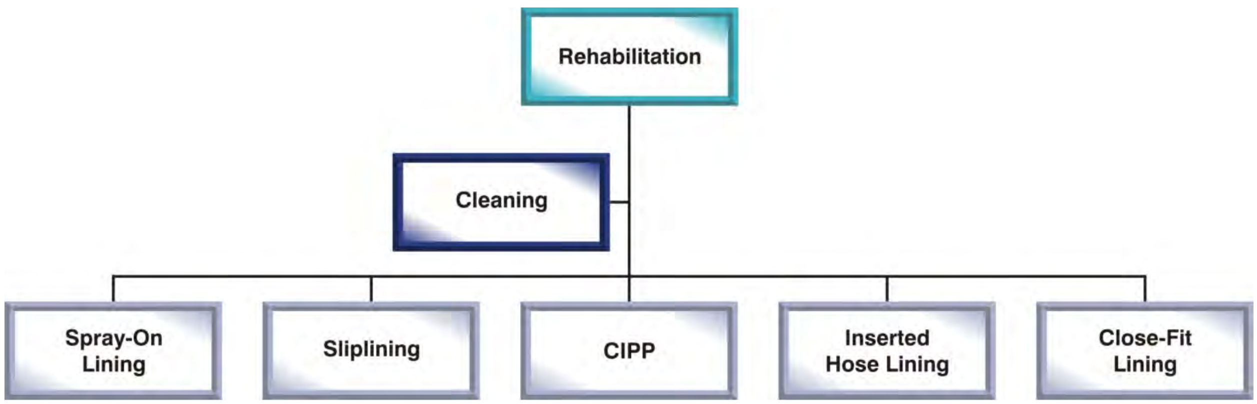


Figure 3-4. Rehabilitation Approaches for Water Mains (EPA, 2013)

Close-fit linings, created by inserting a reduced diameter lining pipe within the host pipe and then expanding it or re-rounding it to fit tightly, emerged in the U.S. in the 1990s.

Hose liners are relatively thin and flexible liners inserted within a pressure pipe that are only designed to withstand the internal pressure loadings in service. The host pipe must continue to resist all the external loads.

CIPP liners for water main rehabilitation have many similarities to the CIPP systems used in gravity sewers, but the application to smaller diameters, the internal pressure resistance requirements, and the requirements of being applied in a drinking water system means that considerable adaptation is required. CIPP for water mains now has a 15+ year history for trenchless rehabilitation in North America.

The interest in trenchless rehabilitation of water systems has been increasing in the U.S. in recent years. Now that structural linings, as well as corrosion protection linings, have reasonable lengths of time in service, it is considered very worthwhile to extend the retrospective evaluation to water system rehabilitation technologies.

3.5 Other Technologies Considered for Evaluation in the Current Phase

As mentioned earlier in this section, the current phase of the research expanded on the number of sites for CIPP evaluations, as well as started to gather information on the long-term performance of other rehabilitation technologies. To identify the most appropriate technologies for evaluation along with the interest of municipalities in providing samples, a review of issues, difficulties, and opportunities for the principal forms of rehabilitation technologies other than CIPP was conducted. A brief summary of the evaluations in terms of suitability for the current phase of the work is given below.

- Newer CIPP systems including UV cure and reinforced liner systems are gaining in application, but have less time in service compared to standard CIPP installations. With the main focus of the research to date being on CIPP, it was desired to address other rehabilitation technologies before adding other CIPP variants.
- Sliplining has a long history of use and has been considered in the two categories of large diameter sliplining and small diameter sliplining. The large diameter applications would allow the removal of samples from the pipe wall by person entry. However, the techniques for patching and the arrangements for access/bypass can present significant barriers. Smaller diameter sliplining often involves continuous lengths of pipe and hence functions more as a replacement pipe than a rehabilitated pipe. Sliplining samples were recovered for testing in this phase of the research as one of the oldest replacement techniques used by the City of Houston, which participated in the study.
- Close-fit linings for sewer application have typically comprised fold-and-form (PVC) and deform-reform (HDPE). Although neither is marketed in the U.S. at present, there is a reasonable service life for samples in some municipalities. Municipalities were available that could provide samples and it was considered worthwhile to study these systems as a guide to municipalities that have such systems and as a guide for evaluating issues should future similar systems come to the market. Samples for both fold-and-form and deform-reform were recovered in this phase of the research.
- Grout-in-place linings and panel linings are typically large diameter installations and access/bypass issues are similar to those for large diameter sliplining. There are, however, installations with reasonable lengths of service around the country.
- Spiral wound linings have been used in small diameter sewers and also as grout-in-place linings in larger diameters. However, they have not been used in many cities and hence it is necessary to find a municipality with older spiral wound installations that are willing to participate in the study. For the larger diameter applications, access/bypass expenses remain issues.
- Spray and spincast lining technologies are mainly applied to manholes within the sewer sector. Manhole rehabilitation technology evaluation is considered an important topic, but is not part of the current research scope.
- Rehabilitation (infiltration and inflow [I/I] sealing) by grouting is an important technique with quite different cost and application criteria when compared with relining strategies. It is considered very worthwhile to collect better information on the longevity and performance issues for grouting applications, but the sampling and evaluation protocols present significant difficulties due to the nature of the process. The precise locations of grouting within a main and the contractor procedures/pressures/materials, etc. used are often unknown for a particular section to be evaluated, complicating any evaluation. It was decided not to include grouting evaluation in this phase of the research.
- Water main rehabilitation technologies are a good target for future evaluations, but were deferred until a later phase of the research because, with the exception of corrosion protection linings, the application of the technologies is more recent than for sewer systems.

- Force main (pressure sewer) rehabilitation technologies also should be a future target, but the same issues apply as for water systems and sewer force mains are not as prevalent as gravity sewer mains or water distribution mains.

3.6 Testing and Measurement Protocols for Fold-and-Form (PVC), Deform-Reform (HDPE), and Sliplining

The retrospective evaluation protocol outlined in the STREAMS TO 1 QAPP was extended to include the additional rehabilitation technologies to be studied in this phase of the research (Battelle, 2013). Additional testing and measurement protocols suitable for each technology under consideration were added to the amended QAPP including both field and laboratory measurements and the changes/additions are presented in this section. Table 3-2 lists the key ASTM standards relating to the installation of fold-and-form liners, deform-reform liners and slipliners. The testing and measurement protocols for these rehabilitation technologies are listed in Appendix A.

Table 3-2. Key ASTM Standards Covering Fold-and-Form (PVC), Deform-Reform (HDPE), and Sliplining

Standard	Description
ASTM D1784	Standard Specification for Rigid Poly(Vinyl Chloride) (PVC) Compounds and Chlorinated Poly(Vinyl Chloride) (CPVC) Compounds
ASTM D3350	Standard Specification for Polyethylene Plastics Pipe and Fittings Materials
ASTM F585	Standard Guide for Insertion of Flexible Polyethylene Pipe Into Existing Sewers
ASTM F1504	Standard Specification for Folded Poly(Vinyl Chloride) (PVC) Pipe for Existing Sewer and Conduit Rehabilitation
ASTM F1533	Standard Specification for Deformed Polyethylene (PE) Liner
ASTM F1867	Standard Practice for Installation of Folded/Formed Poly (Vinyl Chloride) (PVC) Pipe Type A for Existing Sewer and Conduit Rehabilitation
ASTM F1871	Standard Specification for Folded/Formed Poly (Vinyl Chloride) Pipe Type A for Existing Sewer and Conduit Rehabilitation (Withdrawn 2011)

4 RELATED STUDIES OF CIPP PERFORMANCE

In this section, a number of recent and ongoing studies of CIPP performance, QA, and longevity are briefly summarized together with a summary of the findings from the international scan carried out during the pilot study (EPA, 2012). The findings from these studies are then included as appropriate in the discussion of CIPP performance provided in Section 5 and in the overall conclusions from the report. General findings are presented from the literature worldwide including U.S. studies (Section 4.1), Canadian studies (Section 4.2), international scan (Section 4.3), European studies (Section 4.4), and Asian and Australian studies (Section 4.5).

4.1 U.S. Studies

Summaries of the prior pilot study phase of this project have appeared in several journal papers and conference proceedings (Alam et al., 2011; Allouche et al., 2011; Allouche et al., 2014), as well as in the full report available on the EPA Web site (EPA, 2012). The overall findings were summarized in Section 1.3 and are not repeated here.

A paper by Harada et al. (2011) provides an excellent summary of the issues affecting the in-place CIPP liner thickness, as well as appropriate techniques to sample the thickness to ensure that the minimum design thickness is being met. The paper also draws together test data from the Institute für Unterirdische Infrastruktur GmbH (IKT) in Germany showing the proportion of liners tested that met the thickness specified over the years from 2003 to 2008 (see Table 4-1). The IKT reports and their references are provided in Section 4.4.

Table 4-1. IKT Test Results for Wall Thickness

Year	% Passing
2003/2004	79.2-100.0
2004/2005	86.4
2006	82.7
2007	87.8
2008	92.1
2010	89.1
2011	96.2

Source: Harada et al., 2011; IKT, 2011

On a related topic, Shah et al. (2008) present a benchmarking study carried out by the City of Los Angeles to compare the design parameters used to determine the specified CIPP liner thickness.

A paper by Porzio (2014) examines quality issues and the water tightness of CIPP especially regarding deterioration or blistering of the coating and subsequent leakage through the liner.

Muenchmeyer (2007) presents an overview of CIPP quality issues and how the growth and fragmentation of the industry creates QA issues. He outlines the generally more stringent QA/QC requirements in

Europe. Lee and Ferry (2007) discuss the issue of estimating the design life for CIPP rehabilitation in relation to the testing of the creep properties of the liner. The importance of estimating the effective modulus reduction of a liner subjected to continuous loading over 50 years compared to short-term flexural tests is discussed and possible errors in interpreting laboratory creep tests identified. The paper provides some proposed specifications to balance the cost of testing versus the assurance of long-term performance, but does not provide any field evaluation of liner performance over time.

A paper by Herzog et al. (2007) described a study conducted to compare the mechanical properties of field samples from CIPP liners with samples prepared in the laboratory. The conclusions from the study that involved 10 field generated samples and three laboratory prepared samples were as follows:

- The processes used in the field to create the samples are fairly consistent job to job.
- The field application of the CIPP process generates a high degree of cure in the composites.
- The variation found in the degree of cure seen in the samples does not cause any of the differences seen in the physical properties of the composite.
- The tensile properties are not influenced by the percent of resin in the resin/felt composites.
- The tensile properties are not influenced by the difference in the surface quality between the field and laboratory samples.
- The flexural properties are not influenced by the percent of resin in the resin/felt composites.
- The difference in the surface quality between the field and laboratory samples only has a minor effect on the flexural modulus.
- The difference in the surface quality between the field and laboratory samples has a major effect on the flexural strength.

A paper by Shelton (2012a, 2012b) presents data obtained from CIPP inspections over a 6-year period following the introduction of both post-rehabilitation and warranty inspection requirements. The inspections encompassed approximately 50 miles of mainline liners, varying in diameter from 8 in. to 42 in. and approximately 1,200 lateral liners plus review of approximately 5 miles of liners installed under other programs of an earlier vintage (5 to 15 years). The CIPP installations involved cover many different contractors/manufacturers in the U.S. and all of the major variants of CIPP relining materials and processes. The findings of the inspections revealed a frequent occurrence of several types of defects including pinhole leaks, seam defects and delamination or fraying of the sealing layer. Some defects were discernible in the post-rehabilitation inspection, but more became evident in the warranty inspection. The warranty inspection was initially conducted at 12 to 18 months after rehabilitation, but because of the evidence that defects worsened with time and that more defects became visible, the warranty inspection period was extended to 2 to 3 years following rehabilitation. The paper also provides hypotheses for the causes of the defects and specification changes used to help eliminate the defects seen for the various types of CIPP liners according to the site conditions for installation.

Further information on CIPP experience in the U.S. was obtained through discussions with U.S. municipalities participating in the retrospective study (see Appendix D of this report). The lengths installed by individual municipalities ranged from 39,400 ft to approximately 1.5 million ft. All had used thermal cure CIPP and one municipality also reported using UV cure CIPP. The first thermal cure CIPP installations among these municipalities were in the 1970s in New York.

For thermal cure CIPP, the utilities indicated the severity of the installation issues for CIPP to be “almost none” to “minor” and primarily occurring at an estimated frequency below 4% (four out of five participating utilities). Four of the five utilities reported the severity of long-term performance issues for CIPP to be “almost none” to “minor” with one listing this as “moderate.” The occurrence of such long-term performance issues was assessed at an estimated frequency below 4% (five out of five participating utilities). The overall assessment of long-term cost-benefit value for thermal cure CIPP was deemed to be “high” for all of the participating municipalities.

The types of installation issues indicated included the following:

- Wrinkles/folds in liner; poorly sized liner
- Missed taps or over/under cutting
- Failure of resin to cure /inadequate curing resources
- Collapse of liner
- Rough cuts on taps
- Inconsistent resin impregnation
- Care and experienced installers a requirement for success
- Premature resin curing
- Resin slugs in laterals
- Inability to span voids
- Inadequately prepared/televised pipe
- Styrene odor complaints for larger diameter installations.

The key long-term performance issues identified were as follows:

- Delamination of sealing layer
- Excessive wrinkles causing constriction in main
- Wrinkles impact cleaning and CCTV
- Infiltration at lateral openings
- Roots still enter main from non-rehabilitated laterals
- Large piece of CIPP liner found on wastewater treatment plant screen.

Other key issues related to CIPP rehabilitation were as follows:

- Maintenance practices need to be modified/controlled to avoid damage
- Used in larger diameters where loss of cross-section is less important
- Pipe bursting preferred when diameter less than 15 in. and depth less than 15 ft; CIPP preferred for diameters between 24 in. and 108 in.
- Tried and true method; continuing to use CIPP; product holds up well
- Great product, but still have some water entering the system through annular space

- Good results for both thermal and UV-cure CIPP; no long-term failures.

4.2 Canadian Studies

Papers by Macey and Zurek (2012) and Macey et al. (2013) report on the QA program for CIPP lining undertaken by the City of Winnipeg, Manitoba, Canada, which has a sewer system that serves approximately 700,000 people. The city and its consultant also provided physical samples for testing under the program described in this report. These results are provided in Appendix B.

Winnipeg commenced sewer rehabilitation with CIPP in its first trial installations in 1978; CIPP has been used for approximately 75% of the annual rehabilitation program from 1998 to date. The papers present the results of 34 years of QA testing in terms of ASTM D790 flexural modulus of elasticity and flexural strength testing. Most test results in the city's database are from the completion of construction, but retrospective testing on retrieved samples recently has been carried out. The data compiled represent one of the most comprehensive databases of CIPP flexural modulus and strength values in North America.

It was reported in the Macey and Zurek (2012) paper that the database included over 1,500 separate D790 tests for both flexural strength and flexural modulus. Given that each test is comprised of at least five individual tests, the results include the testing of over 7,500 samples. The paper provides graphs of flexural strength and flexural modulus data separated by the type of sampling used (plate sample, confined pipe sample, or tail end sample) and flexural modulus data grouped by contract. At the time of the Macey and Zurek (2012) paper, physical testing was under way for two CIPP liners installed in 1978.

The Macey et al. (2013) paper provides more background on the early installations of CIPP in Winnipeg (in 1978 and 1984) and the evolution of the program into the principal means of renewing sewers in Winnipeg. The test data mentioned in the 2012 paper and presented at the 2012 conference are documented in the 2013 paper. The liners tested were specified to have a minimum flexural modulus of 240,000 psi (1654 MPa), flexural strength of 8,200 psi (~56.5 MPa) and a tensile strength of 4,130 psi (28.5 MPa). They had a nominal thickness of 6 mm, which was shown in the paper to be a smaller thickness than if the liners were designed following current practice. The 2012 test results after 34 years in service are shown in Table 4-2. A third liner installed in 1984 was reported to be scheduled for recovery and testing at the time of writing of the 2013 paper. The full set of flexural data also was provided for inclusion in the database and the average value results are included in Table 5-1 and 5-8.

Table 4-2. City of Winnipeg Test Results for 34-Year Old CIPP Liners

Parameter	Kingsway Liner (454 mm [18 in.] host pipe at 3.76 m [12.3 ft] depth)		Richard Liner (762 mm [30 in.] host pipe at 5.40 m [17.7 ft] depth)	
	Low End MPa (psi)	High End MPa (psi)	Low End MPa (psi)	High End MPa (psi)
Flexural Modulus	1,881 (272,816)	2,586 (375,068)	3,092 (448,457)	3,144 (455,999)
Flexural Strength	38 (5,511)	51 (7,297)	50 (7,252)	58 (8,412)

MPa = megapascal

While there was a wide variation of the results between the sites, the paper provided the following observations:

- All CIPP samples exhibited good, non-brittle material characteristics
- All of the flexural modulus testing was above the specified initial properties
- All of the flexural strength tests, save one, exhibited values very near their initial specified values
- The only low flexural strength value was associated with a liner with visible installation related issues.

The paper also commented on the excellent visual appearance of the CIPP lined sewers in the city based on the city's ongoing sewer condition assessment program.

A paper by Alzraiee et al. (2013) describes a physical testing program that was used to verify the structural integrity of CIPP liners in the Province of Quebec, Canada, which had been installed in 2001. Tests were conducted on sewer pipe samples with nominal host pipe diameters of 450 mm (18 in.) and 300 mm (12 in.) retrieved from two locations in Quebec, after 10 to 11 years in service. The host pipe depths were reported as approximately 1.5 m (5 ft) (only 1 depth provided in the paper) and 3 m (10 ft) long sections of host pipe and liner were retrieved at each site and each cut into three approximately 1 m (3.3 ft) long samples providing six samples in total. The samples were retrieved and tested in 2011. Flexural (ASTM D790) and tensile (ASTM D638) testing were conducted, along with measurements of thickness and annular gap. Testing of four of the samples as a pipe-liner system was mentioned in the paper, but no results were provided. Results were compared with physical and structural design parameters used at the liner design stage and with test results published for another (unidentified) city for liners with an age of 30, 26 and 20 years of service.

The liner was reported to be designed for 2,758 MPa (400,000 psi) flexural modulus and 27.6 MPa flexural strength (4,000 psi). The flexural modulus design value exceeds the ASTM F1216 minimum value (250,000 psi), but the flexural strength design value reported is lower than the ASTM F1216 minimum value (4,500 psi). The C12 liner samples were reported to have the larger sample thickness although the C12 diameter was reported to be smaller than the C14 samples. Average annular gaps between the liner and the host pipe were generally small for four of the six samples (around 0.5 to 0.7 mm). One sample had essentially zero annular gap but the final sample had a large annular gap on one side of the sample (up to 20 mm) with the other side of the liner being tight to the host pipe.

In Table 4-3 abstracted from the 2013 paper, the main test results are summarized. It is assumed that the tensile moduli were reported incorrectly and should have been perhaps 1,000 times greater to bring them into the same range as expected tensile modulus results but they have not been adjusted in the table shown here.

Table 4-3. Retrospective Test Data from Quebec

Sample Sets	Design Min. Thickness (mm)	Av. Sample Thickness (mm)	Av. Tensile Breaking Stress MPa (psi)	Av. Tensile Elongation at break (%)	Av. Tensile Modulus MPa (psi)	Av. Flexural Modulus MPa (psi)	Av. Flexural Strength MPa (psi)

(C12)	7	8.29	19.85 (2879)	3.50	1.75 (254)	-	-
(C14)	5	6.94	24.38 (3536)	10.33	5.16 (748)	-	-
(C12/ C14)	Combined set	7.88	-	-	-	3,460 (501,830)	45.85 (6,650)

Source: Alzraiee et al. (2013)

A follow-up paper (Alzraiee et al., 2014) presents the results of laboratory controlled deflection tests conducted on the liner samples within their vitrified clay host pipe. The tests demonstrated the influence of the CIPP liner on the structural response of the liner host pipe system.

Papers by Araujo et al. (2009, 2010, Araujo and Yao, 2014) explore the potential variability in CIPP test results according to the choices made in sample selection and preparation allowed within the relevant ASTM standards. Variations of several tens of percent in the measured parameters are possible depending on the way that the sample is prepared from the curved liner, whether the surface layers are removed or not, the location within the thickness of the samples and the orientation of the specimen (longitudinal or circumferential). The 2010/2011 paper documented the extent of variation seen and the 2014 paper examined the underlying root causes. These were shown to relate both to the conditions of preparation of the "representative" sample in the field and to how the nature of the sample affects the testing. In the 2014 paper, important testing issues were shown to be: whether the test sample is machined to a parallel sided specimen or tested at full liner thickness, where within a liner thickness a parallel-sided specimen is cut, variation in thickness for full thickness specimens, stress concentrations arising from the contact of the curved liner surface with the support and loading mechanism of the test equipment for full liner thickness specimens, and the influence of a soft sealing layer on the deflection of the specimen measured in the test (affecting the modulus determination).

4.3 Summary of International Scan Findings in the Pilot Study

The utilities interviewed for the international scan conducted under the previous EPA pilot study reported a clear trend in the quality of CIPP work (EPA, 2012). Early installations did suffer from problems such as wrinkling, blistering, and poor reopening of lateral connections, but these issues have been reduced as installers gain experience. The need for trained and experienced installers and for clear and proven installation procedures properly followed was mentioned by several utilities as being key to successful installation. The utilities commented that the curing and cooling cycle is the element of the process that requires closest supervision and monitoring. This is because contractors try to save time in this stage, and this can result in inadequate curing, leading to problems of service life.

The utilities typically used post-installation CCTV surveys and/or an I/I test for in-situ performance testing. The performance test is generally an in-situ water tightness test to look for exfiltration. Most, but not all, of the utilities take samples from the installed liners for testing to verify that the installation meets the specification requirements. The liner parameters that may be tested were: flexural strength, flexural modulus, tensile strength, tensile modulus, water tightness, hardness and thickness. In addition to the process verification and post-works inspections, there is generally a contractual requirement that the contractor provide a warranty for the work.

Of the utilities interviewed, four had taken samples for testing from CIPP installations after a period in service, one had undertaken CCTV surveys after 10 and 15 years in service, and had done so after 12 years of service in one line. In general, the findings from these investigations after a period in service had indicated that there was no serious deterioration in performance of the CIPP linings. None of the findings had raised concerns over the service life, and those defects found were often considered to be installation issues rather than inherent weaknesses of the products themselves. However, cleaning with high pressure water jets was noted to be a potential cause of liner damage. More details on the findings of the international scan are presented below in Sections 4.4 and 4.5.

4.4 European Studies

Lystbaek (2006, 2007) describes a project initiated in 1999 to follow up on the field performance of CIPP liners installed since the early 1980s in Aarhus, Denmark. Five different installations were included in the follow up with a total of six samples and it was intended to repeat the testing of these installations at five yearly intervals (Table 4-4). All the liners included in the sampling had been installed in 1991 to 1992. The host pipes were at depths of 1 to 4 m (3 to 13 ft) in a residential area with light traffic and a normal residential wastewater stream.

Table 4-4. Retrospective Liner Sampling in Denmark

Sample	Impregnation No.	Installed	First Sampling	Second Sampling	Diameter/ Wall thickness
Pipe 1	575/92	Aug 27-28, 1992	16-17 Nov 1999	11 Apr 2005	200 mm/6 mm
Pipe 2	574/92	Aug 27-28, 1992	16-17 Nov 1999	8 Apr 2005	200 mm/6 mm
Pipe 3	574/92 A	Aug 27-28, 1992	16-17 Nov 1999	11 Apr 2005	200 mm/6 mm
Pipe 4	044/91	Jan 28, 1991	4-5 Apr 2000	11 Apr 2005	400 mm/9 mm
Pipe 5	345/92	June 1, 1992	4-5 Apr 2000	8 Apr 2005	250 mm/6 mm
Pipe 6	050/91	Jan 30, 1991	None	26 Apr 2005	500 mm/9 mm

Source: Lystbaek, 2007

The various quality parameters for CIPP lining considered in the paper are shown in Table 4-5 together with their relation to International and European standards. The referenced paper provides a discussion of their applicability and value.

Some of the test results reported in the paper are highlighted in Tables 4-6 and 4-7. It was noted that the samples taken at the time of installation were unrestrained samples taken in the manhole, whereas the study samples were recovered from the pipe itself.

The modulus values for all three sets of tests were well in excess of the 250,000 psi minimum modulus required in ASTM F1216. Due to the sample differences noted above, the paper author focused on the comparison of the 1999-2000 data with the 2005 data and did not find any clear trends (some modulus values increased and some decreased). Likewise, the density values varied slightly across the samples and test periods, but no overall trends could be observed and all of the densities were within a range of

1.15 g/cm^3 to 1.29 g/cm^3. Most (but not all) of the samples showed an increase of water absorption over the 14-year service period, but in no case did the water absorption exceed 1.5% by weight.

The 50-year creep modulus testing indicated that the mean long-term modulus across all of the samples recovered in 1999-2000 was 303,274 psi with a coefficient of variation of 0.13. The 2005 test results gave a mean long-term modulus of 312,121 psi with a coefficient of variation of 0.19. The 1999-2000 testing indicated an effective 50-year long-term modulus at 59% to 65% of the short-term modulus. The 2005 testing indicated a range of 50% to 71% for the same ratio. For Sample 1 only, the 1999-2000 testing was extended to 20,000 hours to allow an extrapolation of the creep test results to a 100-year effective modulus. The testing for this sample indicated that the ratio of the 100-year effective long-term modulus to the short-term modulus was 55%.

Table 4-5. Application of Quality Parameters and Test Standards

Quality Parameters	Testing Standard	Structural Design	Operation of the System	Specific for the Product
Wall thickness		X		
E modulus (3 point)	ISO 178	X		
Flexural stress σ_{fb}	ISO 178	X		
Flexural strain ε_{fb}	ISO 178	X		
Water Absorption	ISO 62			X
Density				X
Ring E modulus (wet)	EN 1228			
Ring E modulus (dry)	EN 1228	X		
Water content				
Residual Styrene	ISO 4901			X
Creep Modulus	EN 761	X		
Root infiltration	CCTV		X	
Self-cleaning ability	CCTV		X	
Coefficient of variation*		X		

Source: Lystbaek, 2007
* Long-term E modulus as 50-year values.
Italicized parameters indicate data from the original installation are available.

Table 4-6. Three-Point Flexural Test Data (ISO 178)

Average Values	E modulus (psi)			Flexural Stress (psi)			Flexural Strain (%)		
	1991/ 1992	1999/ 2000	2005	1991/ 1992	1999/ 2000	2005	1991/ 1992	1999/ 2000	2005
Pipe 1	379274	380434	561296	5656	5802	5482	1.70	1.60	0.98
Pipe 2	378403	421189	456434	5366	5366	5091	1.60	1.30	1.18
Pipe 3	378403	458464	474998	5366	5076	5743	1.60	1.10	1.25
Pipe 4	347655	597700	502266	5802	7107	6643	2.30	1.20	1.35
Pipe 5	404800	541716	498059	6237	6382	6425	2.00	1.20	1.31
Pipe 6	-	-	536204	-	-	6730	-	-	1.30

Source: Lystbaek, 2007
50 mm wide samples – weft direction, support 100 mm; values converted to Imperial Units.

Table 4-7. Average Water Absorption (ISO 62) and Density

Sample	Water Absorption (% of weight)			Density (g/cm^3)		
	1991-1992	1999-2000	2005	1991-1992	1999-2000	2005
Pipe 1	0.80	0.90	1.12	1.28	1.28	1.29
Pipe 2	0.70	1.40	1.12	1.22	1.23	1.20
Pipe 3	0.70	1.10	1.50	1.22	1.16	1.20
Pipe 4	0.69	0.17	0.43	1.16	1.28	1.25
Pipe 5	0.93	0.61	1.04	1.15	1.25	1.18

Pipe 6	-	-	0.99	-	-	-

Source: Lystbaek, 2007

CCTV inspection of the selected pipe sections was carried out prior to the original renovation and at subsequent sampling periods. Prior to renovation, pipe failures, displaced joints and infiltration of roots could be seen. The root infiltration had resulted in obstructions and sedimentation. Since the renovation, it was reported that there have been no signs of root infiltration or critical obstructions in the sampled installations. The conclusions of the paper were as follows:

> *"The test results verify that the longevity of cured-in-place pipes can by all indications be expected to be minimum 100 years. There are further signs that the ring stiffness test of samples taken at the time of installation is representative for an assessment of the CIPP longevity. The product variation over the length of the CIPP installation is an area requiring further study. Simulated tests have consequently been implemented in order to determine the size of the variation and also to find the sampling place that is most representative for the installation."*

It was reported that long-term laboratory testing to establish the 100-year effective creep modulus values was being carried out on the 2005 samples and that the liners would continue to be resampled every 5 years (Lystbaek, 2007).

In a study by Bosseler and Schlüter (2002), 15 CIPP rehabilitation liners (including hot water, steam and UV cure) installed from 1991 to 1998 were evaluated and for three of the liners, 2 m long sections of the host pipe and liner were removed for further evaluation and testing.

Problems, issues, and findings from the study included the following:

- Quality tests and construction site specimens were not made or taken as a rule in the installations evaluated in this study. Since the quality achieved at the time of the repair was not checked and documented, it was difficult to estimate the maximum utilization period of the repaired sections considered.
- Damage was noted in CCTV inspection of all the sections. As a rule, these were limited spatially and in most cases were clearly the result of individual execution errors such as crease formation in the longitudinal and annular directions and erroneous bonding of lateral inlets.
- For eight sections, comparison could be made with a post-installation inspection video. The majority of the above damage could already be recognized immediately after installation. When compared with the new inspection data, it was not possible to notice any mentionable change in the liner through the effects of operation.
- The damage intensity and frequency in the sections studied were categorized as slight on the basis of the inspection results. However, leakage and tree root issues were noted at lateral connections and manhole terminations.
- The sectional leakage tests on the sections revealed satisfactory results in seven out of 10 instances.
- Leakage test results on connection liners were poor.
- The newer construction measures showed a lower quantity of damage patterns resulting from execution errors (i.e., creases in the lateral, longitudinal and annular directions as well as incorrect connections). This indicated improvement of installation quality over time.

- Some issues were seen in terms of obtaining the material values used in the static calculations under certain circumstances.

The Bosseler and Schlüter paper led to significant ongoing work by the IKT on the testing and evaluation of rehabilitation technologies. More information on the range of testing carried out by the IKT can be found at www.ikt.de/english. The series of reports on the evaluation of CIPP liner quality are of particular interest in the context of the current report. References include IKT (2004, 2011) and Waniek and Homann (2006, 2007, 2008, and 2009). These reports provide test results on liner properties at installation, including flexural modulus, flexural strength, liner thickness, and water tightness. The full results are not summarized here, but the test results on liner thickness are summarized in an extension of the table produced by Harada et al. (2011) and shown in Table 4-1. It is clear that, in Germany, the percentage of liners installed at the design thickness has been increasing more or less steadily since 2004.

Gumbel (2009) reviews the international development of testing standards for CIPP and compares practices between Europe and North America. Key topics of the paper are the determination of long- and short-term stiffness characteristics coupled with the use of ring or three-point flexural tests. Field sampling and test selection as a function of liner size and wall structure are reviewed as well as some further tests proposed for use in estimating long-term performance and/or providing enhanced QC.

Summarizing information from the international scan carried out in the pilot study (EPA, 2012), the overall impressions of CIPP suitability were reported by the different European countries as:

- In Germany, Göttingen now considers CIPP to be an excellent long-term repair technology with a service life of 50 years and that it can make individual pipes watertight. But it does not meet their requirement of achieving a permanent, watertight network due to the problems of sealing the liners at service connections and manholes. Leverkusen had concerns over the resistance of CIPP to water jetting used for cleaning. Their view was that quality of installation has improved significantly since the 1990s, especially in areas such as reopening of laterals. Testing has also improved so the overall standard has improved dramatically. Leverkusen was considering introducing infrared spectroscopy to its type of testing to ensure that the correct resins are used.
- In the UK, Thames Water is satisfied that its established system, using preferred contractors, delivers value for money. This experience is considered important in eliminating installation defects which are the main source of performance problems later on. The experience of Severn Trent Water also has been generally good. They report some problems with liner stretch, missed connections, wrinkling and re-rounding severely deteriorated pipe prior to lining.
- In France, the Agglomeration de Chartres uses CIPP to reinforce sewers where there is high risk of root penetration. The condition of lateral connections and frequent displaced pipes means that CIPP is considered ineffective in combating I/I. The Agglomeration des Hauts-de-Bièvre considers CIPP to be a reliable method that will remain the main one used for sewer rehabilitation works. They now enter into annual contracts with one contractor only to ensure experience and quality, and do not use a competitive tender for each project. In 14 years of CIPP usage, only two projects were considered to have failed: a 200 m (656 ft) installation at a very difficult location could not be completed; and a 500 m (1,640 ft) installation was taken out because of poor installation and curing control. This represented approximately 2% of the total length installed to date.

4.5 Asian and Australian Studies

No specific papers were found in the literature search from Asia and Australia that discussed retrospective evaluation data or approaches. However, summarizing information from the international scan carried out in the pilot study (EPA, 2012), the overall impressions of CIPP suitability were reported by some different countries as follows:

- In Singapore, more than 80% of the lining undertaken to date is CIPP and this was expected to continue to be the case in current and future phases of work. The specifics of the methods used have evolved to meet the needs of a tropical climate and the rigorous performance requirements of the Public Utilities Board (PUB) for Singapore. As a result, PUB considers CIPP to be a viable, long-lasting means of achieving a watertight sewerage system.
- In Australia, the situation is different because of the predominance of polyethylene and PVC fold-and-form and spirally-wound linings. Sydney Water has used such plastic liners for rehabilitation for over 25 years. Use of CIPP has been limited mainly to patches, private sewers and laterals and, more recently, junctions. Queensland Urban Utilities in Brisbane also makes greater use of PVC and polyethylene-based lining systems than of CIPP. It shares the concerns of the other utilities over jetting for cleaning in CIPP-lined pipes. The utility considers that CIPP is a valuable technology when the right product is used in the right conditions, but that it is important to understand its limitations and risks.
- In Japan, at a site level, CCTV examination, measurement, sampling, and testing are required on all installations in accordance with Japan Sewerage Works Agency regulations and many sites are re-examined after one year. Regarding quality controlled testing of liner materials after curing, most municipalities are requesting a test of the actual cured liner. However, their requirement varies municipality by municipality.

4.6 Summary

The above findings indicated that CIPP rehabilitation is considered, by the owners using it, a reliable technique with a good track record but that it should be recognized that CIPP mainline rehabilitation does not generally ensure a "watertight" sewerage system. As a site-constructed lining process, a number of defects can occur at the time of installation which must be guarded against and design decisions about the features and/or implementation of the CIPP method may affect the ability of the CIPP approach to provide a full solution to obtaining a leak-free sewer system.

Few problems have been found so far with long-term performance except that maintenance practices must be adapted to avoid damage to the liners. The data presented in the reported studies and the experiences related by the owners involved are considered, along with the findings from the current study in Section 5 of this report.

5 SUMMARY RESULTS AND COMMON THREADS

The detailed results for the current case studies are presented in Appendix B for CIPP liners and in Appendix C for other rehabilitation technologies. This section is intended to summarize the test results and to look for any indications of liner deterioration and/or the overall longevity of the liners that may be expected. The CIPP test results from the current 13 sites are presented in Section 5.1; these CIPP results are integrated with those from the previous four sites from the pilot study in Section 5.2 where trends of properties with liner age and correlations with other liner properties also are explored. The use of the database of test results is explored for the CIPP samples in Section 5.3. The test results for the other rehabilitation technologies evaluated are discussed in Section 5.4.

5.1 Current CIPP Case Studies

Table 5-1 gives the average results for key parameters tested for each CIPP site in the current study.

Table 5-1. Summary of Key Laboratory Test Results from Current Case Studies

Location	Liner Age (years)	Average Values							
		ASTM D638 (psi)		ASTM D790 (psi)		Specific Gravity	Shore D Hardness		Thickness (mm)
		Tensile Strength	Tensile Modulus	Flexural Strength	Flexural Modulus		Inner	Outer	
Edmonton 1 (10 in.)	19	3,241	436,710	6,135	331,333	1.25	68.6	78.1	4.7
Edmonton 2 (8 in.)	19	3,653	510,132	6,816	364,788	1.25	68.2	79.2	4.8
Houston 1 (21 in.)	17	3,409	465,322	6,893	337,638	1.17	61.2	61.3	10.7
Houston 2 (18 in.)	17	3,252	450,985	7,204	338,565	1.18	65.4	75.7	11.0
Indianapolis (42 in.)	25	2,718	351,294	4,712	237,264	1.08	57.4	65.7	22.2
Nashville 1 Dunston (8 in.)	19	3,436	375,807	6,832	301,724	1.14	65.2	72.2	5.6
Nashville 2 Wyoming (8 in.)	9	2,672	400,926	5,497	282,460	1.21	64.6	67.4	7.1
New York 2 (15 in.)	23	3,729	554,101	7,978	477,609	1.31	73.3	72.1	7.3
New York 3 (12 in.)	24	3,275	324,406	7,200	285,177	1.15	57.7	58.7	7.1
Northbrook (12 in.)	34	4,402	433,541	7,761	322,360	1.19	65.6	76.0	4.7
Winnipeg 1 Richard (30 in.)	34	(a)	(a)	8,592[b]	452,134[b]	1.21	57.4	65.8	6.6
Winnipeg 2 Kingsway (18 in.)	34	(a)	(a)	6,779[b]	323,930[b]	1.14	54.1	60.9	6.7
Winnipeg 3 Mission (30 in.)	28	(a)	(a)	4,469[b]	245,753[b]	1.07	57.3	64.9	22.8

(a) Samples received at TTC not large enough to test for this parameter.
(b) Samples received at TTC not large enough to test for this parameter but test data for the liners was received from City of Winnipeg. See also Table 4-2 in this report showing the data from Macey et al. (2013).

A full set of results were obtained from 10 sites in the U.S. and Canada with additional test results from three sites in Winnipeg for which the sample sizes received at the TTC precluded ASTM D638 and D790 testing as a part of this study. For the flexural properties of the Winnipeg samples, however, such testing had been carried out by the city itself and flexural strength and flexural modulus test data were provided to the project. These external data are included in the database and in the presentation and discussion of the results. Summary flexural data also are reported in Macey et al. (2013) for Winnipeg Samples 1 and 2 (see Table 4-2).

5.1.1 Visual Inspection. The visual condition of all of the liners in the current study (with the exception of the New York Sample 1) was deemed to be excellent. New York Sample 1 was found to be largely unsaturated with resin and was not included in the determination of other physical properties. A new sample was added in New York (New York Sample 3) to replace this sample.

The sealing layer was found to be in place in some sites (e.g., in the two 20-year old Edmonton samples and in the 34-year old Winnipeg 2 sample), but missing for others (e.g., the 23-year old New York Sample 2).

5.1.2 Annular Gap. Annular gaps were measured wherever possible in the field and/or in the laboratory. It was not always possible to measure the field values due to site configurations and/or conditions. In addition for panel samples, where the field samples were cut out from within the liner, annular gap measurements were not possible in the laboratory. The available observations are summarized in Table 5-2.

The liners were generally quite tight to the host pipe and the annular gaps did vary around the circumference of the host pipe. Where annular gaps could be measured, they were mostly less than 0.08 in. (2 mm) and often much less than this value. The Northbrook liner had a localized region around the circumference with a maximum annular gap of about 0.42 in. (10.7 mm). This was noted to occur at approximately the 5 o'clock position within the liner.

Table 5-2. Annular Gap Observations for the Current Case Studies

Sample	Annular Gap Observations
Edmonton 1 (10 in.)	Either tight or with annular gap less than 0.04 in. (1 mm)
Edmonton 2 (8 in.)	Either tight or with localized annular gap up to 0.08 in. (2 mm)
Houston 1 (21 in.)	N/A
Houston 2 (18 in.)	N/A
Indianapolis (42 in.)	Annular gap less than 0.02 in. (0.4 mm)
Nashville 1 Dunston (8 in.)	Annular gap less than 0.03 in. (0.8 mm)
Nashville 2 Wyoming (8 in.)	Annular gap less than 0.05 in. (1.2 mm)
New York 2 (15 in.)	Either tight or less than 0.01 in. (0.2 mm) (measured in field)
New York 3 (12 in.)	N/A
Northbrook (12 in.)	Varies from 0.01 in. (0.2 mm) to localized value of 0.42 in. (10.7 mm) at 5 o'clock position
Winnipeg 1 (30 in.)	N/A
Winnipeg 2 (18 in.)	N/A
Winnipeg 3 (30 in.)	N/A

N/A = Sample only retrieved and no field measurements possible

5.1.3 Soil and Pipe Sediment pH Values. The pH values of soil samples and any sediment inside the CIPP liner were measured for many of the sample sites and the results are tabulated in Table 5-3. The pH values for sediment retrieved from inside the pipe varied from approximately 4 to 11. The pH values for the external soil samples varied from approximately 4 to 9. There was no consistency in the results as to whether the pH values were higher inside the pipe or outside the pipe. Together with the depth of the host pipe (affecting potential traffic and groundwater loadings) and any comments from the municipality about their impressions of the severity of the environmental condition, these data provide only a preliminary assessment of the lifetime environmental exposure for the liner. It is not considered, however, that the impact of any severe exposure conditions were captured in the retrospective samples recovered to date.

Table 5-3. Measurements of pH for the Current Case Studies

Sample	Inner Pipe Sediment pH	External Soil pH
Edmonton 1 (10 in.)	7 to 8	N/A
Edmonton 2 (8 in.)	N/A	8 to 9
Houston 1 (21 in.)	4 to 5	5
Houston 2 (18 in.)	6 to 7	4 to 5
Indianapolis (42 in.) (2 panels)	5 and 6 to 7	6 to 7 and 6 to 7
Nashville 1 Dunston (8 in.)	10 to 11	N/A
Nashville 2 Wyoming (8 in.)	9 to 10	6 to 7
New York 2 (15 in.)	N/A	N/A
New York 3 (12 in.)	N/A	N/A
Northbrook (12 in.)	6 to 7	6 to 7
Winnipeg 1 (30 in.)	N/A	N/A
Winnipeg 2 (18 in.)	N/A	N/A
Winnipeg 3 (30 in.)	N/A	N/A

N/A = Sediment or soil sample not available for testing

5.1.4 Liner Ovality. Liner ovality was measured whenever a full circumference liner sample could be retrieved. The measurement procedures are described in Appendix B. The ovality measurement results are provided in Table 5-4.

The maximum liner ovality measured was 5.75% for an individual reading within one sample. The minimum ovality measured was around 0.35%. Liner ovality reduces the resistance to buckling of an oval liner compared to an otherwise equivalent circular liner and this effect is included in the design equations in ASTM F1216. If the ovality of a host pipe is significant, then the in-place ovality should be measured. Otherwise, a minimum value of ovality can be assumed to cover unmeasured variations and conditions.

5.1.5 Liner Thickness. The liner thicknesses for the 13 sites in the current study were measured and the results presented in Table 5-5. The thinnest liner was 4.6 mm thick for a 19-year old liner in a 10 in. inner diameter host pipe at a depth of approximately 9.8 ft below ground in Edmonton. This liner was found to have a flexural strength of 6,135 psi and a flexural modulus of 331,333 psi both still well above the ASTM requirements at installation. The thickest liners were 22.8 mm for Winnipeg Sample 3 in a 30 in. diameter host pipe and 22.2 mm in the Indianapolis sample in a 42 in. diameter host pipe. Both of these thickest liners were found to have low specific gravities and low strength and modulus properties as discussed in Section 5.1.6.

Table 5-4. Measured Liner Ovality for the Current Case Studies

Sample	Liner Ovality
Edmonton 1 (10 in.)	2.7% to 4.3%
Edmonton 2 (8 in.)	4.5 % to 5.75%
Houston 1 (21 in.)	1.4%
Houston 2 (18 in.)	1.7%
Indianapolis (42 in.)	N/A
Nashville 1 Dunston (8 in.)	3.7%
Nashville 2 Wyoming (8 in.)	3.6%
New York 2 (15 in.)	N/A
New York 3 (12 in.)	N/A
Northbrook (12 in.)	0.33% to 0.38%
Winnipeg 1 (30 in.)	N/A
Winnipeg 2 (18 in.)	N/A
Winnipeg 3 (30 in.)	N/A

N/A = Ovality measurement not possible because only a panel sample was available

For most of the liners, the design/specified thickness of the liner at the time of installation could not be retrieved from the records. Where this thickness is available, the measured thickness is compared with the specified value in Table 5-5. Two liners had thicknesses less than that specified (at 78% and 93% of the specified value) and two liners had thicknesses more than that specified (at 110% and 112% of the specified value).

Table 5-5. Measured and Specified Liner Thickness for the Current Case Studies

Sample	Measured Thickness (mm)	Specified Thickness (mm)	Average as Percent of Specified Value
Edmonton 1 (10 in.)	4.66 ± 0.21	5.0	93 %
Edmonton 2 (8 in.)	4.76 ± 0.21	-	-
Houston 1 (21 in.)	10.65 ± 0.35	-	-
Houston 2 (18 in.)	10.95 ± 0.23	-	-
Indianapolis (42 in.)	22.39 ± 0.21; 21.92 ± 0.21	-	-
Nashville 1 Dunston (8 in.)	5.60 ± 0.32	-	-
Nashville 2 Wyoming (8 in.)	7.05 ± 0.28	-	-
New York 2 (15 in.)	7.27 ± 0.26	-	-
New York 3 (12 in.)	7.09 ± 0.27	-	-
Northbrook (12 in.)	4.66 ± 0.21	6.0	78 %
Winnipeg 1 (30 in.)	6.60 ± 0.68	6.0	110 %
Winnipeg 2 (18 in.)	6.69 ± 0.31	6.0	112 %
Winnipeg 3 (30 in.)	22.83 ± 3.11	-	-

Note: The as-specified thickness was often not available from municipalities for the retrieved samples.

5.1.6 Specific Gravity. The specific gravity of all 13 liners included in the current study was determined using ASTM D792 and the results are listed in Table 5-1. The average specific gravity determined for each of the 13 liners varied from a low of 1.07 to a high of 1.25. There is no requirement for a particular specific gravity for a CIPP liner, but as can be seen in Section 5.2.7, the specific gravity of a liner does show correlation with the structural liner parameters and can be an indication of the quality of the liner. The lowest specific gravities (1.07 and 1.08) were measured for the two thickest liners (22.8 mm and 22.2 mm respectively). These liners (the Indianapolis liner in a 42 in. diameter host pipe and the Winnipeg 3 sample in a 30 in. diameter host pipe) both had the lowest flexural strength and flexural modulus values in the current study. This may indicate that thicker liners demand particular attention to make sure that the appropriate specific gravities and strength/modulus properties are achieved.

Additional measurements of porosity were tried using a mercury vapor intrusion test, but these tests produced unrealistically high specific gravities and were not included in the results presented. It is hypothesized that this method is not appropriate for measuring the porosity of CIPP liner materials under substantial pressure as the liner has tendency to be compressed (e.g., behaving like a sponge).

5.1.7 Tensile Properties. The tensile properties of the liners from 10 sites in the current study were evaluated according to ASTM D638 and are listed in Table 5-1. The three samples received from Winnipeg did not have sufficient material to complete the tensile testing at the TTC according to ASTM D638. The average tensile strengths from each site varied from 2,672 psi to 4,402 psi and the average tensile moduli from each site varied from 324,406 psi to 554,101 psi. The mean and standard deviation for the tensile strength from all samples in the current study was 3,379 psi and 498 psi and the mean and standard deviation for the tensile modulus was 430,322 psi and 70,470 psi, respectively. For these non-pressure pipe installations, there is no requirement for tensile properties in ASTM F1216 at the time of installation.

5.1.8 Flexural Properties. The flexural properties of the liners from 13 sites in the current study were evaluated according to ASTM D790 and are listed in Table 5-1. The three samples received from Winnipeg did not have sufficient material to complete the flexural testing at the TTC according to ASTM D790. However, for these sites, the test data for flexural properties obtained through third party testing by the City of Winnipeg were made available. Also, for two of the sites (Winnipeg 1 and Winnipeg 2) minimum and maximum flexural properties had been published in Macey et al. (2013). These data are provided in Table 4-2 as part of the discussion of Canadian retrospective evaluation research. From the TTC testing plus the Winnipeg provided data, the average flexural strengths for each site varied from 4,469 psi to 8,592 psi and the average flexural moduli from each site varied from 237,264 psi to 477,609 psi. The mean and standard deviation for the flexural strength from all samples in the current study was 6,682 psi and 1,211 psi and the mean and standard deviation for the flexural modulus was 330,825 psi and 70,060 psi, respectively. ASTM F1216 does provide minimum values for each of these parameters at the time of installation.

For the flexural strength, all but one of the average test values met the minimum ASTM flexural strength at installation requirement of 4,500 psi even after 5 to 34 years of service. This low value was 4,469 psi – only just below the current ASTM requirement after 28 years of service. The oldest liner had a flexural strength of 7,761 psi.

For the flexural modulus, all of the average test values except two met the minimum ASTM flexural modulus at installation requirement of 250,000 psi after 5 to 34 years of service. The Winnipeg 3 (Mission) sample had an average modulus of 245,753 psi that exceeded the flexural modulus requirement at the time of its installation (240,000 psi), but is slightly below the current ASTM specification value of 250,000 psi. The other value not meeting the ASTM installation standard was from a 25-year-old liner in Indianapolis, which had the largest diameter in the current study (42 in.), had the deepest depth recorded

(20 ft) and was the second thickest liner in the current group (22.2 mm). The oldest liner tested (the Northbrook liner with 34 years in service) had a flexural modulus of 322,360 psi.

5.1.9 Shore D Hardness. The Shore D Hardness values for both the inner and outer surfaces of the retrieved liner samples were determined for all 13 liners included in the current study using ASTM D2240 and the results are listed in Table 5-1. For the liners in the current study, the hardness of the inner surface was almost always lower than the hardness of the outer surface (sometimes marginally and sometimes significantly). The inner hardness value ranged from a low of 54.1 to a high of 73.3 and the outer hardness value ranged from 58.7 to 79.2. It was postulated in the pilot study that differences between the inner and outer hardness values in an older liner could be an indication of deterioration of the CIPP liner due to the effects of the service conditions within the sewer. Such an evaluation is greatly complicated by the use of the sealing layer during the installation process for the CIPP liner. This may or may not be eroded or hydrolyzed in an older liner and also its presence during wet out and curing may impact the local hardness properties of the CIPP resin. This issue is explored a little further in Sections 5.2.4 and 5.2.9 because a test for the inner surface hardness of a CIPP liner could be a useful non-destructive in-service test for a liner if appropriate correlations could be established.

5.1.10 Short-Term Buckling Tests. Short-term buckling tests were able to be conducted on three of the retrospective samples (Table 5-6). The tests provide an indication of the continued structural capability of the full circumference of the liner, but the results cannot be interpreted directly in terms of design parameters. For practical test reasons, the liners are inserted in a new host pipe in the laboratory with a significant annular gap (approximately 1 in.), which will significantly lower the buckling resistance of thin liners. The lengths of the buckling test sections also are too short to be able to avoid end effects in the testing process. Such end effects are likely to increase the buckling resistance of the liner in the laboratory test. Finally, the buckling tests measure a short-term buckling resistance rather than the long-term buckling resistance. The long-term buckling resistance is affected by creep of the liner over time. Nevertheless, all of the buckling results for these 19 to 34 year-old liners still exceeded the resistance that would be necessary to resist a water table at the ground surface at each site.

Table 5-6. Short-Term Buckling Test Results for the Current Case Studies

Sample	Maximum Pressure Sustained in Short-term Buckling Test (psi) (water head)
Edmonton 1 (10 in.)	12 (28 ft)
Edmonton 2 (8 in.)	20 (46 ft)
Houston 1 (21 in.)	N/A
Houston 2 (18 in.)	N/A
Indianapolis (42 in.)	N/A
Nashville 1 Dunston (8 in.)	N/A
Nashville 2 Wyoming (8 in.)	N/A
New York 2 (15 in.)	N/A
New York 3 (12 in.)	N/A
Northbrook (12 in.)	5 (11.5 ft)
Winnipeg 1 (30 in.)	N/A
Winnipeg 2 (18 in.)	N/A
Winnipeg 3 (30 in.)	N/A

N/A = Buckling test not carried out due to the nature of the sample (e.g., panel sample or sample length)

5.1.11 Glass Transition Temperature. The glass transition temperature (Tg) represents the temperature region in which the resin transforms from a hard, glassy solid to a viscous liquid. As a thermosetting resin cures, the Tg increases and the heat of cure decreases. These changes can be used to characterize and quantify the degree of cure of the resin system. In general, an increase in the Tg is a function of curing and represents the increase in the molecular weight of the resin system (Perkin-Elmer, 2000). Table 5-7 summarizes the average Tg values for the CIPP samples from the current case studies.

Table 5-7. Average Glass Transition Temperature for the Current Case Studies

Sample	Average Tg (ºC)
Edmonton 1 (10 in.)	115.48
Edmonton 2 (8 in.)	112.91
Houston 1 (21 in.)	119.91
Houston 2 (18 in.)	119.69
Indianapolis (42 in.)	125.23
Nashville 1 Dunston (8 in.)	120.37
Nashville 2 Wyoming (8 in.)	109.43
New York 2 (15 in.)	87.28
New York 3 (12 in.)	90.10
Northbrook (12 in.)	105.74
Winnipeg 1 (30 in.)	122.28
Winnipeg 2 (18 in.)	76.72
Winnipeg 3 (30 in.)	129.24

5.2 Synthesis of Current CIPP Data with Pilot Study Data

In this section, the laboratory test data for the 13 sites in the current study are combined with the four sites (five test samples) from the pilot study for further analysis. These analyses will use the average test results for each parameter for each site, plus some calculated parameters as shown in Table 5-8 (note that the test data from Table 5-1 are repeated within Table 5-8 for convenience). All of the individual test data from this retrospective evaluation project (pilot study and current sites) have been entered into the database described in Section 2 and an exploration of the retrospective data in terms of data relationships and variability within sites and across all CIPP sites will be provided in Section 5.3. The analysis in this section will concentrate on the broad interpretation of the results of the retrospective testing so far.

5.2.1 Flexural Properties. Since the flexural properties of a gravity CIPP liner have specified minimum values in ASTM F1216, these are typically considered the key test parameters. The liner sample ages mostly ranged from 17 to 34 years in service with two younger liners included (with 5 years and 9 years in service).

The average flexural modulus values across the 17 sites (18 samples) ranged from a low of 206,805 psi to a high of 477,609 psi. The mean and standard deviation of the average test results from each sample were 317,503 psi and 70,171 psi, respectively. The percent standard deviation for the flexural modulus was higher at 22.1% than for the flexural strength (16.2%), the tensile modulus (16.0%) and tensile strength (13.7%). Four of the 18 average test values fell below the ASTM F1216 requirement of 250,000 psi, but there is no indication that these low values represent deterioration of the liner as opposed to a poor liner quality in the as-installed liner. In the Winnipeg Mission 30 in. sample case, the flexural modulus value was above the value specified at the time of installation. The Denver 48 in. (upstream) liner was noted to have significant variation in localized liner properties and the flexural modulus shown for the upstream liner is the average of two sets of flexural test samples that were tested. When the upstream and downstream samples are averaged together for the Denver 48 inch site, the combined average value is above the ASTM F1216 requirement. Thus, it can be said that out of the 17 separate "sites" tested, only two of the liners did not meet the average flexural modulus values that had been required at the time of installation. It is not possible to fully determine if the low values represent ongoing deterioration or poor liner properties that had existed since the time of installation.

The flexural strength values across the 17 sites (18 samples) ranged from a low of 4,469 psi to a high of 8,592 psi. The mean and standard deviation of the average test results from each sample were 6,594 psi and 1,066 psi, respectively. The percent standard deviation for the flexural strength was 16.2%. All of the samples but one had an average test value that met the ASTM requirement of 4,500 psi. It was noted regarding the Winnipeg liner that did not meet the ASTM value (see Section 4.2) that the "low flexural strength value was associated with a liner with visible installation related issues."

5.2.2 Tensile Properties. For the 15 sites with average tensile test results, the mean and standard deviation for tensile strength were 3,323 psi and 455 psi, respectively. The mean and standard deviation for tensile modulus were 413,460 psi and 65,961 psi, respectively. Similarly to the flexural results, the percent standard deviation was less for the strength properties (13.7%) than for the modulus properties (16.0%). For gravity sewers, there is no ASTM test value requirement.

5.2.3 Specific Gravity. For the 18 sites with specific gravity test results, the average specific gravity was 1.16 and the standard deviation was 0.07. The percent standard deviation was 5.7%, which was the lowest among the various test parameters measured. In the pilot study report (EPA, 2012), Section 5.4.4 provides a discussion and calculation of theoretical liner specific gravity values depending on the porosity, use of filler (which may be used to increase flexural modulus) and proportions of resin and felt. With typical proportions of resin and felt and no filler, the theoretical specific gravities for the liner range from 1.075 for a porosity of 10% to 1.191 for no porosity. For the use of talc filler with 12% by volume, the respective values would range from 1.224 for 10% porosity to 1.360 for no porosity. In these calculations, it is assumed that the felt fibers occupy 14% of the final resin volume. The remaining volume is occupied by resin, any filler that is used, and air (the result of porosity in the liner). When no filler is used and the porosity approaches 20%, the specific gravity of the liner will fall below 1.0 and a liner sample will float. This is sometimes useful as a simple test for whether a liner has a very high porosity or not.

5.2.4 Shore D Hardness. Examining the full set of Shore D hardness values (18 samples) for both the inner and outer surfaces of the retrieved liner samples did not affect the interpretation of the results presented in Section 5.1.9. The hardness of the inner surface was still almost always lower than the hardness of the outer surface (sometimes marginally and sometimes significantly). The range of hardness values also remained unchanged, i.e., the inner hardness value ranged from a low of 54.1 to a high of 73.3 and the outer hardness value ranged from 58.7 to 81.4. Examining the difference between the inner and outer hardness value, this change ranged from a low of -1.7% to a high of 25.7%. An examination of how this variability might relate to the value of other parameter values is given in Section 5.2.9. It is noted again here that such an evaluation is complicated by the use of the sealing layer during the installation process for the CIPP liner. This may or may not be eroded or hydrolyzed in an older liner and also its presence during wet out and curing may impact the local hardness properties of the CIPP resin.

5.2.5 Liner Thickness. The thickness of the liner is a design parameter that is related to the expected service parameters of the liner and the design procedures used at the time of the original liner installation. However, several aspects of liner thickness have potential relevance to the interpretation of liner deterioration. These include:

1. The extent to which the specified liner thickness was realized in the field;
2. The variation of liner thickness within a sample (relating to QC in the liner preparation/installation or variations in installation conditions within the liner); and
3. The extent to which the design assumptions correctly reflected the actual in-service conditions (e.g., the assumptions about the level of deterioration of the host pipe, the water table assumptions and the actual versus assumed liner strength/modulus properties).

Only the first issue is examined here and in Section 5.2.10.

The liner thicknesses for the 13 sites in the current study were measured and the results presented in Table 5-8. For most of the liners, the design/specified thickness of the liner at the time of installation could not be retrieved. However, two liners had thicknesses less than that specified (at 78% and 93% of the specified value) and two liners had thicknesses more than that specified (at 110% and 112% of the specified value). In the pilot study, four out of the five samples retrieved had liner thickness less than the specified thickness, so the realization of the expected liner thickness in the field during installation is an issue to watch in QA/QC procedures.

5.2.6 Key Liner Properties versus Age of Liner. Liners with service lives ranging from 5 to 34 years have been included in the study thus far. This provides an opportunity to examine whether there are any clear trends of the change of liner properties with length of service. At this stage of the assembly of retrospective evaluation data for CIPP liners, a number of issues make the evaluation of such trends difficult:

- The relatively small number of samples available;
- The lack of equivalently measured parameters at the time of installation (which might provide a real measure of change in properties); and
- The absence of information as to whether the measured properties after a portion of the expected service life represent liner deterioration, poor QC in the installation or variation among the as-installed liner properties.

Figure 5-1 shows the flexural modulus and tensile modulus measurements versus the age of the liner. It includes the average flexural modulus data from each of the 18 samples retrieved across the current and pilot study, plus the average tensile modulus data from 15 samples (excluding the Winnipeg sites). In each case, the calculated linear regression trend line is slightly positive, i.e. both moduli increase with age. However, the data show a large amount of scatter (R^2 value less than 0.01 in each case as calculated within Microsoft® Excel) and the lack of any obvious trend with age combined with the issues raised above has suggested that adding trend lines would not add substantial value to the information presented. In the following discussions, R^2 values are provided to indicate the level of scatter and noted when they exceed 0.5 in value. No "strong" correlations were found (e.g., with R^2 values greater than 0.8).

Figure 5-2 shows the equivalent plot for flexural strength and tensile strength versus the age of the liner for the same sample sets used in Figure 5-1. As was noted in terms of the lower percent standard deviations of the strength data in Section 5.2.1 and 5.2.2, the measured strengths have less scatter than the measured moduli and particularly so for the tensile strength but the calculated R^2 values are still both below 0.05. There is still no clear relationship to the service life of the liner, although the calculated trend lines both have a positive slope, i.e. both strengths tend to increase with age.

Figure 5-3 shows a plot of the measured specific gravity of the liner versus the age of the liner samples. Since the graph is less cluttered, a linear trend line (calculated within Microsoft® Excel) has been shown on the graph. The caveats discussed earlier as to whether any apparent trends with age are real still apply and it also should be noted that the vertical axis of the graph in this case only starts at a value of 1.0 rather than having its origin at 0. This makes the plot clearer, but accentuates the apparent variation of the trend line. The R^2 value is 0.0025 indicating the huge amount of scatter present.

Overall, there is nothing seen in the measurements to date to document a real trend of diminishing liner properties with time. It should be noted that the main determinant of service life for CIPP liners is often the time to failure via buckling of the liner. This is controlled by the creep properties of the liner through an assessment of the "apparent long-term flexural modulus" of the liner. Under this design case, the liner will still have a certain time to failure even if the short-term flexural modulus remains unchanged.

Table 5-8. Measured and Calculated Average Test Parameters for the 18 Retrospective Samples

Location	Average Values per Site											Age (years)
	D638 (psi)		D790 (psi)		Specific Gravity	Shore D Hardness			Thickness (mm)			
	Tensile Strength	Tensile Modulus	Flexural Strength	Flexural Modulus		Inner	Outer	Change %	Design Thickness	Average Measured Thickness	Change %	
Columbus 36 in.	2,958	315,259	6,039	206,805	1.17	64.8	78.6	17.5	15.0	11.9	-20.7	21
Columbus 8 in.	3,866	362,588	6,416	346,050	1.11	62.7	81.4	23.0	6.0	5.7	-4.8	5
Denver 8 in.	3,029	411,621	6,756	335,340	1.16	58.9	77.0	23.5	6.0	5.9	-1.7	25
Denver 48 in. Downstream	2,995	382,420	7,031	302,960	1.07	65.2	78.9	17.4	18.0	12.5	-30.6	23
Denver 48 in. Upstream	3,208	426,787	5,575	223,165	1.08	46.6	62.7	25.7	13.5	14.2	5.2	23
Edmonton 10 in.	3,241	436,710	6,135	331,333	1.25	68.6	78.1	12.2	5.0	4.7	-6.0	19
Edmonton 8 in.	3,653	510,132	6,816	364,788	1.25	68.2	79.2	13.9	N/A	4.8	N/A	19
Houston 21 in.	3,409	465,322	6,893	337,638	1.17	61.2	61.3	0.1	N/A	10.7	N/A	17
Houston 18 in.	3,252	450,985	7,204	338,565	1.18	65.4	75.7	13.6	N/A	11.0	N/A	17
Indianapolis 42 in.	2,718	351,294	4,712	237,264	1.08	57.0	65.7	13.3	N/A	22.2	N/A	25
Nashville Dunston 8 in.	3,436	375,807	6,833	301,724	1.14	65.2	72.2	9.7	N/A	5.6	N/A	19
Nashville Wyoming 8 in.	2,672	400,926	5,497	282,460	1.21	64.6	67.4	4.1	N/A	7.1	N/A	9
NYC 15 in.	3,729	554,101	7,978	477,609	1.31	73.3	72.1	-1.7	N/A	7.3	N/A	23
NYC 12 in.	3,275	324,406	7,200	285,177	1.15	57.7	58.7	1.7	N/A	7.1	N/A	24
Northbrook 12 in.	4,402	433,541	7,761	322,360	1.19	65.6	76.0	13.7	6.0	4.7	-21.7	34
Winnipeg Richard 30 in.	(a)	(a)	8,592[b]	452,134[b]	1.21	57.4	65.8	12.8	6.0	6.6	10.0	34
Winnipeg Kingsway 18 in.	(a)	(a)	6,779[b]	323,930[b]	1.14	54.1	60.9	11.2	6.0	6.7	11.6	34
Winnipeg Mission 30 in.	(a)	(a)	4,469[b]	245,753[b]	1.07	57.3	64.9	11.8	N/A	22.8	N/A	28
Average	3,323	413,460	6,594	317,503	1.16	61.88	70.92	12.41	-	9.52	-6.50	-
Standard Deviation	455	65,961	1,066	70,171	0.07	6.26	7.48	7.71	-	5.55	14.89	-
Percent Standard Deviation	13.7	16.0	16.2	22.1	5.7	10.1	10.5	-	-	58.3	-	-

(a) Samples received at TTC not large enough to test for this parameter.
(b) Samples received at TTC not large enough to test for this parameter but test data for the liners was received from City of Winnipeg. See also Table 4-2 in this report showing the data from Macey et al. (2013).

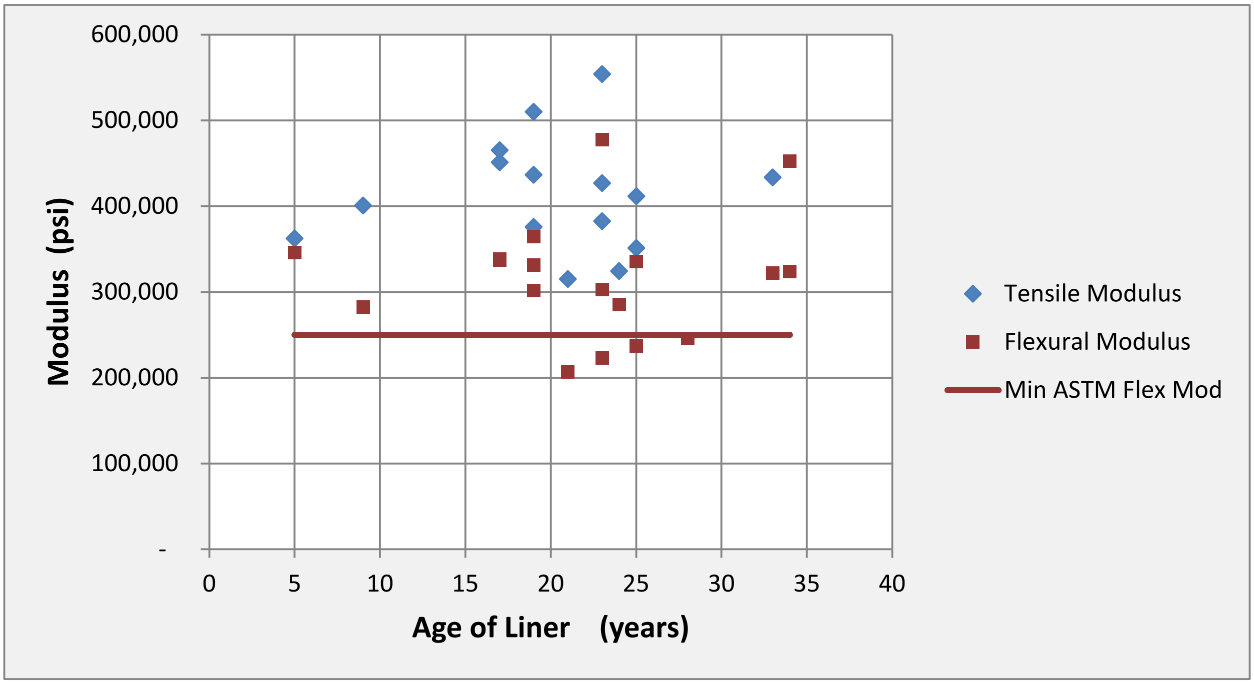


Figure 5-1. Flexural and Tensile Moduli versus Age of Liner

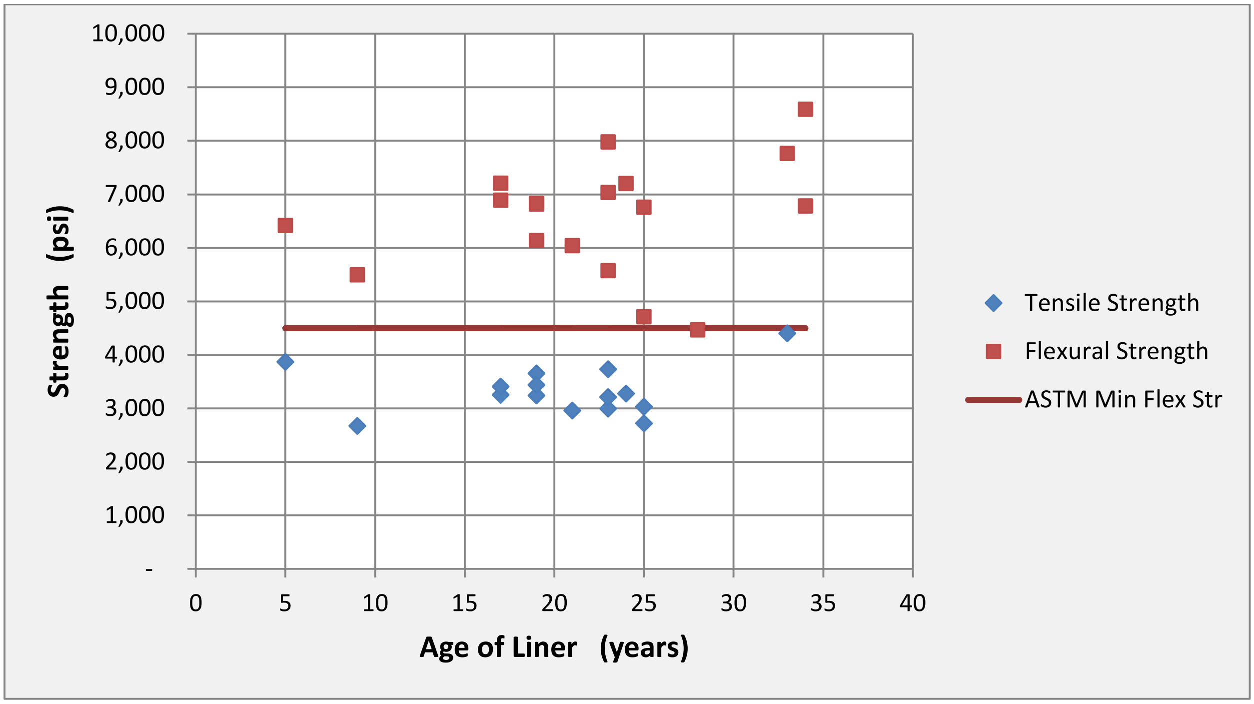


Figure 5-2. Flexural and Tensile Strengths versus Age of Liner

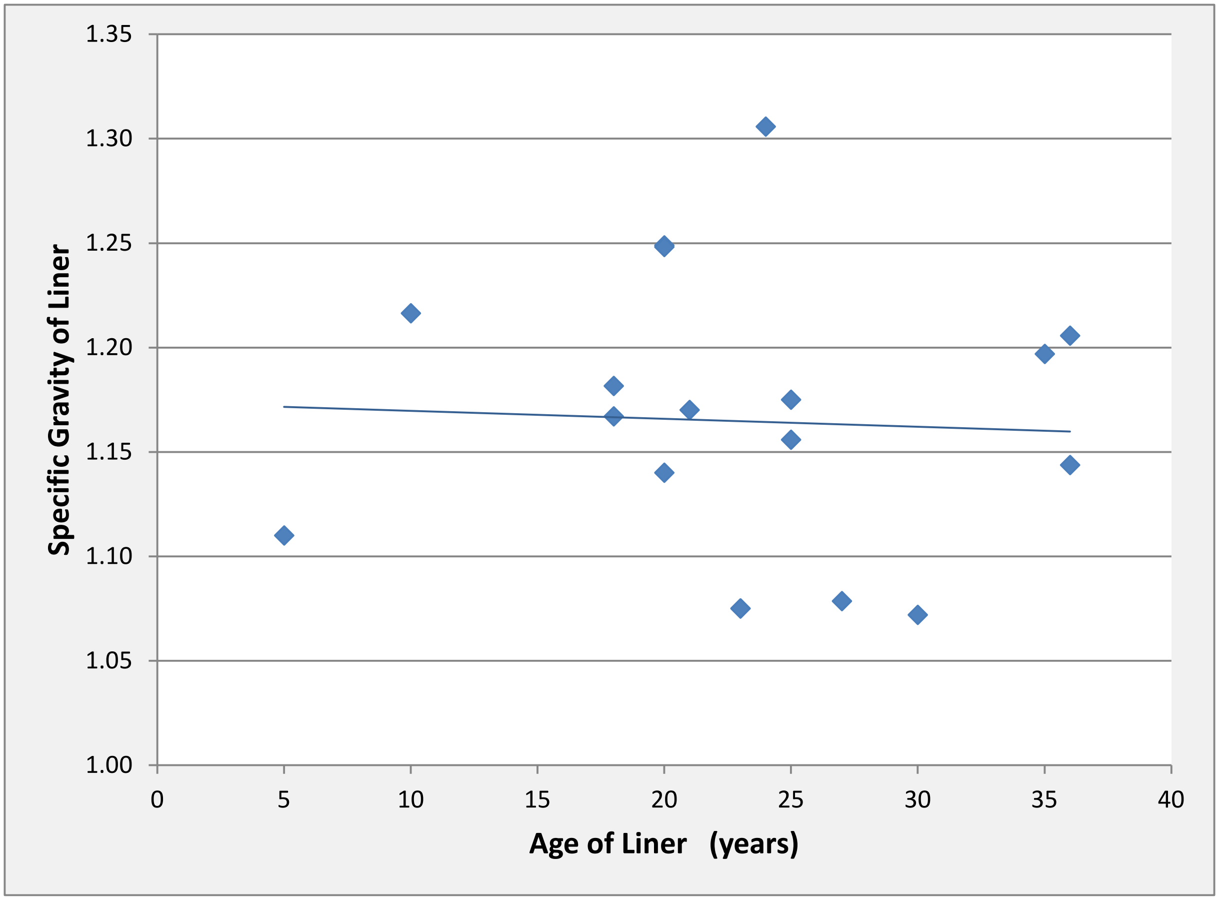


Figure 5-3. Specific Gravity of Liner versus Age of Liner

5.2.7 Strength and Modulus Properties versus Specific Gravity. Figures 5-4 and 5-5 plot the relationships between the average strength and modulus properties and the average specific gravity of each of the liner samples. The intent is to examine whether, as might be expected, a higher specific gravity for a sample would correlate to higher strength and modulus properties. Linear trend lines have been added for these plots since there is a strong underlying meaning for such a relationship and each of the data points represents the average of multiple individual tests. It can be seen by inspection of the graph that there is an observable relationship in terms of higher strength and modulus properties with higher specific gravities. The relationship is more noticeable in the flexural properties and particularly in the flexural modulus than in the tensile properties but the R^2 values for the trend lines still show only a weak correlation (tensile strength 0.10, flexural strength 0.28, tensile modulus 0.44 and flexural modulus 0.46). The results indicate that the specific gravity of a sample could be a useful addition to the parameters used to assure the quality of an installed CIPP liner. The size of sample needed for the specific gravity evaluation is much smaller than that needed for flexural testing.

5.2.8 Relationships among the Strength and Modulus Parameters. Figures 5-6, 5-7, 5-8 and 5-9 explore the relationships among the strength and modulus parameters measured for the 15 samples (with data available for both parameters). It would be expected that a high quality CIPP liner or one with an inherently stronger resin would show increases in all strength and modulus properties. Such relationships are seen in the graphs, but to a greater or lesser extent according to the variable compared.

In Figure 5-6, tensile modulus shows a weak correlation (R^2 equal to 0.17) when compared to tensile strength, but there is still a visible trend that as the tensile strength of a sample increases, the tensile modulus also tends to increase.

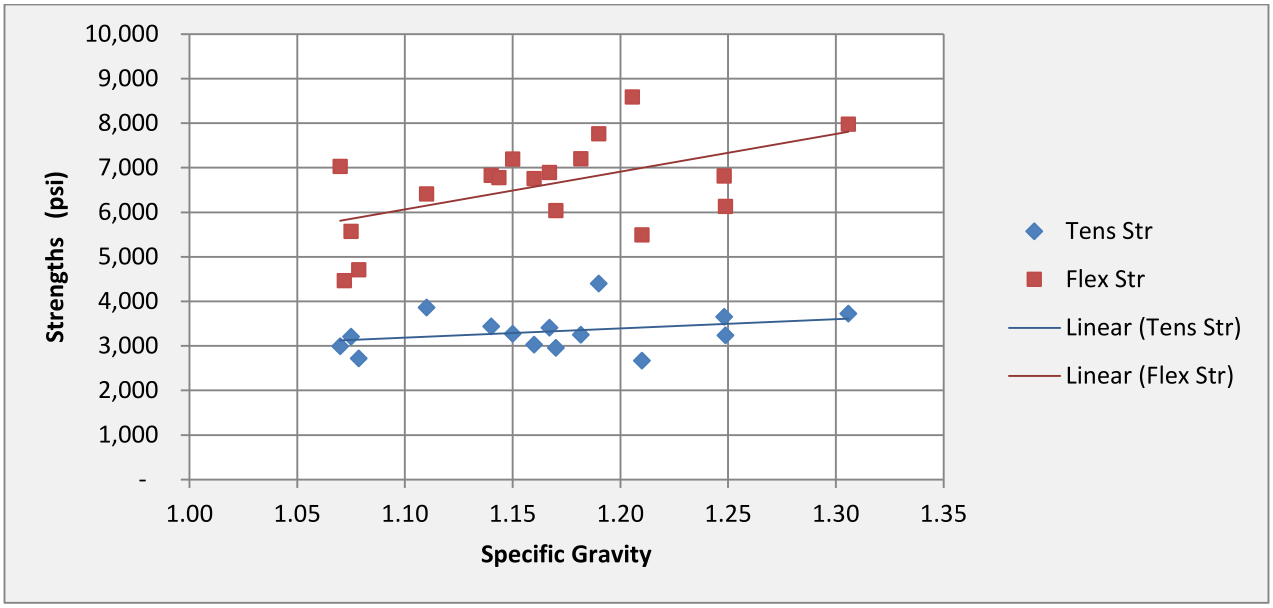


Figure 5-4. Flexural Strength and Tensile Strength versus Specific Gravity

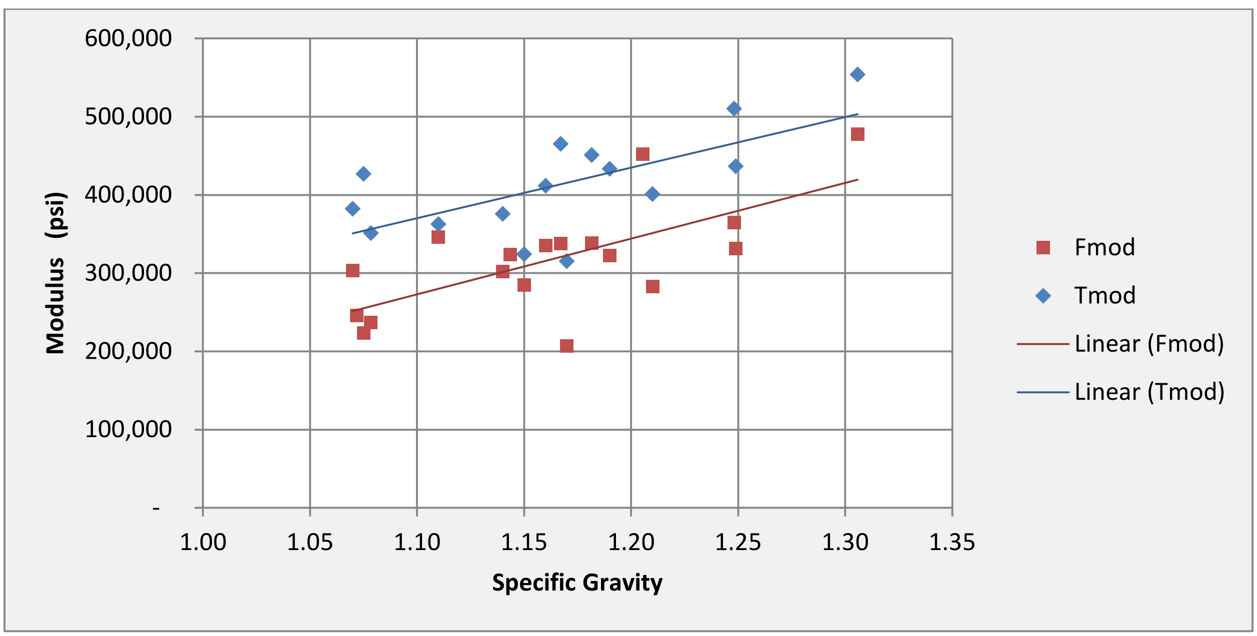


Figure 5-5. Flexural Modulus and Tensile Modulus versus Specific Gravity

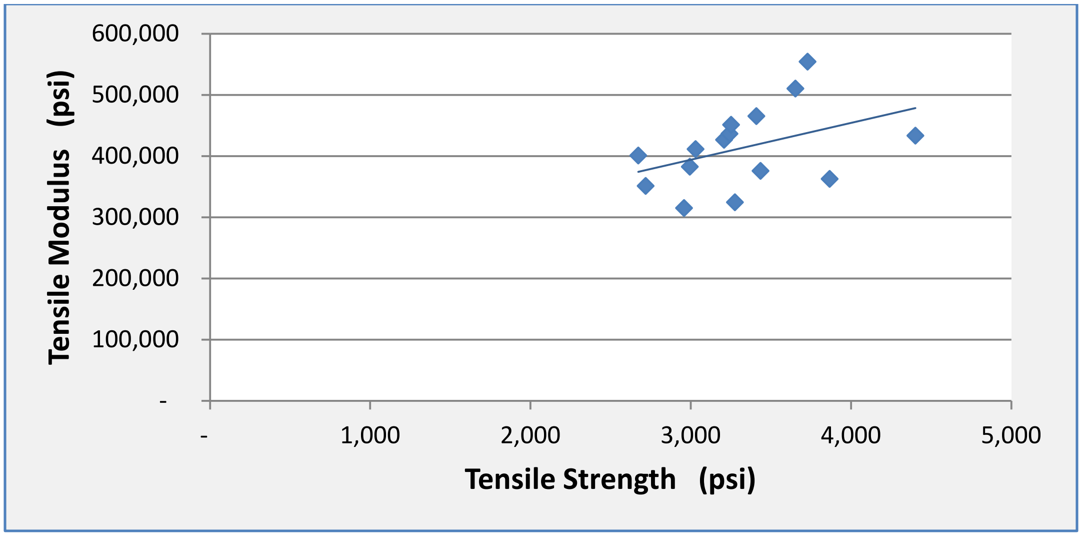


Figure 5-6. Tensile Modulus versus Tensile Strength

In Figure 5-7, the flexural strength values are compared to the tensile strength values. The trend in this case is more pronounced (R^2 equal to 0.46) than for the Figure 5-6 comparison and it is clearly discernible that flexural strength tends to increase with higher tensile strength.

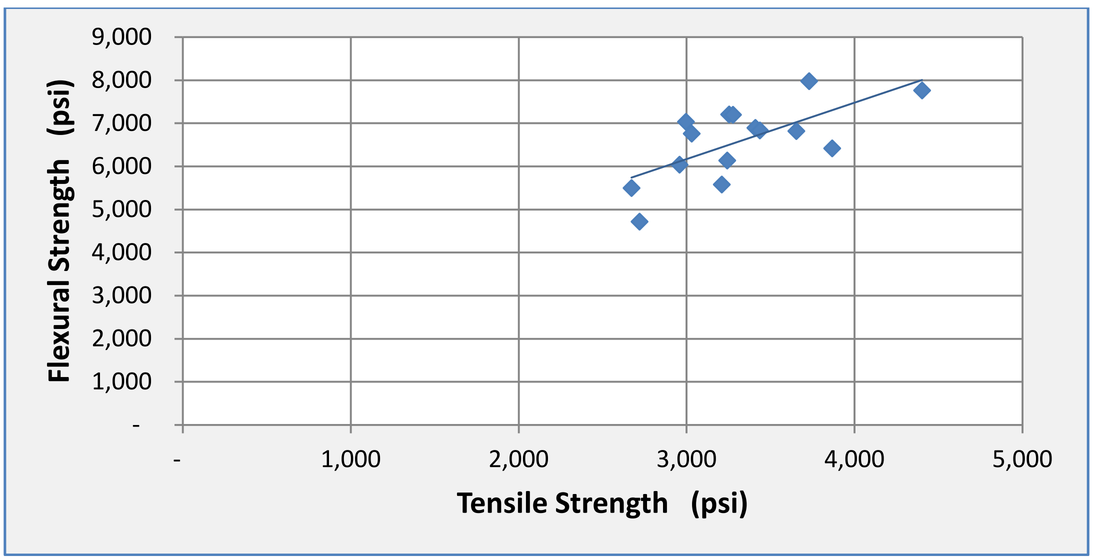


Figure 5-7. Flexural Strength versus Tensile Strength

In Figure 5-8, the flexural modulus values are compared to the tensile modulus values with similar results and a more significant correlation (R^2 equal to 0.60). Perhaps the most interesting comparisons are for the flexural and tensile strengths compared to the flexural modulus as shown in Figure 5-9. The general increase of flexural strength with increasing flexural modulus (R^2 also equal to 0.60) is much more pronounced than for the increase of tensile strength with increasing flexural modulus (R^2 equal to 0.28).

This suggests that flexural strength or tensile modulus is better predicted from flexural modulus than is tensile strength.

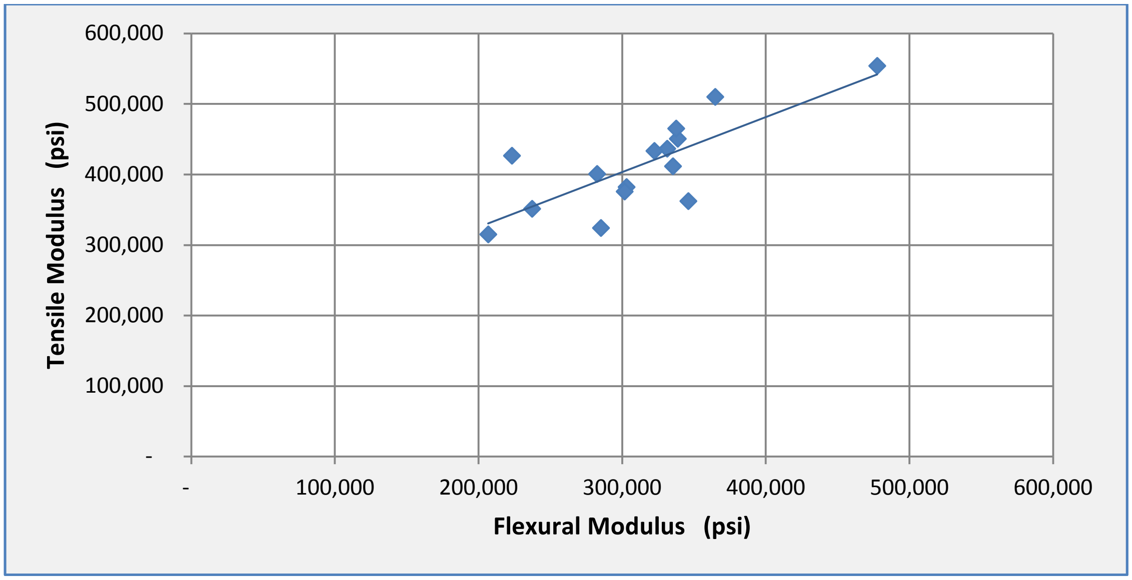


Figure 5-8. Tensile Modulus versus Flexural Modulus

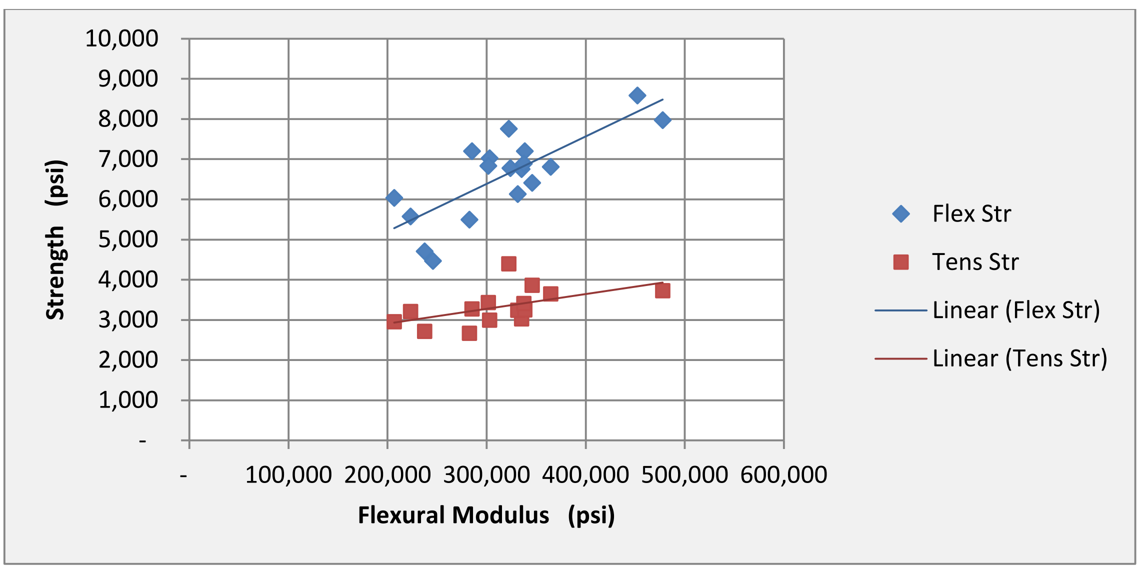


Figure 5-9. Flexural Strength and Tensile Strength versus Flexural Modulus

5.2.9 Evaluations of Shore D Hardness Relationship to Other Parameters. In this section, the possibility that surface hardness might have value as a proxy for other properties of a CIPP liner is examined further (bearing in mind the caveats discussed in Section 5.1.9). The relationship of surface hardness to the key liner parameter of flexural modulus is plotted in Figure 5-10, which plots the Shore D hardness for both inner and outer liner surfaces versus the average flexural modulus measured for that sample. All 18 samples are included in the data plotted.

There is a significant amount of scatter in the data, particularly for the outer surface hardness results (R^2 equal to 0.03 compared to 0.21 for the inner hardness). Linear trend lines have been shown in the graph, but it should be noted that the axis for the hardness value starts at 40 rather than 0. This accentuates the apparent relationship of hardness to flexural modulus. There is, however, an observable overall trend of higher surface hardness with increased flexural modulus and this is physically reasonable.

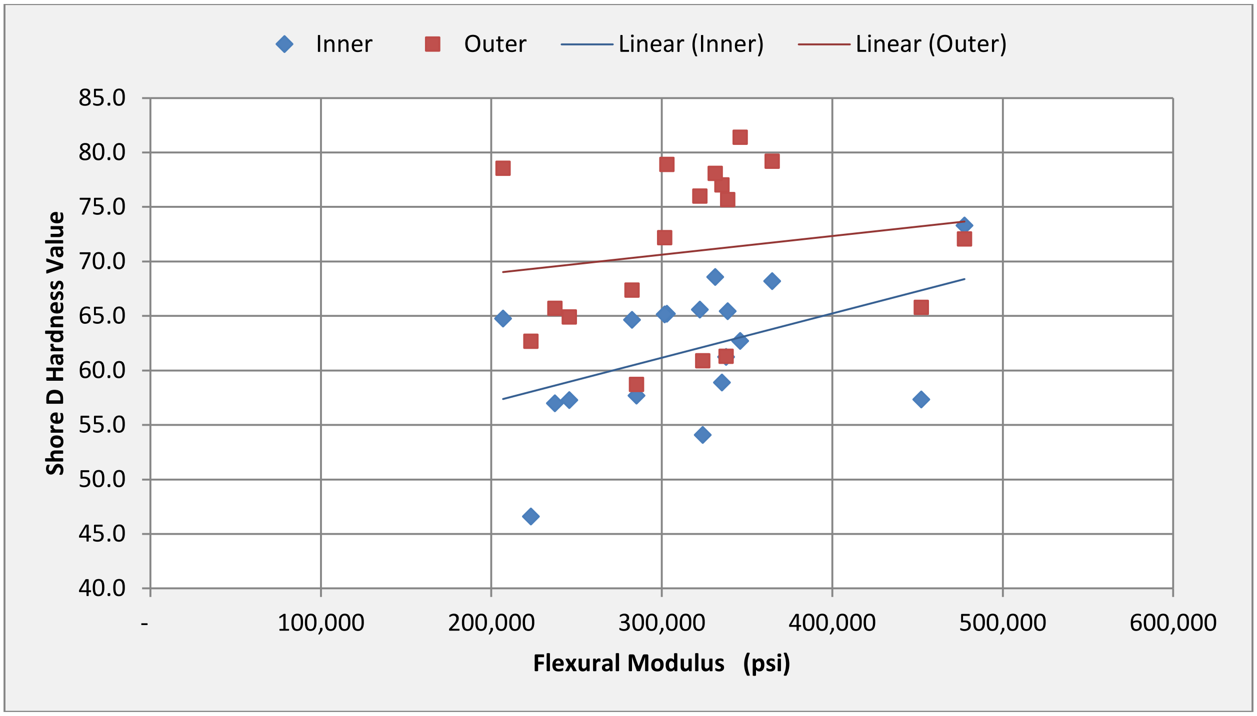


Figure 5-10. Shore D Hardness versus Flexural Modulus

Two additional figures have been developed to further explore possible relationships. Figure 5-11 plots the surface hardness of the inner liner surface versus the age of the liner. There is large scatter (R^2 equal to 0.12) but a slight trend towards a decreasing surface hardness with increasing age. Again, it should be noted that the vertical axis scale starts at a hardness of 40 rather than 0, which accentuates the slope of the trend line. Figure 5-12 plots the percent change in hardness between the outer and inner surfaces (i.e., [outer-inner]/outer) of the liner versus the age of the liner. Here there is an even larger amount of scatter and no observable trend.

In summary, the attraction for exploring this relationship further is that it may provide a means of evaluation of the properties of constructed or in-service liners. Surface hardness testing would be a non-destructive test if equipment could be developed to conduct some form of surface hardness measurement for the inner surface of a liner in-situ. Alternatively, only a small cored sample would be necessary to conduct meaningful surface hardness evaluations in the laboratory. These could be obtained robotically from within the lined pipe and the damage to the in-place liner could be easily patched robotically. Conceptually, the coupons removed to reinstate service laterals could also be used for this purpose although the curing conditions for the liner would be locally affected by the presence of the service line. However, in order to go further in this direction, a better understanding first needs to be established of the typical variation of hardness through the thickness of CIPP liners and a larger database developed to study the potential for meaningful correlations. A consistent procedure for dealing with the presence or absence of the sealing layer would also need to be established.

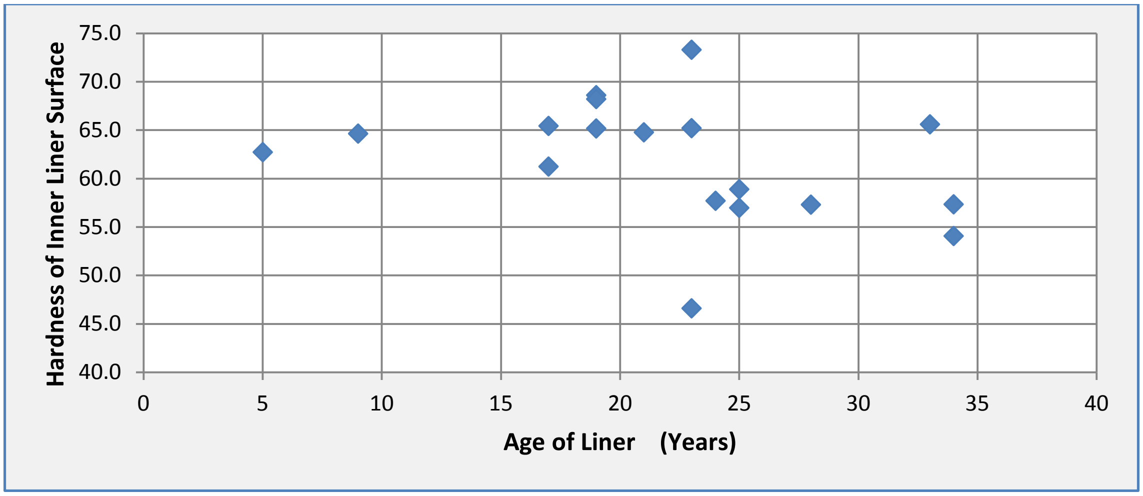


Figure 5-11. Shore D Hardness of Inner Liner Surface versus Age of Liner

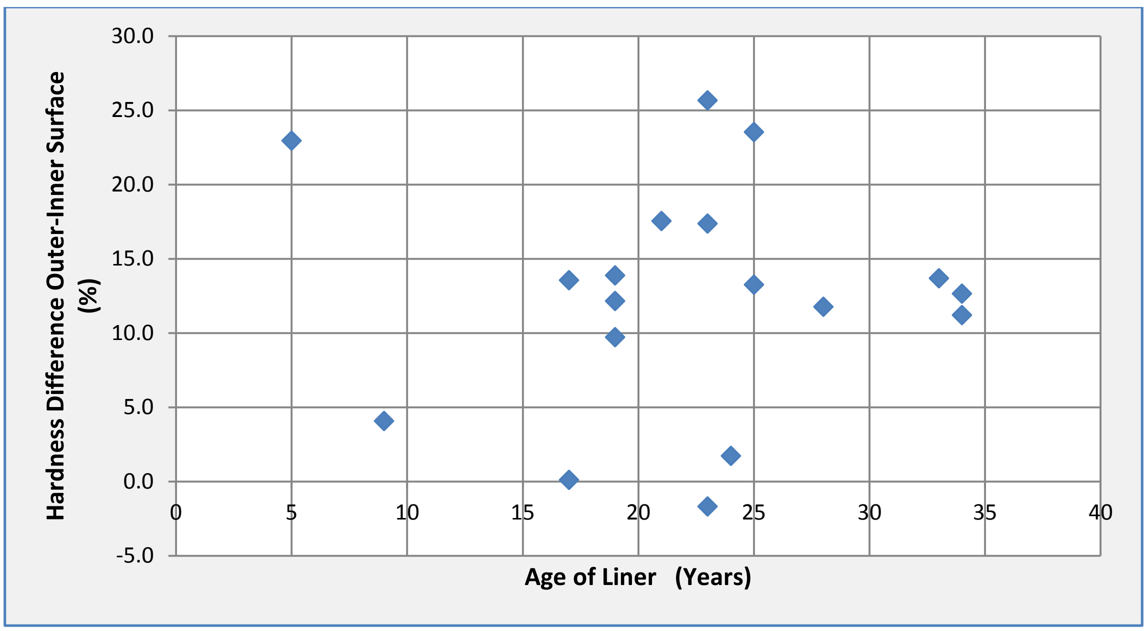


Figure 5-12. Hardness Difference Outer-Inner Liner Surface versus Age of Liner

5.2.10 Flexural Modulus of a Liner Compared to Liner Variations. There are many possible reasons for variations in liner quality and variations in the values measured for various test parameters. In this section, two quantities that suggest variations in liner properties are used for comparison with the average flexural modulus of the liner sample. In Figure 5-13, the flexural modulus is plotted against the percent change of surface hardness between the outer and inner surface of the liner. It was postulated that, if the inner surface of the liner was experiencing deterioration from in-service conditions, then its surface hardness may decrease and the change in hardness between the outer and inner surfaces would hence increase. A small visible trend towards lower flexural modulus with a higher percent difference in surface hardness can be seen in the graph but with a very low correlation (R^2 equal to 0.08). Also, for the reasons stated earlier, it is not possible to make firm conclusions from the current data collected.

Another parameter can be constructed by comparing the specified design thickness with that measured for the field samples in the laboratory. Lack of adherence to the specified thickness might be related to QC issues that may have an impact on the other properties of a liner, including flexural modulus (i.e., it can be postulated that a liner showing a deviation in thickness from that specified might have more QC issues than a liner that meets the specified thickness). However, Figure 5-14, with the limited number of samples that could be related to a specific design thickness, shows no relationship.

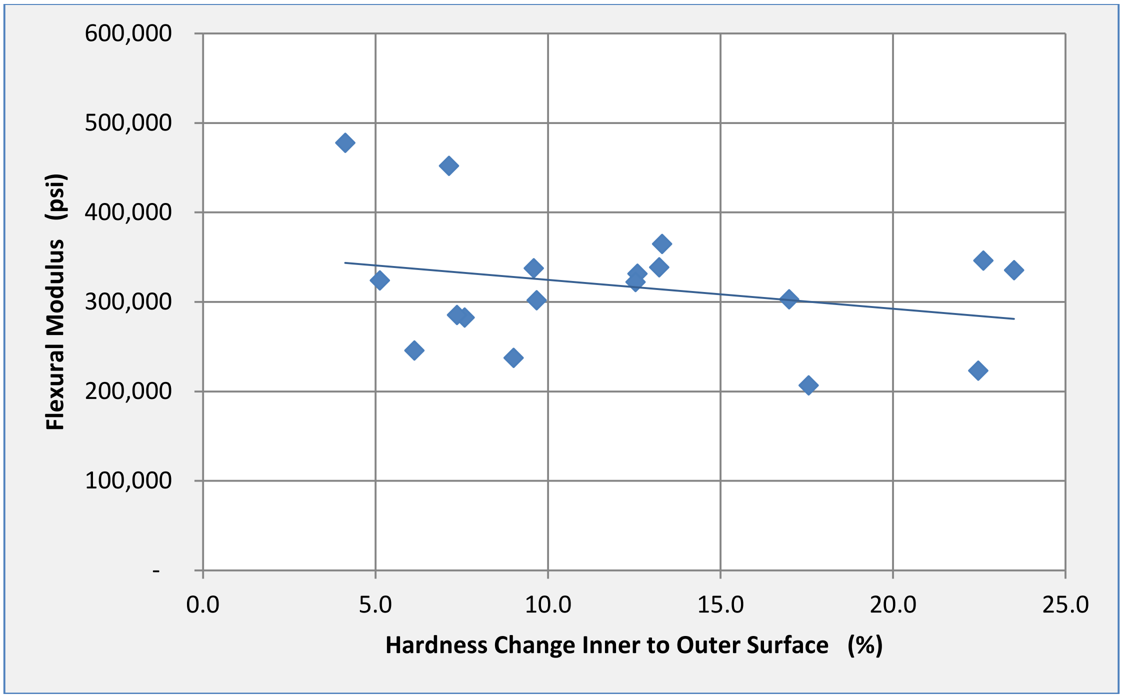


Figure 5-13. Flexural Modulus versus Variation in Surface Hardness

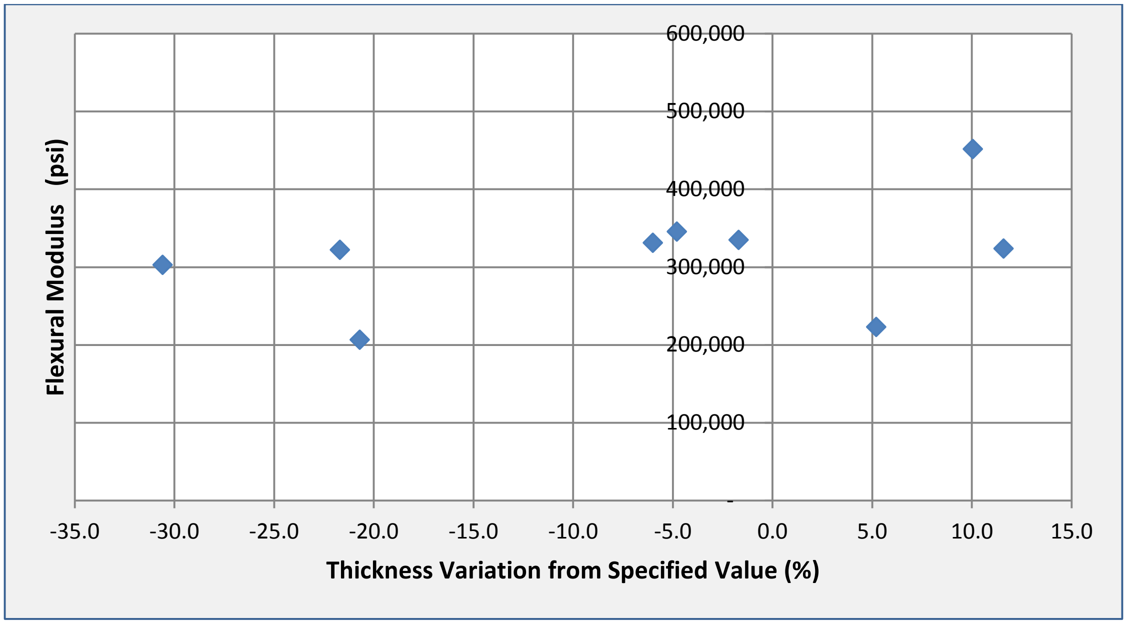


Figure 5-14. Flexural Modulus versus Thickness Variation from Specified Value

5.2.11 Summary of Results from Liner Testing at Different Ages. This section draws together the results and observations where the same liner was tested/evaluated at different ages. Although this may seem a more exact comparison, there may be a number of reasons why the results can differ for reasons unrelated to aging processes. Some of the key reasons are:

- Samples collected at the time of installation are typically created outside the host pipe being relined and the installation and curing conditions may be different from the liner within the host pipe.
- Differences in results can occur due to spatial variability in test results rather than aging processes.
- In one case, it was not clear whether prior testing results were for the same liner or not. When liners are old (e.g., 23 years old), this can be difficult to establish.

Taking first the results reported in the pilot study (EPA, 2012), the following observations can be made:

- City of Denver 48 in. host pipe: This was reported to have been tested at an age of 8 years prior to its testing under the pilot study at 23 years old. The average flexural modulus at 8 years was reported to be 490,000 ± 40,000 psi. However, it should be noted that there was a discrepancy in that the 8-year old sample was marked as coming from an oval-shaped 48-in. equivalent diameter brick sewer in this location, whereas the actual sewer in this location is circular. Such discrepancies are often impossible to resolve after many years have passed since the data was recorded. The average flexural moduli at 23 years was measured as 302,960 ± 24,303 psi (downstream of the manhole), 182,622 ± 23,126 psi and 263,707 ± 70,398 psi (two sets both upstream of the manhole) depending on the location of the sets of samples. As noted in the pilot study report, the 2010 sample showed a high degree of variability, especially upstream of the manhole. The similar figures for the flexural strength are respectively: 6,900 ± 40 psi at 8 years and 7,031 ± 346 psi, 5,032 ± 652 psi and 6,117 ± 888 psi.

- City of Columbus 8 in. host pipe: The as-installed test results gave the average flexural modulus as 464,652 ± 30,000 and the flexural strength as 7,264 ± 500. The 2010 testing (5 years old) gave the average flexural modulus as 346,050 ± 49,748 and the flexural strength as 6,416 ± 2,028. The results indicate a 5-year flexural modulus that is 25% lower than the as-installed modulus and a flexural strength that is 12% lower. As noted above, however, this is not a direct comparison since the as-installed sample was not cut from the actual liner installation.
- Thames Water has published data for the first commercial CIPP installation in London (EPA, 2012). The average 20-year test results were 420,000 psi for flexural modulus and 6,700 psi for flexural strength. The average 30-year test results were 480,000 psi for flexural modulus and 6,200 psi for flexural strength. By these results, the flexural modulus increased and the flexural strength decreased as the liner aged from 20 years to 30 years in service.

Moving to the current study, a few additional data/observations have been identified that directly compare the same liner at different ages. These are:

- City of Northbrook (34-year old 12 in. diameter liner): This liner had previously been examined through an EPA-funded study of the lining process during the period of installation and near-term follow up (Driver and Olson, 1983). Table 5-9 shows the comparative results.

All of the test results show a decrease over the 34 years, but it again must be stressed that a laboratory-prepared flat plate sample is very unlikely to give the same results as a sample cut from within a field-installed liner.

Table 5-9. Comparison of Northbrook, Illinois Retrospective Data

Parameter	Laboratory Flat Plate Sample at Time of Installation (psi)	Field Sample Tested After 34 Years in Service (psi)
Tensile Strength	5,420	4,402
Tensile Modulus	475,000	433,541
Flexural Strength	9,320	7,761
Flexural Modulus	403,000	322,360

- Section 4 of this report examined the recent literature for other studies of CIPP liner performance. The only study reporting test values from different ages of liners was the study by Lystbaek (2007). The test results are shown in Table 4-6. Results are available using retrieved samples for five liners at the ages of 8 years and 13 to 14 years. For these five liners, three showed increases in flexural modulus and two showed decreases. Similarly, for flexural strength, three showed increases and two showed decreases. However, the liners showing increases for flexural modulus were not necessarily the same as for the case of flexural strength.

In summary, while some of the comparisons show a reduction of liner mechanical properties with years in service, these results are at times comparing different types of samples at the different ages. Focusing on the results for which "retrieved" samples of the actual liner installation are compared and the liner identification is secure (i.e., only the Thames Water and Lystbaek data), the results show no consistent pattern of change with age with some results increasing by modest amounts and others decreasing by modest amounts. These results are consistent with the graphs comparing different liners with age (Figures 5-1 and 5-2), which do not show any clear trends.

5.3 Examples of Exploration of Relationships for CIPP Liners Using the Database

In this section, the database generated in the retrospective evaluation project and described in Section 2 will be explored to illustrate its use and to look at the variations in CIPP performance data across sites. Only some selected plots from the database are shown here and readers are invited to visit the database site and either download the entire database for further study or use the graphing function available through the Web site to examine a wider variety of data comparisons and relationships.

5.3.1 Exploring the Potential for the Database. At present, the plot parameters are restricted to the laboratory measured test values obtained. In the future, as a larger database is available, it is intended to broaden the range of relationships that can be explored. In Section 5.2, a number of relationships among the test parameters were already explored using the average values from each site for comparison. In this section, all of the individual test values are available and the data variation can be examined within sites, as well as across sites. Although the Winnipeg test data have been reported in the average value tables above, the Winnipeg data currently are not used for the database plotting since the flexural testing would be the only data that was not done in the same laboratory as the remaining data. As the database is expanded, testing from various sources across the country will be included for plotting in the database.

5.3.2 Exploration of 2-D Scatter Plot Data Relationships. Figure 5-15 shows a plot of flexural modulus (y-axis) against tensile strength (x-axis) using a 2-D scatter plot. The user choices shown in the select boxes are *All cities CIPP, Number of Synthetic Values = 0* and *Curve Fitting not Selected*. The similar trends to those already identified in Section 5.2 are seen in the plot, but with a greater number of individual data points to better represent the full scatter in the data. Because the number of synthetic values is chosen as zero, the number of data points plotted for each city is the least of the number of values available for either parameter.

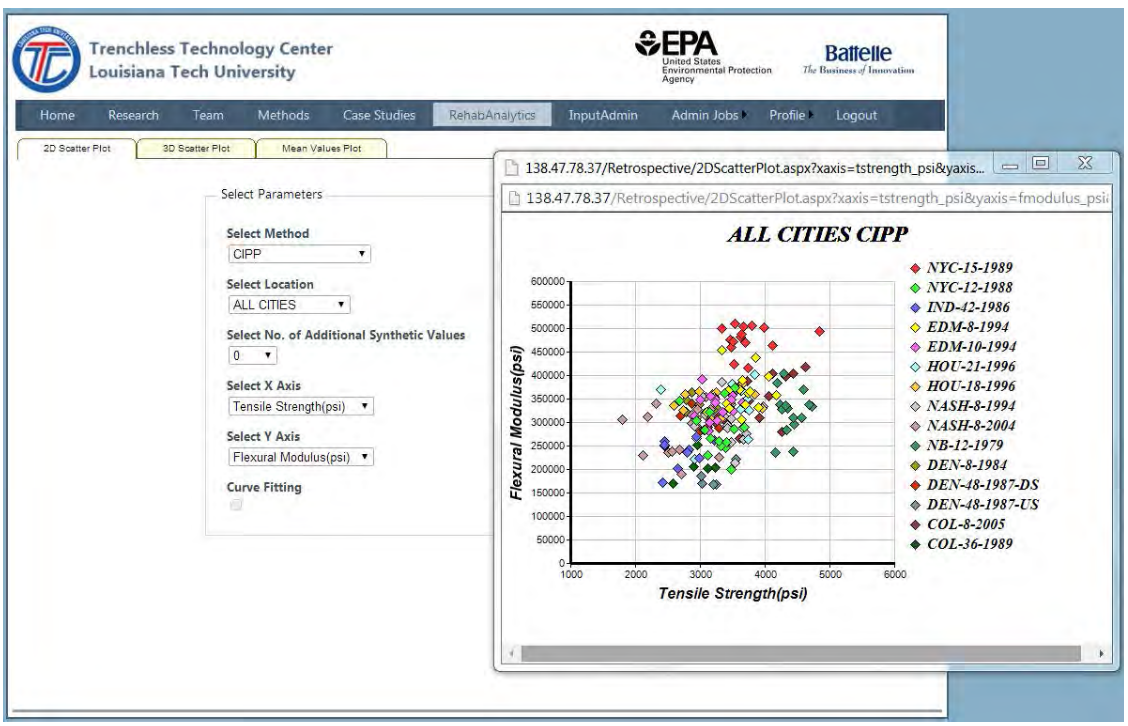


Figure 5-15. Web Site Plot of Flexural Modulus versus Tensile Strength

In Figure 5-16, the same plot parameters (flexural modulus versus tensile strength) are used, but with the dataset restricted to just the NYC-15-1989 (NYC Sample 2) data. This sample had one of the highest sets of flexural modulus results and it can be seen from the plot that there is a lower variation of flexural modulus values than for many sites making for a reduced trend in the increase in flexural modulus against tensile strength than is seen in the overall data plot in Figure 5-15. Figure 5-17 shows the same plot as in Figure 5-16, but with the curve fitting option selected. The linear regression trend line and 95% confidence intervals are added to the previous graph.

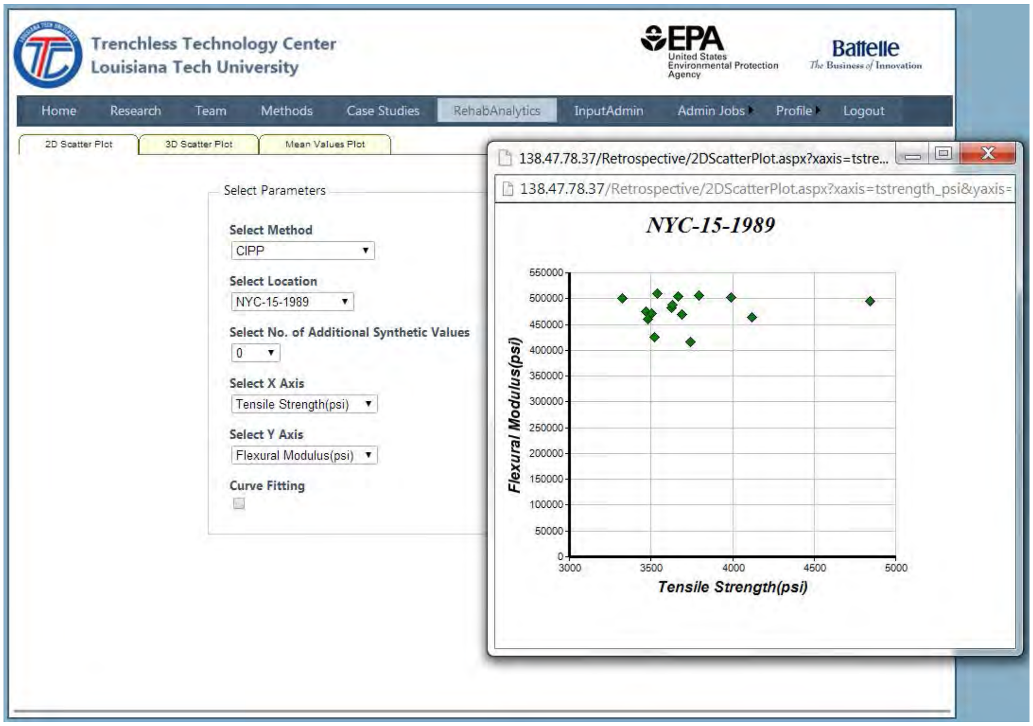


Figure 5-16. Web Site Plot of Flexural Modulus versus Tensile Strength for NYC-15 Sample

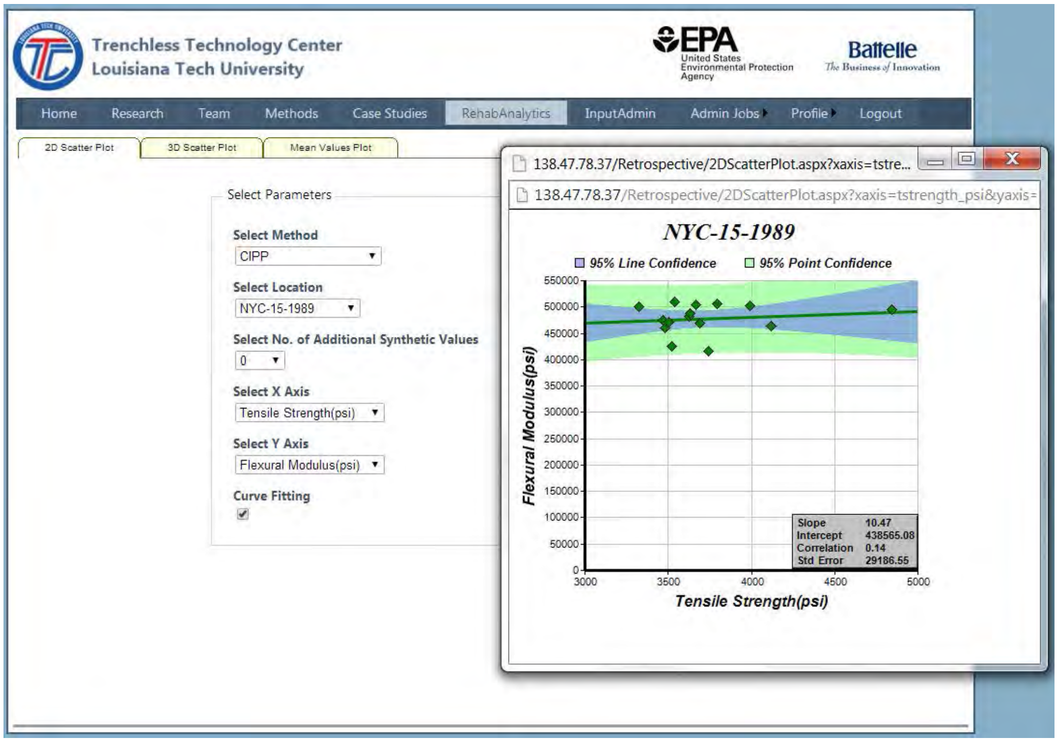


Figure 5-17. Web Site Plot of Flexural Modulus versus Tensile Strength with Trend Line for NYC-15 Sample

Figure 5-18 shows a plot for all of the CIPP sites of flexural modulus versus flexural strength. Visually, there is slightly less scatter than exhibited in the plot of flexural modulus versus tensile strength, making for a more discernible trend.

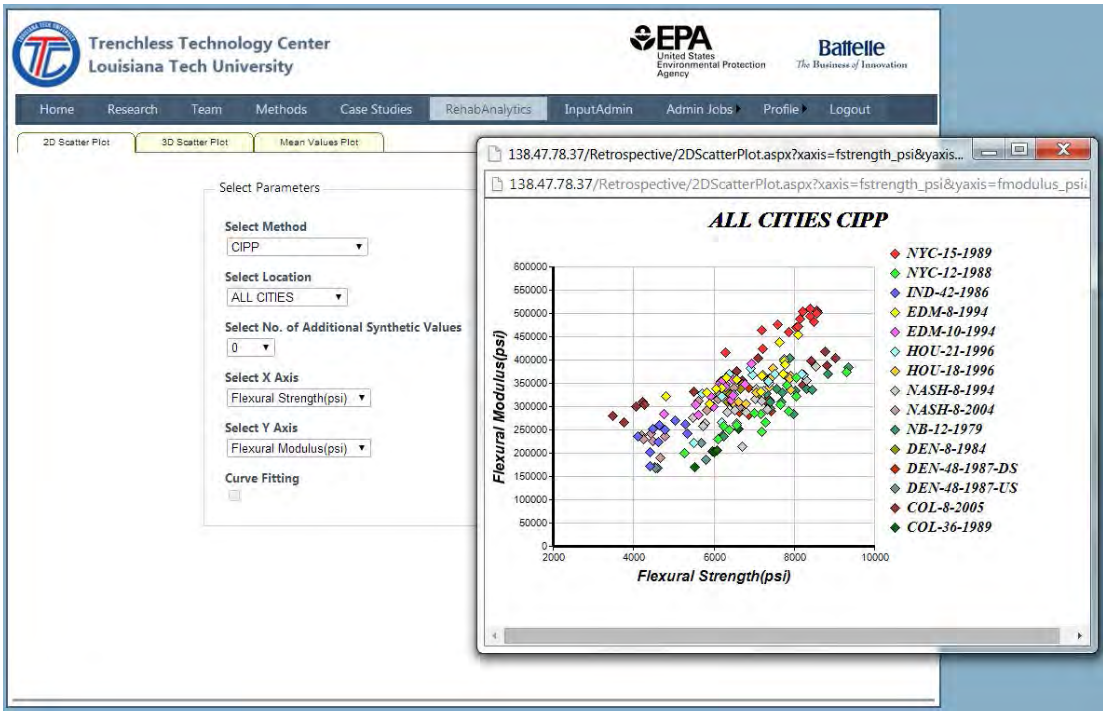


Figure 5-18. Web Site Plot of Flexural Modulus versus Flexural Strength

Figure 5-19 shows the relationship of flexural modulus to liner specific gravity for all of the CIPP sites. While there is a wide scatter in the flexural modulus results in any specific gravity range, there is a clear overall trend towards increasing flexural modulus with increasing specific gravity.

Figure 5-20 illustrates the use of the “synthetic” value parameters (set to 100 “synthetic” values) in the plot as discussed in Section 2.0. This parameter creates additional estimated values for each dataset keeping the mean and standard deviation of each dataset unchanged.

Figures 5-21 and 5-22 both show a comparison of plots of flexural modulus versus inner surface hardness for all of the CIPP sites. Figure 5-21 has the synthetic value parameter set to 0 and Figure 5-22 sets the parameter to 100.

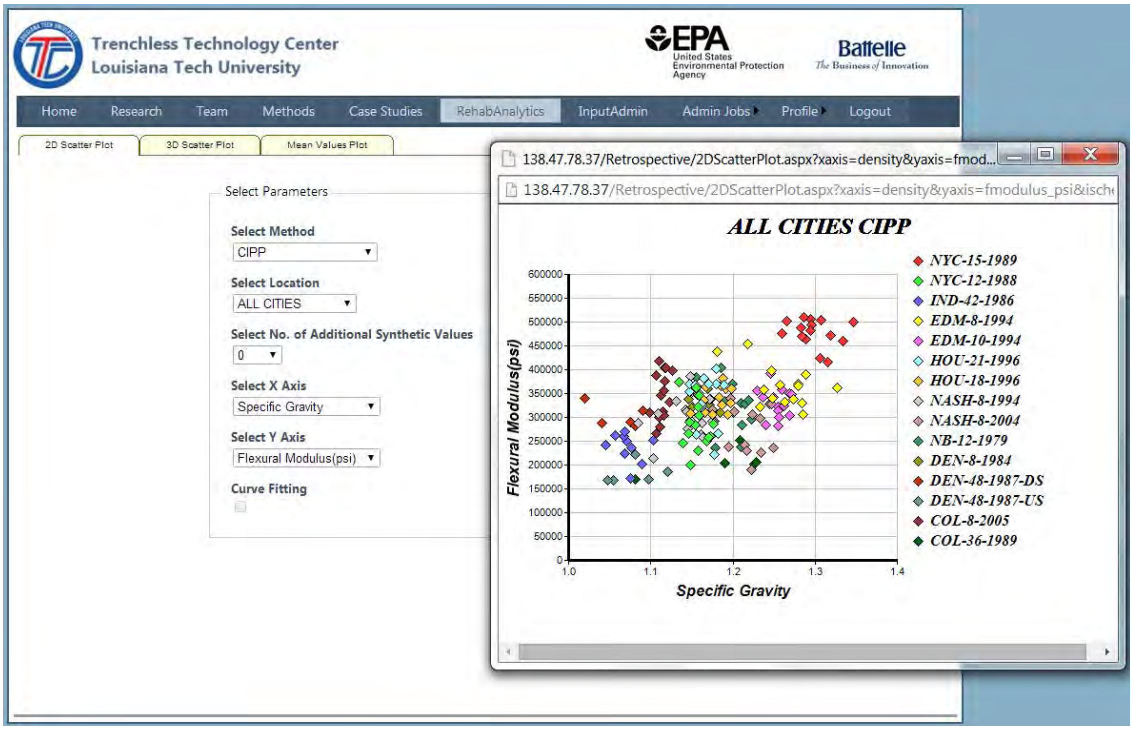


Figure 5-19. Web Site Plot of Flexural Modulus versus Specific Gravity for All CIPP Sites

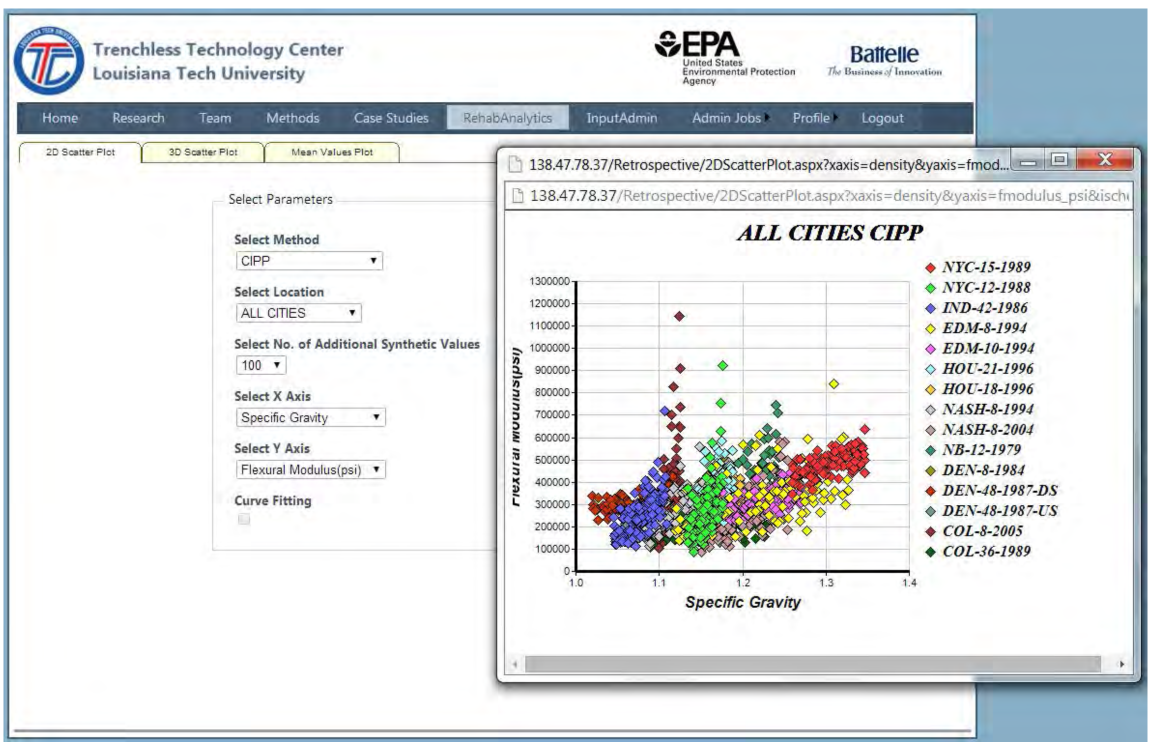


Figure 5-20. Web Site Plot of Flexural Modulus versus Density (100 Synthetic Values) for All CIPP Sites

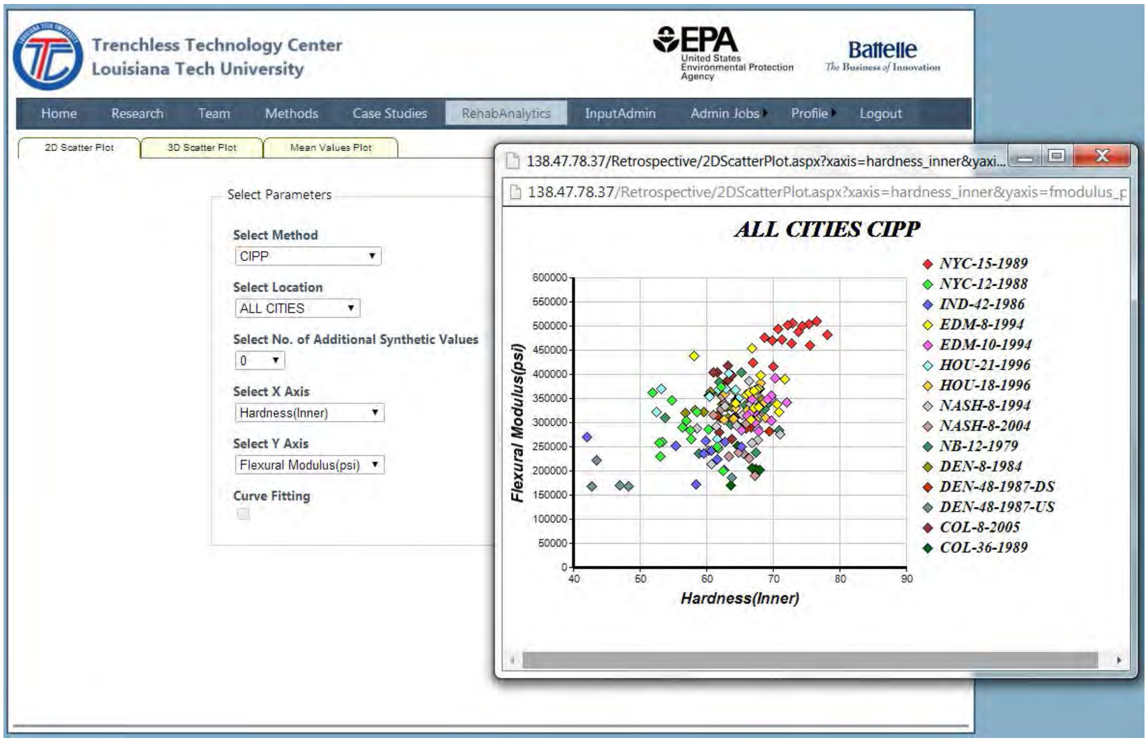


Figure 5-21. Web Site Plot of Flexural Modulus versus Inner Surface Hardness (No Synthetic Values) for All CIPP Sites

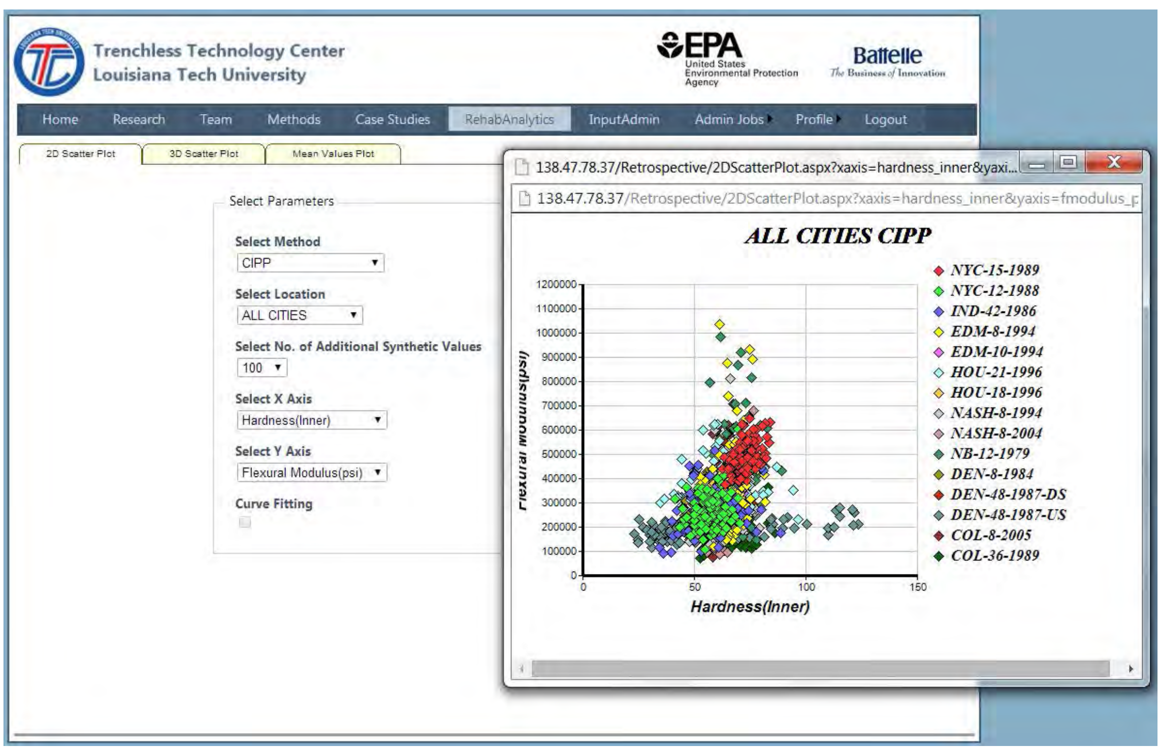


Figure 5-22. Web Site Plot of Flexural Modulus versus Inner Surface Hardness (100 Synthetic Values) for All CIPP Sites

Figures 5-23 and 5-24 examine whether the relationships appear to vary among the individual sites. Figure 5-23 plots the data for the Indianapolis site (which has low flexural modulus values) against the inner surface hardness. Figure 5-24 plots the data for the NYC-15 (NYC Sample 2) site, which has high flexural modulus values. In contrast to the plots including data from all the sites, both graphs show little trend for the flexural modulus to increase with increasing inner surface hardness.

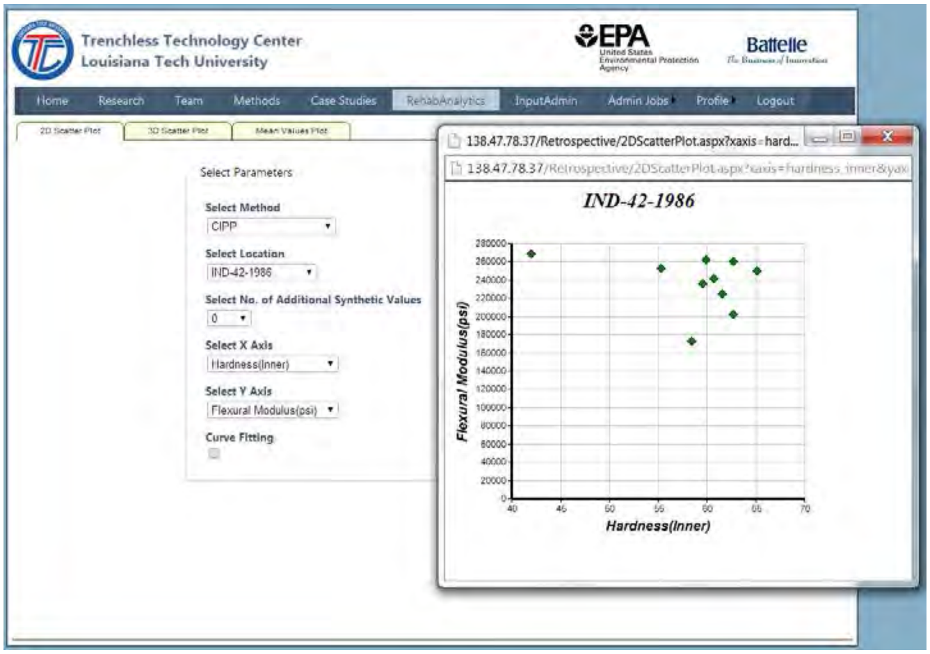


Figure 5-23. Web Site Plot of Flexural Modulus versus Inner Surface Hardness for Indianapolis

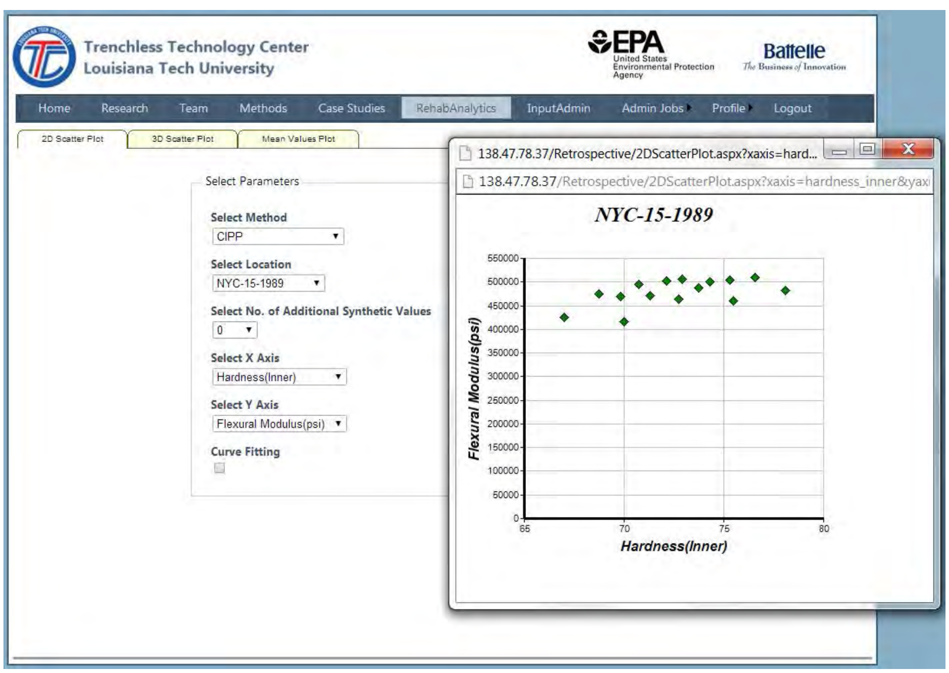


Figure 5-24. Web Site Plot of Flexural Modulus versus Inner Surface Hardness for NYC-15

5.3.3 Database Mean Value Plots. The Web site provides the facility to plot bar charts of the mean values for specific laboratory test parameters across all CIPP sites. Three examples are shown in this section. Figure 5-25 shows the mean values of flexural modulus for all of the sites. Figure 5-26 shows the mean values of flexural strength and Figure 5-27 shows the mean values of liner specific gravity. The interpretation of these results in terms of meeting design standards and CIPP life-cycle performance was presented in Sections 5.1 and 5.2.

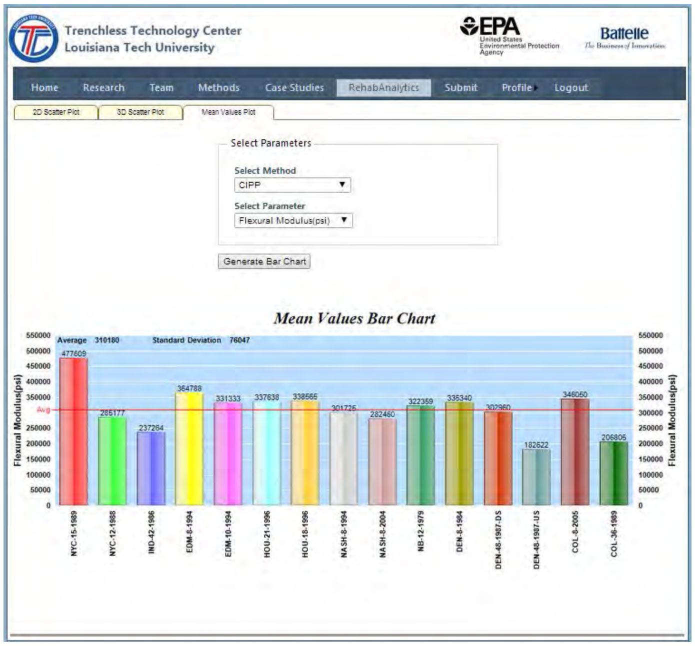


Figure 5-25. Web Site Bar Chart for Mean Values of Flexural Modulus

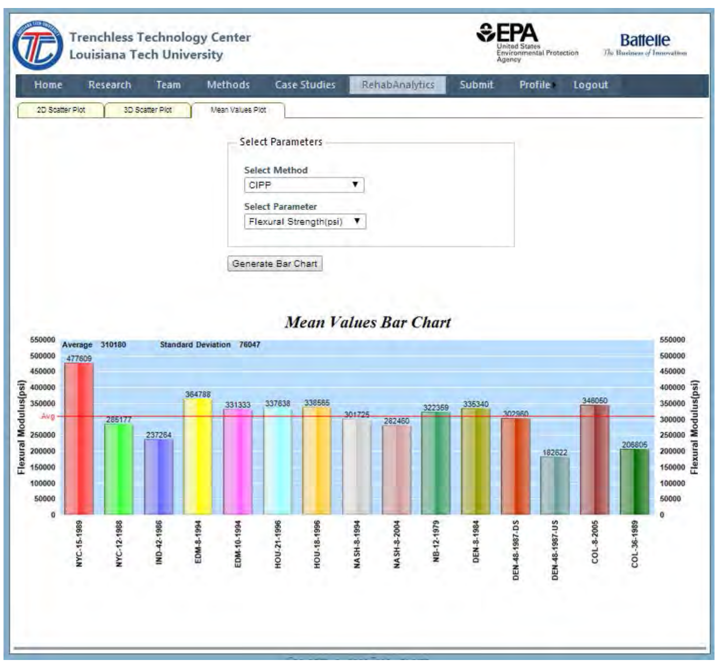


Figure 5-26. Web Site Bar Chart for Mean Values of Flexural Strength

Figure 5-27. Web Site Bar Chart for Mean Values of Liner Specific Gravity

5.3.4 Summary for Database. In Section 5.3, a preview of the possibilities represented by the database has been provided. Users can download both the test data and the full set of site data in a Microsoft® Excel spreadsheet format providing users with the possibility to evaluate these datasets in different ways and in combination with other sets of data. The database includes data for CIPP liners that had been in the ground for up to 34 years in comparison with an original design life of 50 years. With such a large national investment already made (and continuing) in the rehabilitation of sewers, it is reassuring to see that the retrospective evaluation of these CIPP systems is very positive in terms of the potential for these systems to last beyond their expected 50-year lifetime.

5.4 Other Rehabilitation Technologies

The pilot retrospective evaluation effort for trenchless rehabilitation technologies focused on CIPP installations for gravity sewers. These were the earliest installations (other than sliplining) and CIPP has become the dominant technology for rehabilitation. However, as the research thrust moves ahead, in addition to finding more sites for CIPP evaluation, attention has been given to providing a retrospective evaluation of various other trenchless rehabilitation technologies. In the current phase, these evaluations have been restricted to technologies used in gravity sewers, but in future phases it is hoped to broaden the retrospective evaluations to technologies used in pressure sewers and water distribution systems. In this report, the evaluation of other rehabilitation technologies is restricted to the PVC fold-and-form liner, the HDPE deform-reform liner and sliplining.

This section provides:

- Identification of the key test parameters used for acceptance and QC criteria in the relevant standards for fold-and-form liners, deform-reform liners and slipliners.
- A summary of the results and their interpretation obtained from the retrospective evaluation.

Description of the sample retrieval and test protocols used for the collection of fold-and-form, deform-reform, and sliplining samples collected in the current project phase are given in Appendix A. The detailed site information and test results for each site are given in Appendix C.

5.4.1 Sample Sites and Key Test Parameters. Table 5-10 lists the seven sites from four cities that were used in the retrospective evaluation of PVC fold-and-form liners, HDPE deform-reform liners and polyethylene slipliners. Two fold-and-form liners, three deform-reform liners and two slipliners were included in the current evaluation.

5.4.1.1 PVC Fold and Form Standards. Both of the PVC fold-and-form liners evaluated are reported to be liners provided by the company Ultraliner. The installation of these liners was covered by ASTM Standards F1867 and F1871. The PVC liner material used in these standards should meet the requirements of cell classification 12111 as defined in ASTM D1784. A different standard for PVC fold-and-form rehabilitation also exists as ASTM F1504 for which materials should meet the cell classifications 12334, 13223, 32334 or 33223 as defined in ASTM D1784. However, the retrospective samples collected in this phase of the data collection relate to the F1867 and F1871 standards. The key parameters for comparison with the test results are in terms of tensile strength, tensile modulus, flexural strength and flexural modulus.

5.4.1.2 HDPE Deform-Reform Standards. The deform-reform liner materials and installation follow the ASTM standard practice F1606 and standard specification ASTM F1533. These in turn refer to two types of polyethylene: PE2406 (cell classification 234333[C, D or E]) and polyethylene PE3408 (cell classification 345434[C, D or E]) as defined in ASTM D3350 *Standard Specification for Polyethylene Plastics Pipe and Fittings Materials*. The key parameters for comparison with the test results are in terms of density, flexural modulus, tensile strength and environmental stress crack resistance (ESCR). The specifications used by the City of Nashville at the time of installation specifically identify PE3408 as the cell classification to be used for the deform-reform process and hence the retrospective values will be compared with the values required for this classification.

5.4.1.3 Polyethylene Sliplining Standards. Polyethylene sliplining installation is covered in ASTM F585 *Standard Guide for Insertion of Flexible Polyethylene Pipe into Existing Sewers* but this guide does not specify the particular standards for the polyethylene pipe materials themselves. Hence, the most appropriate standard with which to reference the retrospective test results is ASTM D3350 *Standard Specification for Polyethylene Plastics Pipe and Fittings Materials*. Using this standard, and similarly to the deform-reform linings, the key parameters for comparison with the test results are in terms of density, flexural modulus, tensile strength and ESCR. The PE3408 classification is used as the reference for comparison with the retrospective results.

5.4.2 Summary of Results for Other Rehabilitation Technologies. Table 5-10 gives the average results for key parameters tested in the laboratory for each site for the non-CIPP retrospective samples tested in the current study.

Table 5-10. Summary of Key Laboratory Test Results for Other Rehabilitation Technologies

Location	Years of Service	Average Values							
		ASTM D638 (psi)		ASTM D790 (psi)		Specific Gravity	Shore D Hardness		Thickness (mm)
		Tensile Strength	Tensile Modulus	Flexural Strength	Flexural Modulus		Inner	Outer	
Denver (F&F) (8 in.)	15	5,418 ± 547	288,335 ± 31,968	7,791 ± 197	273,471 ± 8,975	1.32 ± 0.01	63.72 ± 1.12	69.38 ± 1.50	4.17 ± 0.05
Nashville (F&F) (8 in.)	14	5,914 ± 163	314,873 ± 36,523	8,581 ± 299	279,551 ± 8,260	1.30 ± 0.08	64.2 ± 1.44	69.72 ± 1.96	5.21 ± 0.89
Denver (D-R) (8 in.)	15	3,019 ± 403	145,851 ± 15,144	3,364 ± 193	108,816 ± 5,891	0.94 ± 0.01	55.90 ± 1.67	59.49 ± 1.16	7.98 ± 0.25
Miami (D-R) (8 in.)	15	3,053 ± 92	142,479 ± 15,584	3,154 ± 113	103,646 ± 4,015	0.94 ± 0.01	54.03 ± 2.69	56.00 ± 1.99	8.33 ± 0.11
Nashville (D-R) (8 in.)	19	2,975 ± 149	162,567 ± 19,705	3,133 ± 75	108,126 ± 3,385	0.94 ± 0.01	57.56 ± 0.95	59.72 ± 0.98	6.85 ± 0.03
Houston 1 (SL) (8 in.)	18	2,979 ± 239	137,875 ± 81,053	3,152 ± 116	100,636 ± 4,728	0.94 ± 0.01	52.84 ± 1.14	58.15 ± 1.15	7.57 ± 0.09
Houston 2 (SL) (8 in.)	Not known	3,098 ± 542	147,875± 32,900	3,174 ± 255	101,881 ± 10,373	0.97 ± 0.01	53.65 ± 1.29	56.4 ± 1.73	8.45 ± 0.05

F&F = fold-and-form; D-R = deform/reform; and SL = sliplining

5.4.2.1 Visual Inspection. All of the fold-and-form (PVC), deform-reform (HDPE) and sliplining (PE) samples were deemed to be in good condition.

5.4.2.2 Annular Gap. Annular gaps were measured wherever possible in the field and/or in the laboratory. It was not always possible to measure the field values due to site configurations and/or conditions. In addition, where the host pipe could not be retrieved from the field, annular gap measurements were not possible in the laboratory. The available observations are summarized in Table 5-11.

Table 5-11. Annular Gap Observations for Other Rehabilitation Technologies

Sample	Annular gap observations
Denver (F&F) (8 in.)	Varied from 0 to 2 mm with average of 0.35 mm
Nashville (F&F) (8 in.)	Varied from 0 to 6.4 mm with average of 2.83 mm
Denver (D-R) (8 in.)	N/A
Miami (D-R) (8 in.)	N/A
Nashville (D-R) (8 in.)	Varied from 0 to 12.7 mm with average of 5.55 mm
Houston 1 (SL) (8 in.)	N/A
Houston 2 (SL) (8 in.)	N/A

N/A = Annular gap could not be measured

5.4.2.3 Soil and Pipe Sediment pH Values. The pH values of any sediment inside the CIPP liner were measured for most of the sample sites together with values from any sediment available from the outside of the pipe. The results are tabulated in Table 5-12. The pH values for sediment retrieved from inside the pipe varied from approximately 5 to 8.5. The pH values for the external soil samples were all in the range of 6 to 7. Where a comparison was possible, the pH values outside the pipe tended to be higher than inside the pipe.

Table 5-12. Measurements of pH for Other Rehabilitation Technologies

Sample	Inner Pipe Sediment pH	External Soil pH
Denver (F&F) (8 in.)	6 to 7	6 to 7
Nashville (F&F) (8 in.)	5	6 to 7
Denver (D-R) (8 in.)	N/A	N/A
Miami (D-R) (8 in.)	7 to 8	N/A
Nashville (D-R) (8 in.)	5 to 6	6 to 7
Houston 1 (SL) (8 in.)	8 to 8.5	N/A
Houston 2 (SL) (8 in.)	7 to 8	N/A

N/A = Sediment or soil sample not available for testing

5.4.2.4 Liner Ovality. Liner ovality was measured whenever a full circumference liner sample could be retrieved. The measurement procedures are described in Appendix B. The ovality measurement results are provided in Table 5-13.

The maximum liner ovality measured was 2.96% for the fold-and-form samples, 6.68% for the deform-reform samples and 3.33% for the sliplining samples. Liner ovality reduces the resistance to buckling of an oval liner compared to an otherwise equivalent circular liner and this effect is included in the design equations in ASTM F1216, which are also typically applied for the buckling determination of other types of plastic liners. The ovalities for all three deform-reform samples are similar and significantly higher than for the fold-and-form and sliplining samples. Since the ovalities were measured after the liners were released from the host pipes, it is possible that these ovalities represented the tendency of the liner type rather than being representative of the three host pipes from the three different cities.

Table 5-13. Measured Liner Ovality for Other Rehabilitation Technologies

Sample	Liner Ovality (%)
Denver (F&F) (8 in.)	1.66
Nashville (F&F) (8 in.)	2.96
Denver (D-R) (8 in.)	5.20
Miami (D-R) (8 in.)	6.65
Nashville (D-R) (8 in.)	6.68
Houston 1 (SL) (8 in.)	1.76
Houston 2 (SL) (8 in.)	3.33

N/A = Ovality measurement not possible because only a panel sample was available

5.4.3 Liner Thickness. The liner thicknesses for the seven sites for other rehabilitation technologies are presented in Table 5-14. The fold-and-form liners were the thinnest at 4.2 and 5.2 mm, respectively. The deform-reform liners ranged from 6.9 to 8.3 mm thick and the slipliners were 7.6 and 8.5 mm thick. For most of the liners, the design/specified thickness of the liner at the time of installation could not be retrieved from the records.

All of the host pipes had a nominal 8 in. inside diameter and hence the dimension ratios are directly comparable. The maximum dimension ratio (DR) was 48.7 for the Denver fold-and-form liner. This value is significantly higher than the range provided in ASTM F1871. The Nashville fold-and-form liner DR of 39 can be compared to the Nashville specifications that called for a maximum DR of 35, i.e., the liner is slightly thinner than specified. The deform-reform liners had DRs ranging from 24.4 to 29.7. The Nashville deform-reform liner had a DR of 29.7, which met the Nashville deform-reform specification for a maximum DR of 32.5. The sliplining DRs were 24.0 and 26.8, but there is no specific value with which to compare these values.

Table 5-14. Measured and Specified Liner Thickness for Other Rehabilitation Technologies

Sample	Measured Thickness (mm)	Actual Average DR	Cell Class. (ASTM)	DR Range in 8 in Host Pipe or Specified Minimum Value
Denver (F&F) (8 in.)	4.17 ± 0.04	48.7	12111 (D1784)	26-35
Nashville (F&F) (8 in.)	5.21 ± 0.89	39.0	12111 (D1784)	35
Denver (D-R) (8 in.)	7.98 ± 0.25	25.5	PE3408	17-32.5
Miami (D-R) (8 in.)	8.33 ± 0.11	24.4	PE3408	17-32.5

Nashville (D-R) (8 in.)	6.85 ± 0.03	29.7	PE3408	32.5
Houston 1 (SL) (8 in.)	7.57 ± 0.09	26.8	N/A	N/A
Houston 2 (SL) (8 in.)	8.45 ± 0.06	24.0	N/A	N/A

5.4.4 Specific Gravity. The specific gravity of all seven liners for the other rehabilitation technologies was determined using ASTM D792 and the average results are listed in Table 5-10. The standard deviations for the tests on each liner were small, indicating a good consistency of density even after many years of service.

The average specific gravity for the PVC fold-and-form liners was in the range of 1.30 to 1.32. The specific gravity of the PVC material is not used as a classification or specification tool in the relevant standards and hence there is no specific reference for comparison in this application.

For the HDPE deform-reform liners, the average specific gravity was approximately 0.94. For the polyethylene slipliners, the average specific gravity was in the range of 0.94 to 0.97. ASTM D3350 classifies polyethylene by density as low density (0.910 to 0.925), medium density (0.926 to 0.940) and high density (0.941 to 0.965). This matches the HDPE designation for the deform-reform liners and also indicates that the slipliners represented, in one case, a high density polyethylene and, in the other case, a polyethylene on the border between high and medium density.

The specific gravity measurements of the liners after removal from service did not provide any evidence of material degradation.

5.4.5 Tensile Properties. The tensile properties of the liners from the seven sites for other rehabilitation technologies were evaluated according to ASTM D638 and are listed in Table 5-10. No test data from the time of installation were available for any of the liner types.

The average tensile strengths for the fold-and-form liners were 5,418 psi and 5,914 psi compared to the as-installed required tensile strength from ASTM F1867 of 3,600 psi. The average (short-term) tensile moduli for the fold-and-form liners were 288,335 and 314,873 psi compared to the minimum required in ASTM F1867 of 155,000 psi. Both the tensile strength and the tensile modulus values measured after 14 to 15 years of service significantly exceed the original requirements of the cell classification 12111.

The average tensile strengths for the deform-reform liners ranged from 2,975 psi to 3,053 psi compared to the minimum permissible values at installation of 2,600 psi for PE3408. Hence, the retrospective test values exceeded the as-installed requirement after 15 to 19 years of service. The average (short-term) tensile moduli ranged from 142,479 psi to 162,567 psi, but there is no corresponding requirement in the standard.

The average tensile strengths for the slipliners were 2,979 psi and 3,098 psi compared to the minimum permissible values at installation of 2,600 psi for PE3408. The average (short-term) tensile moduli were 137,875 psi and 147,875 psi, but there is no corresponding requirement in the standard.

5.4.6 Flexural Properties. The flexural properties of the liners from the seven sites for other rehabilitation technologies were evaluated according to ASTM D790 and are listed in Table 5-10. No test data from the time of installation were available for any of the liner types.

The average flexural strengths for the fold-and-form liners were 7,791 psi and 8,581 psi compared to the as-installed required flexural strength from ASTM F1867 of 4,100 psi. The average (short-term) flexural moduli for the fold-and-form liners were 273,471 and 279,551 psi compared to the minimum required in ASTM F1867 of 145,000 psi. Both the flexural strength and the flexural modulus after 14 to 15 years of service are well in excess of the required values at the time of installation.

The average flexural strengths for the deform-reform liners ranged from 3,133 psi to 3,364 psi, but there is no corresponding requirement in the standard. The average (short-term) flexural moduli ranged from 103,646 psi to 108,816 psi compared to the minimum value of 80,000 psi for PE3408 and hence all the retrospective values exceeded the as-installed requirement.

The average flexural strengths for the slipliners were 3,152 psi and 3,174 psi, but there is no corresponding requirement in the standard. The average (short-term) flexural moduli were 100,636 psi and 101,881 psi compared to 80,000 psi for PE3408.

5.4.7 Shore D Hardness. The Shore D hardness values for both the inner and outer surfaces of the retrieved liner samples were determined for the seven sites for other rehabilitation technologies using ASTM D2240 and the results are listed in Table 5-10.

The average inner hardness for the fold-and-form liners varied from 63.7 to 64.2, whereas the outer hardness varied from 69.4 to 69.7. The average inner hardness for the deform-reform liners varied from 54.0 to 57.6, whereas the outer hardness varied from 56.0 to 59.7. The average inner hardness for the slipliners varied from 52.8 to 53.7, whereas the outer hardness varied from 56.5 to 58.2.

As expected, the PVC liners have a higher hardness than the polyethylene deform-reform liners and slipliners. All three types of liners have lower internal surface hardness values than external surface hardness values after their years of service. This may be due to a slight softening of the interior surface due to in-service exposure to the sewage flow. It would be interesting to carry out similar tests on newly installed liners to see if there are any hardness differences caused by the reforming processes within the host pipe.

5.4.8 Pipe Stiffness. The pipe stiffness was determined according to ASTM D2412 using three samples for each of the seven retrospective test sites for other rehabilitation technologies. The average values measured are listed in Table 5-15. For the PVC Type A material (Ultraliner) and for the polyethylene materials, there are no direct pipe stiffness requirements for comparison.

Table 5-15. Pipe Stiffness for Other Rehabilitation Technologies

Sample	Actual Average DR	Average Pipe Stiffness lb/in/in
Denver (F&F) (8 in.)	48.7	19.8
Nashville (F&F) (8 in.)	39.0	35.1
Denver (D-R) (8 in.)	25.5	36.5
Miami (D-R) (8 in.)	24.4	43.1
Nashville (D-R) (8 in.)	29.7	31.3
Houston 1 (SL) (8 in.)	24.0	41.2
Houston 2 (SL) (8 in.)	26.8	61.6

6 CONCLUSIONS AND RECOMMENDATIONS

This section presents the overall conclusions from the retrospective study along with recommendations for future work. Testing so far has been conducted on 18 CIPP samples from 17 separate sites across the U.S. and Canada. These sites include both the five CIPP samples from four sites studied as part of the pilot study (EPA, 2012) and the 13 CIPP samples tested as part of the current project. Testing also has been conducted on seven retrospective samples from four cities for other rehabilitation technologies (PVC fold-and-form, HDPE deform-reform and polyethylene sliplining).

6.1 Conclusions

6.1.1 Overall Observations for CIPP. The overarching conclusions from the study of the retrospective samples of CIPP lining are as follows:

- The CIPP-lined sewers examined are holding up very well after their current in-service exposures from 5 to 34 years. The only two ASTM F1216 mechanical strength related quality parameters for CIPP liners are defined in terms of flexural modulus and flexural strength. Out of the 17 retrospective sites for which data were available, only one of the average flexural strengths was below the as-installed requirement from ASTM F1216 and, for the flexural modulus, four of the sites had average values that were below the ASTM F1216 as-installed requirement. For the City of Winnipeg Mission St. sample, the specification at the time of installation in 1984 only required a flexural modulus of 240,000 psi and this was met by the retrospective sample even though it did not meet the current ASTM standard. It also should be noted that the Denver 48 inch site had two separate samples with averages falling above and below the 250,000 psi value but with an overall combined average above 250,000 psi. Even for the samples with low modulus values, there was no visible evidence of distress in the liner that would indicate a progressive deterioration and it is not possible to gauge whether the low values represent a change over time or that the original liner did not meet the specified values.
- While some defects were noted in the samples or the associated CCTV inspections, it is believed that most of these defects were created at the time of installation and do not represent a degradation of the liner with time.
- In general, lining of a sewer pipe is only carried out when the existing host pipe has experienced significant defects. For the sites studied, the CIPP lining has stabilized that deterioration and is providing a long continued service life for the pipe. This has been accomplished without the necessity of excavating and replacing the line from the surface.
- While the current dataset does not allow definitive conclusions to be made about the average expected lifetime of CIPP liners, it does appear that the original design life of 50 years aimed at by most municipalities will be met and that much longer lifetimes can be achieved.
- The above conclusions are not meant to imply that no CIPP liners will fail or have performance issues. A number of quality/performance issues have been noted in this study and other studies reported in the literature (see Section 4 for the review of U.S. and international experience with CIPP linings and in particular the papers by Shelton (2012a, 2012b). These should be addressed in designs, specifications, and QA/QC procedures to ensure that high quality liners are installed. It should also be noted that, while CIPP relining has been shown to stabilize the deterioration of the host pipes in which it was installed and to have a significant impact on inflow and infiltration, it does not mean that a leak-free system

has been achieved unless special measures are taken to seal the liner at manholes and lateral openings.

6.1.2 Overall Observations for the Other Rehabilitation Technologies Tested. The overarching conclusions from the study of the other retrospective samples are as follows:

- The non-CIPP liners evaluated in this study comprised two PVC fold-and-form liners with 14 and 15 years of service, three HDPE deform-reform liners with 15 to 19 years of service, and two polyethylene slipliners. One of the slipliners had 18 years of service and the other had an unknown installation date, but is believed to be of a similar or older age. No historic test data from the time of installation were available for any of these liner types.
- For the two PVC fold-and-form liners, the key parameters for evaluation are in terms of tensile strength, tensile modulus, flexural strength and flexural modulus. Both the tensile and flexural liner properties after 14 and 15 years of service are well in excess of the required values at the time of installation.
- For the three HDPE deform-reform liners, the key parameters for evaluation are in terms of density, flexural modulus, tensile strength and ESCR. The retrospective test values exceeded the as-installed requirements after 15 to 19 years of service.
- For the two polyethylene slipliners, the key parameters for evaluation are in terms of density, flexural modulus, tensile strength and ESCR. The installation test parameters are all satisfied after 18 years of service for one liner and an unknown length of time for the other liner.
- The results of the other evaluation tests conducted on these liner types are provided in the report, but did not indicate any distress or deterioration of these types of liners.
- Neither the fold-and-form nor the deform-reform liners are currently marketed in the U.S. and sliplining is not often used in smaller diameter sewers. This reflects competitive pressures in the marketplace and also the tendency of both the fold-and-form and deform-reform liners to not be locked into position longitudinally after installation (causing potential misalignment of lateral openings cut in the liner). However, in terms of the retrospective evaluation of liner material condition, these types of liners are all performing well.

6.1.3 Some Common Threads

6.1.3.1 Lack of Historic Records for Rehabilitation Work. For a variety of reasons, many agencies do not have full historical records for their sewer systems. This lack of information (or having erroneous information) can be in terms of locational information, ages, materials and properties of elements of the system and details of rehabilitation work previously undertaken. In some agencies, there may be city-wide directives to dispose of historical data more than a certain number of years old.

These issues make it much more difficult or perhaps impossible for agencies to establish life-cycle expectancies based on experience with various products or rehabilitation technologies within their system. Commercial database structures are available to assemble such data in a consistent format and it is a critical part of good asset management that agencies maintain a good dataset for future evaluation.

6.1.3.2 Quality Control in Installation. While CIPP relining has proved a fairly forgiving technology in terms of its overall performance in the presence of local defects, the technology can continue to benefit from improvements in QC. The New York Sample 1 example of uncured/missing resin demonstrated the criticality of performing a comprehensive post-installation inspection of a CIPP lining project, as conditions can vary significantly along the length of the host pipe and can result in defective regions within the newly installed liner. Some balancing trends are at work here. The worldwide experience with CIPP installations over more than 40 years has given a strong understanding of the materials and installation parameters that are necessary for a successful installation. However, the change from the existence of a few large and highly experienced installers of CIPP linings to the growth of many small installers creates the situation where the prior industry experience is not always incorporated in projects by the less experienced installers. This is also coupled to the evolution of the materials used within the CIPP family of techniques. While such changes were designed for the improvement of the technology, they may introduce issues that were not present in the previous installations.

The fold-and-form, deform-reform and sliplining technologies also present their own challenges for QC and successful installation. Qualitative municipal experiences (see Appendix D for discussion of these issues) indicate potential problems with the proper re-rounding of the fold-and-form and deform-reform liners to avoid folds in the finished liner, loose liners or failure of the host pipe due to excessive internal pressures. Slipliners are inherently installed as loose liners and hence must be grouted or anchored longitudinally to prevent movement.

Owners and designers need to have strong QA procedures in place, checking materials used, measuring key parameters and inspecting the key phases of the work. Contractors should make sure that they have adequate QC procedures to deliver high quality liners that meet the specifications and will have a long service life.

6.1.3.3 Usefulness of Various Test Parameters. One of the goals of the retrospective evaluation program has been to investigate the most meaningful and most easily tested parameters for CIPP and other lining types that would provide insight into a liner's quality and life expectancy. Flexural modulus and flexural strength continue to be the most tested parameter and provide good measures for the quality and strength of a CIPP liner. There are issues, however, with the preparation of representative samples of the liner at the time of installation and the testing procedures themselves can allow variation in the measured results. The specific gravity of an installed liner also is a useful measure of liner quality and requires smaller sample sizes than for the mechanical testing. Surface hardness measurements have been examined in this research as a potential indicator of other mechanical properties. Some degree of correlation has been seen, but field testing protocols that would ensure removal of the sealing layer in the area of the test would be necessary before such a test could be applied as a field testing procedure. Other measures, not evaluated in this research but reported on by others, include permeability testing of CIPP liners, either by laboratory testing of samples or by exfiltration testing of in-situ liners.

For the PVC and polyethylene liners, the standard material tests have demonstrated that these materials do not tend to deteriorate noticeably under normal service conditions underground. There has not been enough testing yet to explore the value of other test parameters for NDT or evaluation through removal of small samples. However, the use of specific gravity and interior surface hardness may offer a similar potential for in-service evaluations of deterioration to their use in CIPP liner systems.

6.2 Recommendations

6.2.1 Future Research Needs. It is believed that the research presented in this report provides critical information relative to the life cycle performance of relining technologies to the owners of systems and the consultants and contractors supporting the renovation of the nation's sewerage systems. The analysis of samples from only 18 CIPP sites plus seven other rehabilitation technology sites across the U.S. and Canada cannot, however, provide a comprehensive answer to the questions surrounding the performance issues that may be experienced with pipe rehabilitation technologies.

The following future research activities are recommended to build on the current work to make the conclusions more robust and to extend this type of study to other infrastructure systems.

- Continue to collect and test samples from additional sewerage systems in North America and especially to encourage municipalities and agencies to use opportunities where rehabilitated sections of pipes or manholes are to be uncovered to include such collection and testing in their work;
- Extend the range of non-CIPP rehabilitation/renewal systems that are investigated for sewer systems;
- Apply a similar methodology to gain an understanding of the performance of rehabilitation systems for pressure pipes, both water distribution systems and sewer force mains;
- Expand the database by adding new data as they become available and encouraging municipalities to add their own test data to the database through administrative access procedures with appropriate data vetting;
- Expand the qualitative assessment information from the large number of municipalities that have experience with various forms of rehabilitation/renewal technologies. While such data are not as precise as the retrospective sample test data, they can provide much broader insights into the issues experienced with a rehabilitation technology and the overall level of satisfaction with the technology; and
- Prepare guidelines for owners and consultants as to how to address the creation of reasonable estimates of service life based on the design, installation and service parameters for rehabilitation systems and incorporating the experience gained through the retrospective testing program and database development.

6.2.2 Recommendations for Agencies and Municipalities. The attention to asset management procedures in sewerage systems has grown considerably in the past decade in North America. There is still much to be done in many agencies, however, to make sure that the right systems are in place for the effective management of the systems and to make sure that the necessary high-quality data are collected and preserved for the future. Many agencies are fighting a battle against an aging sewer system with inadequate funds and personnel, but an appropriate level of understanding of system performance and deterioration trends can allow the most effective use of limited resources.

Based upon the topics explored in this study, it is recommended that:

- Agencies treat the rehabilitation/renewal of a pipe or other element of the system as an opportunity to build the asset management starting point for the renovated element.
- Accurate positional information and host pipe details are easily gathered while such work is underway.

- The QA/QC data used to control/document the work provides the starting point for tracking the performance of the rehabilitation/renewal technology. Such data should be maintained within the agency's system for future comparisons.
- Where feasible, agencies are encouraged to share their performance findings through the database established in this project.

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APPENDIX A

TEST PROTOCOLS

In this appendix, the testing and measurement protocols used in the retrospective data collection are outlined for both the CIPP data collection and the data collection for the other rehabilitation technologies. This is followed by a brief description of the ASTM standard test procedures used for the laboratory testing.

Table A-1 provides the testing and measurement protocols for field-based measurements and Table A-2 for laboratory-based measurements for the CIPP retrospective evaluations. The parameters to be measured included visual inspection, annular gap, liner thickness, specific gravity, tensile strength/modulus, flexural strength/modulus, surface hardness, glass transition temperature, and porosity. The testing parameters also depended on the size of the sample retrieved and are defined as noted below for small and large diameter liner samples. For example, ovality and buckling tests were only applicable to whole pipe samples collected from small diameter pipes. In some cases, due to the sample retrieval process, the site conditions or the host pipe/liner condition, it was not possible to collect all of the data for all of the samples. The specific information collected for each sample is provided with the discussion for each test location in Appendix B.

Table A-1. Protocol for CIPP Field Measurements and Retrieved Samples

Field Measurements	No. of Measurements	Sample	Test Standard/ Instrument	Notes
Large Diameter Sewer				
Liner only specimen	1	24 in. × 24 in.	N/A	Shipped to TTC
Visual liner inspection	Continuous	N/A	N/A	Digital photos
Liner thickness (Retrieved Sample)	4	N/A	Caliper	1 measurement on each side of the removed CIPP panel (to nearest mm).
Annular gap (Remaining Host Pipe)	8	N/A	Feeler gauge	2 measurements on each side of existing CIPP liner at removed section. Note measurements to be conducted by City contractor after sample removal.
Small Diameter Sewer				
Liner + host pipe specimen	1	6 ft length	N/A	Shipped to TTC
Visual liner inspection	Continuous	N/A	N/A	Digital photos
Soil conditions + bedding	6	Grab samples	N/A	Soil lab analysis and visual inspection.
Liner thickness (Remaining Host Pipe and Retrieved Sample)	8 × 2 = 16 for remaining host pipe 8 × 2 = 16 for retrieved sample	N/A	Caliper	8 measurements at 45° each side (north and south) of host pipe and removed section.
Annular gap (Remaining Host Pipe and Retrieved Sample)	8 × 2 = 16 for remaining host pipe 8 × 2 = 16 for retrieved sample	N/A	Feeler gauge	8 measurements at 45° each side (north and south) of host pipe and removed section.

N/A = not applicable

Table A-2. Protocol for CIPP Laboratory Measurements

Laboratory Measurements	Samples	No. of Measurements (each site)	Sample Size	Test Standard/ Instrument	Notes
Visual Liner Inspection	All samples	Continuous	N/A	N/A	Surface film, leakage, corrosion, bacterial growth, etc.
Apparent Specific Gravity/Density	All samples	3 each	2 in. × 2 in.	ASTM D792	N/A
Tensile Strength and Elongation at Failure	Small Diameter	3	0.75 in. × 7.2 in. each	ASTM D638	N/A
Tensile Strength and Elongation at Failure	Large Diameter	3	1.13 in. × 9.7 in. each	ASTM D638	N/A
Flexural Strength and Flexural Modulus	Small Diameter	5	1 in. × 5 ft each	ASTM D790	N/A
Flexural Strength and Flexural Modulus	Large Diameter	5	2 in. × 12 in. each	ASTM D790	N/A
Durometer (Shore) Hardness	All samples	5 each	N/A	ASTM D2240	N/A
Glass Transition Temperature	All samples	2 each	3 in. × 0.5 in.	ASTM E1356 Differential Scanning Calorimetry	N/A
Porosity	All samples	1	N/A	Mercury vapor intrusion test	N/A
Pipe Ovality	Small Diameter	1	1 ft	Profile plotter	Measurements continuous in buckling test sample
Short-Term Liner Buckling Strength	Small Diameter	1	4 ft sample length	ASTM F1216	Modified according to sample condition
Soil Analysis	Small Diameter	6	500 g	ASTM C136 sieve analysis; ASTM C128 density; ASTM D2216 moisture content; and Thermo Orion meter for soil pH	N/A

N/A = not applicable

For the other rehabilitation technologies, the sample field collection protocol was similar to that previously used for CIPP. A pipe length of 6 to 8 ft was retrieved including the liner and host pipe. Table A-3 summarizes the information to be collected in the field.

Table A-3. Protocol for Field Measurements and Retrieved Samples for Other Rehabilitation Technologies

Field Measurements	No. of Measurements	Sample	Test Standard/ Instrument	Notes
Liner + host pipe specimen	1	6 to 8 ft[(a)]	N/A	Shipped to TTC
Visual liner inspection	Continuous	N/A	N/A	CCTV or digital photos. Verify that the liner is tight at the ends and at any reinstated laterals. Document any evidence of holes, splitting, cracking, or breaking. Note any localized areas indicating uneven stretching. Verify that the reinstated laterals are fully opened.
Liner thickness (Remaining Host Pipe and Retrieved Sample)	8 × 2=16 for remaining host pipe 8 × 2=16 for retrieved sample	N/A	Caliper	8 measurements at 45° each side (north and south) of host pipe and removed section.
Annular gap (if applicable) (Remaining Host Pipe and Retrieved Sample)	8 × 2=16 for remaining host pipe 8 × 2=16 for retrieved sample	N/A	Feeler gauge	8 measurements at 45° each side (north and south) of host pipe and removed section.
Grout thickness (if applicable) (Remaining Host Pipe and Retrieved Sample)	8 × 2=16 for remaining host pipe 8 × 2=16 for retrieved sample	N/A	Caliper	8 measurements at 45° each side (north and south) of host pipe and removed section.

N/A: not applicable
[(a)]Depending on material and presence of pipe joints, laterals or bends

The laboratory analyses were established according to the type of liner sample. Tables A-4 to A-6 summarize the laboratory analyses employed to test the samples for fold-and-form (using polyvinyl chloride [PVC]), deform/reform (using polyethylene [PE]), and sliplining [using PVC or PE]).

Table A-4. Laboratory Measurements for Fold-and-Form Samples (PVC)

Laboratory Measurements	Samples	No. of Measurements (each site)	Sample Size	Test Standard/ Instrument
Visual Inspection	N/A	1	6 to 8 ft	Any evidence of holes, splitting, cracking, or breaking.
Pipe Inside Diameter	1	16	18 in.	ASTM D2122
Pipe Outside Diameter	1	16	18 in.	ASTM D2122
Wall Thickness	1	16	18 in.	ASTM D2122
Pipe Ovality	1	3	6 to 8 ft	Profile plotter
Tensile Strength and Elongation at Failure	6	6	6 in. long × 1 in. wide	ASTM D638
Flexural Strength and Flexural Modulus	6	6	6 in. long × 1 in. wide	ASTM D790
Pipe Stiffness	3	3	6 in.	ASTM D2412
Density	6	6	1 in. × 1 in. Coupon	ASTM D792

N/A: not applicable

Table A-5. Laboratory Measurements for Deform/Reform Samples (PE)

Laboratory Measurements	Samples	No. of Measurements (each site)	Sample Size	Test Standard/ Instrument
Visual Inspection	N/A	1	6 to 8 ft	Any evidence of holes, splitting, cracking, or breaking.
Pipe Inside Diameter	1	16	18 in.	ASTM D2122
Pipe Outside Diameter	1	16	18 in.	ASTM D2122
Wall Thickness	1	16	18 in.	ASTM D2122
Pipe Ovality	1	3	6 to 8 ft	Profile plotter
Tensile Strength and Elongation at Failure	6	6	6 in. long × 1 in. wide	ASTM D638
Flexural Strength and Flexural Modulus	6	6	6 in. long × 1 in. wide	ASTM D790
Pipe Stiffness	3	3	6 in.	ASTM D2412
Density	6	6	1 in. × 1 in. Coupon	ASTM D792
Hardness	6	20	1 in. × 1 in. Coupon	ASTM D2240
Environmental Stress Cracking (ESCR)	6	6	6 in. long × 2 in. wide	ASTM D1693

N/A: not applicable

Table A-6. Laboratory Measurements for Sliplining (PVC or PE)

Laboratory Measurements	Samples	No. of Measurements (each site)	Sample Size	Test Standard/ Instrument
Visual Inspection	N/A	1	6 to 8 ft	Any evidence of holes, splitting, cracking, or breaking.
Pipe Inside Diameter	1	16	18 in.	ASTM D2122
Pipe Outside Diameter	1	16	18 in.	ASTM D2122
Wall Thickness	1	16	18 in.	ASTM D2122
Pipe Ovality	1	3	6 to 8 ft	Profile plotter
Tensile Strength and Elongation at Failure	6	6	6 in. long × 1 in. wide	ASTM D638
Flexural Strength and Flexural Modulus	6	6	6 in. long × 1 in. wide	ASTM D790
Pipe Stiffness	3	3	6 in.	ASTM D2412
Density	6	6	1 in. × 1 in. Coupon	ASTM D792
Hardness	6	20	1 in. × 1 in. Coupon	ASTM D2240

N/A: not applicable

The main sample test data included are thickness (ASTM D2122), flexural modulus and flexural strength (ASTM D790), tensile modulus and tensile strength (ASTM D638), apparent specific gravity (ASTM D792), and hardness (ASTM D2240). The procedures for the collection of the main sample test data are provided below.

Sample Thickness Measurement. In ASTM D2122, specimens were cut into 1 in. × 1 in. squares and the thickness was measured using a micrometer with a resolution of ±0.0025 mm (see Figure A-1).

Figure A-1. Micrometer Set (left) and Measurement of Thickness Using a Micrometer (right)

Flexure and Tensile Testing. Flexure (ASTM D790) and tensile (ASTM D638) tests were performed using a 2.2 Kip capacity universal testing machine. No slippage was ensured by employing the pneumatic grips during the tensile test. The samples were prepared according to the relevant standard (see Figure A-2) and later tested using the universal testing machine (see Figure A-3). It should be noted that, for the tensile testing, the extensometer used had a range of up to 2 in. elongation and hence the tensile tests were stopped if the specimen extension reached this value.

Figure A-2. ASTM D638 Specimens (left) and ASTM D790 Specimens (right)

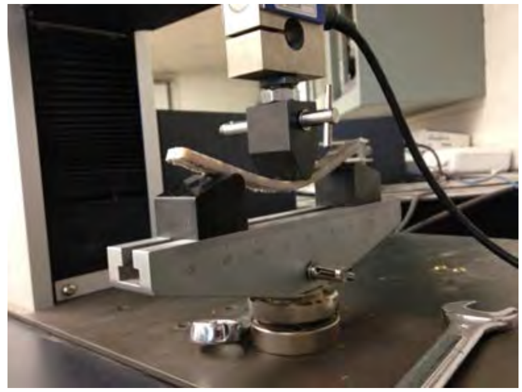

Figure A-3. ASTM D638 Test (left) and ASTM D790 Test (right)

Apparent Specific Gravity. Apparent specific gravity was measured following ASTM D792. Specimens of 1 in. ×1 in. size were cut from the CIPP liner/panel. The weight of each specimen was measured first in air and later in water. A sinker was used to ensure submersion of the test sample (see Figure A-4). The water temperature also was read to allow the appropriate water density to be used.

Figure A-4. Weight Measured in Air (left) and in Water (right)

Durometer (Shore Type D) Hardness. Durometer (Shore Type D) hardness (ASTM D2240) was used to determine the hardness of the liner samples (see Figure A-5). Samples (1 in. × 1 in.) were cut from the retrieved CIPP liner with a band saw. The Shore D hardness scale utilizes a weight of 10 lb (4,536 g). The tip diameter and angle are 0.1 mm and 35°, respectively. Readings were taken on the inner and outer surfaces of the liner specimens.

Figure A-5. Hardness Test Instrument (left) and Hardness Test on a Specimen (right)

APPENDIX B

CIPP CASE STUDIES

The recovery and testing of the retrospective samples collected in this phase of the research are presented in this appendix. A total of 14 samples from seven different wastewater collection systems were collected for the CIPP portion of the retrospective study and 13 of these samples were tested according to the test protocols established (one of the New York samples had a major defect that precluded detailed testing). The municipalities/entities providing samples included the following: Edmonton, Canada; Houston, Texas; Indianapolis, Indiana; Nashville, Tennessee; New York, New York; Northbrook, Illinois; and Winnipeg, Canada. The testing protocols are similar from one case study to the next and the standard laboratory testing procedures for the key material properties were described and illustrated in Appendix A. Additional test protocols (e.g., buckling tests) are described in this appendix with photographs of the associated procedures and test setup when they first appear but are not repeated for the subsequent case studies. The case studies are presented below in alphabetical order.

This appendix describes the data collection, analyses, and project documentation in accordance with EPA NRMRL's QAPP Requirements for Applied Research Projects (EPA, 2008) and the project-specific QAPPs (Battelle, 2012a; 2012b; and 2013). A QA review was performed on the CIPP case study data presented in Appendix B. All of the results met the QC objective for completeness. Completeness refers to the percentage of valid data received from the testing laboratory. A few results for flexural strength/modulus (3.1%) and for tensile strength/modulus (3.8%) were outside of the QC criteria for relative percent difference (RPD) of + 25%. However, this could be attributable to variations within the material properties of the field-installed CIPP product itself. These data were retained for study purposes, but are noted in the tables below.

B.1 City of Edmonton

B.1.1 Introduction. This report contains the test results performed on two liners exhumed from 119 St., south of 111 Ave., Edmonton, Alberta, Canada. Two samples were collected with inside host pipe diameters of 10 in. and 8 in. (250 mm and 200 mm).

B.1.2 Edmonton Sample 1: A 19-Year Old CIPP Liner in a 10 in. (250 mm) Non-reinforced Concrete Pipe. Edmonton Sample 1 was retrieved from 119 St. and 109A Ave. in Edmonton, Canada on June 21, 2013. The host pipe and liner information are shown in Table B-1. The exposure of the liner due to operating conditions within the sewer was considered relatively benign. The host pipe was at a depth of approximately 3 m (9.8 ft) below ground level.

Table B-1. Edmonton 1: Host Pipe and Liner Information

Host pipe	Non-reinforced concrete pipe, 10 in. (250 mm) in diameter
Liner Thickness	4.81 mm @ 10:00 and 4.92 mm @ 1:00 (design thickness of 5 mm)
Resin	Information not available
Primary Catalyst	Information not available
Secondary Catalyst	Information not available
Felt	Information not available
Seal	Polyurea was used for internal coating
Year of Installation	November 1994
Liner Vendor	Insituform Technologies
Resin Supplier	Camtron or Ashland

The retrieval process and the retrieved sample are shown in Figure B-1. The specimens were received at the TTC South Campus Lab Facility on July 23, 2013.

B.1.2.1 Visual Inspection. The sample was found to be in excellent condition. The polyurea coating was still present and the thickness was uniform around the circumference.

Figure B-1. Edmonton 1: Retrieval of the Sample (left) and Received Sample (right)

B.1.2.2 Annular Gap. The annular gap was measured using a feeler gauge at the ends of the host pipe/liner that remained in the ground. At the north end of the sample, recorded as "Remaining Host Pipe (North)", the initial measurement was recorded in the trench box where the lower half of the pipe was not accessible. Only a 0.036 in. gap was measured at the 10 o'clock position and a 0.011 in. gap was measured at the 2 o'clock position. The remaining locations above the spring line of the liner were found to be fairly tight. Eight readings also were taken at the other end of the sample, recorded as "Remaining Host Pipe (South)". Both sets of readings are shown in Table B-2.

Table B-2. Edmonton 1: Field Readings of Annular Space with Feeler Gauge

O'Clock Position	Annular Gap Measured for Remaining Host Pipe (north end of sample)	Annular Gap Measured for Remaining Host Pipe (south end of sample)
12:00	Tight	0.014 in. (0.40 mm)
1:30	Tight	0.014 in. (0.40 mm)
2:00	0.011 in. (0.28 mm)	N/A
3:00	Tight	0.024 in. (0.61 mm)
5:00	N/A	0.025 in. (0.63 mm)
6:00	N/A	0.011 in. (0.28 mm)
7:30	N/A	0.013 in. (0.33 mm)
9:00	Tight	0.018 in. (0.46 mm)
10:00	0.036 in. (0.91 mm)	N/A
11:00	Tight	0.25 . (0.63 mm)

B.1.2.3 Environmental Service Conditions. 2 g of waste material was scooped from the inside surface of the sample and mixed in 200 mL of distilled water stored in a bottle; pH was measured using a pH-indicator strip (see Figure B-2). The pH was found to be between 7 and 8. No material could be collected from the outer side of the liner for comparison.

Figure B-2. Waste Material Collected from Sample (left) and Measurement of pH using a pH-Indicator Strip (right)

B.1.2.4 ***Ovality.*** A profile plotter was used to accurately map any deformation inside the liner (see Figure B-3 for the setup that was used for the Edmonton 8 in. [200 mm] liner). The system features a linear variable displacement transducer (LVDT) connected to a motor-gear system that rotates around the inner circumference of the liner. An encoder system provides position information regarding the location around the pipe at which the data are taken.

The liner was placed on a wooden saddle, clamped with the platform, and careful measurements were taken to ensure that the liner center was aligned with the measuring device. Next, the profile plotter was aligned with the center of the CIPP liner tube. Continuous readings were taken around the circumference of three cross-sections spaced 8 in. apart and averaged. The liner was found to be approximately circular with reference to its center (see Figure B-4). The ovality of the liner was found to vary from 2.70% to 4.30%.

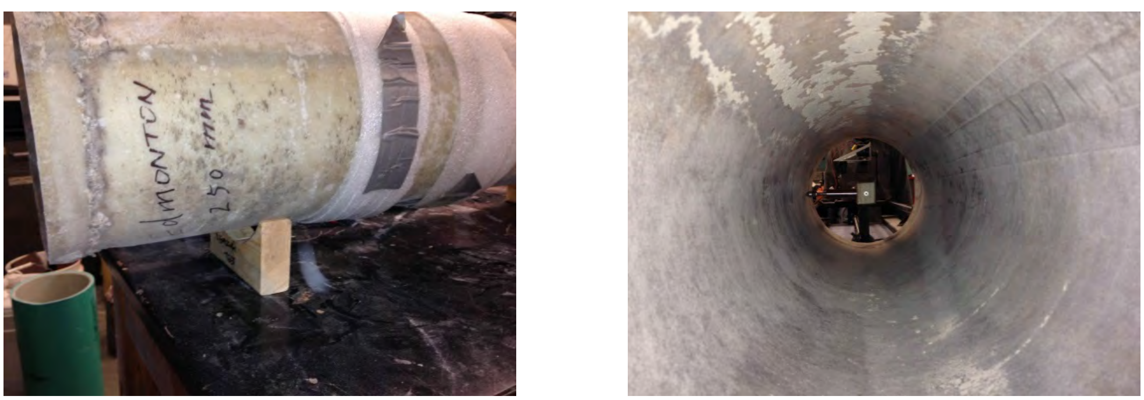

Figure B-3. Profile Plotter Setup (left) and Ovality Measurement (right)

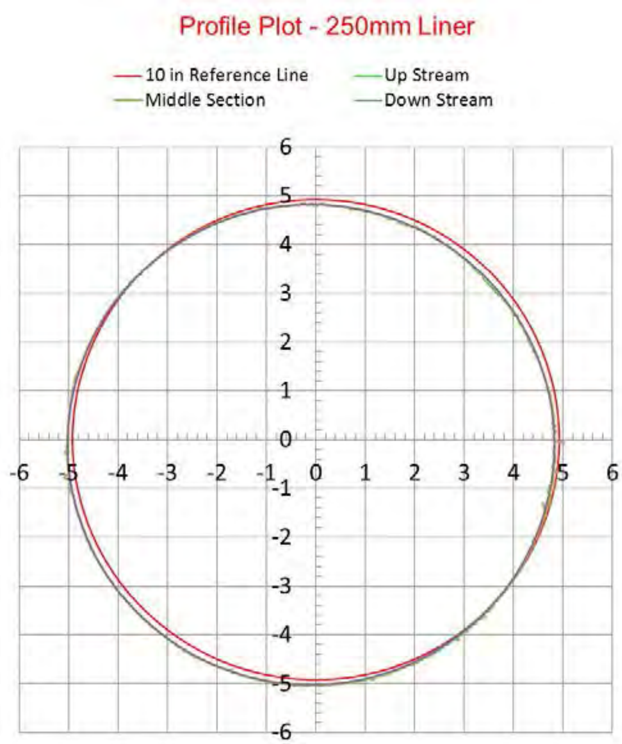

Figure B-4. Edmonton 1: Ovality of the Liner at Up Stream, Middle and Down Stream Sections

B.1.2.5 ***Thickness.*** A total of 120 readings were taken on 20 1 in. × 1 in. samples cut from different locations of the liner specimen. The thickness was measured randomly using a micrometer with a resolution of ± 0.0025 mm as described in Section 2. The average thickness was found to be 4.66 mm ± 0.21 mm as shown in Figure B-5. The design thickness was 5 mm.

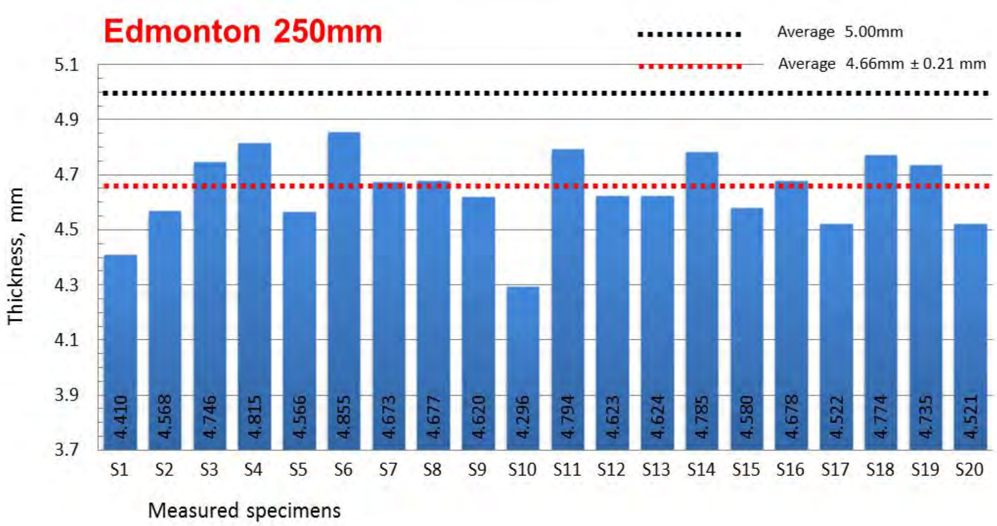

Figure B-5. Edmonton 1: Thickness of the Sample

B.1.2.6 ***Specific Gravity.*** The specific gravity of the liner was measured on 20 1 in. ×1 in. samples in accordance with the ASTM D792 standard. The weight of the sample was measured in air and in water. The water temperature was read at 77°F. A sinker was used to ensure submersion of the test sample.

The specific gravity values from the sample are shown in Figure B-6. The obtained values were between 1.16 and 1.27. The average specific gravity was 1.25.

Figure B-6. Edmonton 1: Measured Specific Gravity

B.1.2.7 ***Tensile Test (ASTM D638).*** Specimens, as described in ASTM D638, were cut from the liner using a table saw and a band saw. The Type II specimen dimension was used for the ASTM D638 tensile test. The sides of the specimens were smoothed using a grinder. A total of 15 specimens were prepared and tested. Marked tensile specimens and the test setup are shown in Figures B-7 and B-8.

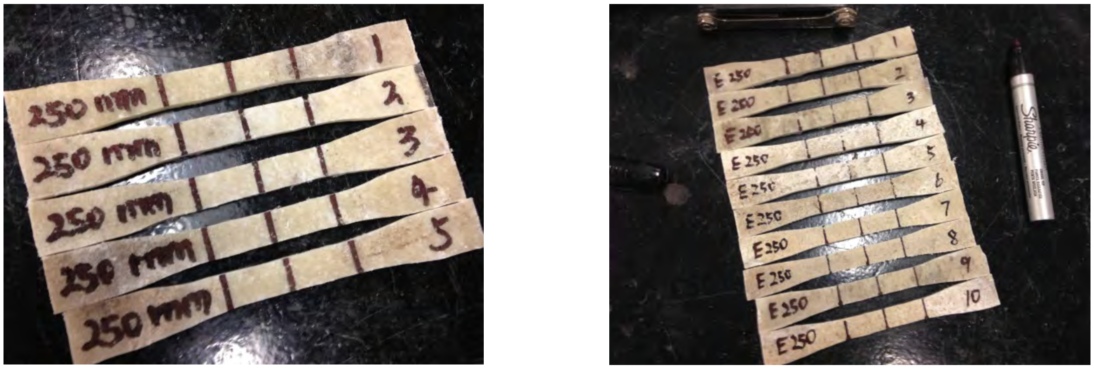

Figure B-7. Five Specimens (left) and 10 More Specimens (right) Prepared for Tensile Testing

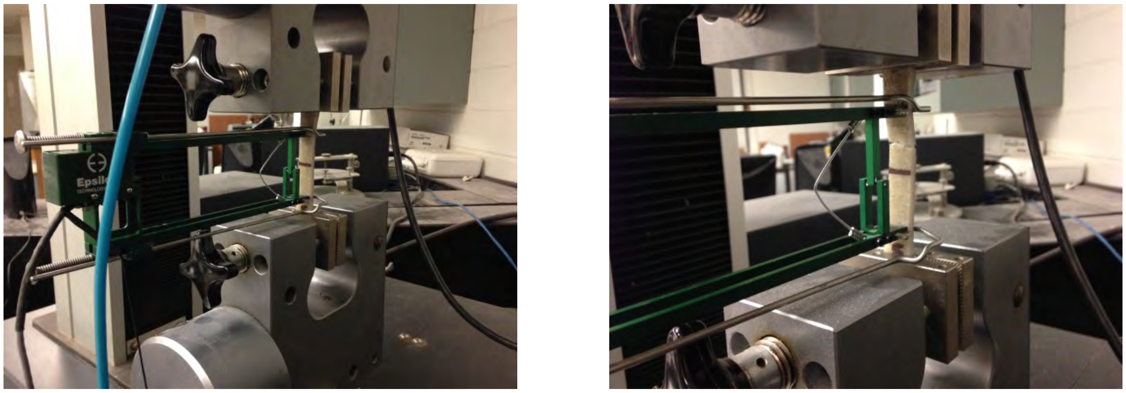

Figure B-8. Tensile Testing in Accordance with ASTM D638 (left) and Samples after Test (right)

The tensile test results are presented in Figure B-9 and Table B-3. The average tensile strength was 3,241 ± 214 psi. The average tensile modulus was calculated to be 436,709 ± 68,229 psi.

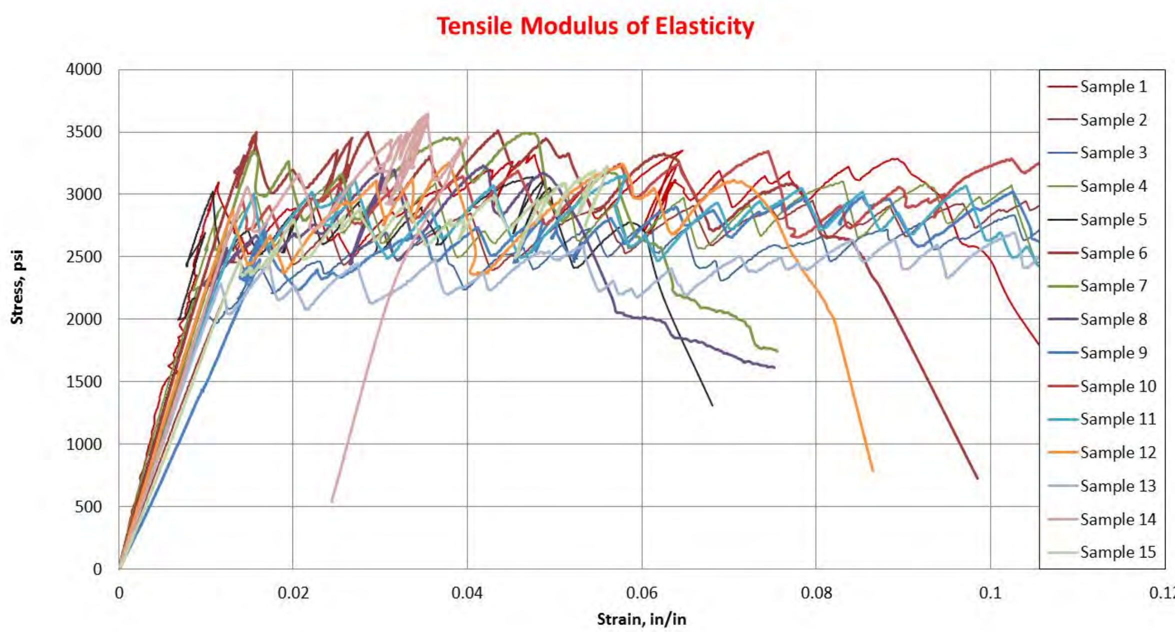

Figure B-9. Edmonton 1: Stress-strain Curves from Tensile Testing

Table B-3. Edmonton 1: Tensile Test Results

Sample ID	Area (in.^{2})	Peak Load (lb)	Peak Stress (psi)	Tensile Modulus (psi)
1	0.0845	283.30	3,353	580,343*
2	0.0820	251.10	3,062	369,959
3	0.0822	239.91	2,919	425,821
4	0.0825	258.64	3,135	529,530
5	0.0848	266.31	3,140	497,291
6	0.0829	291.15	3,512	483,457
7	0.0836	292.03	3,493	446,496
8	0.0948	306.27	3,231	424,398
9	0.1000	302.22	3,022	304,417*
10	0.0968	336.12	3,472	425,937
11	0.0911	287.51	3,156	409,601
12	0.0827	269.16	3,255	457,080
13	0.0846	253.35	2,995	402,287
14	0.0867	316.16	3,647	429,778
15	0.0765	246.86	3,227	364,254
Average		280.01	3,241	436,709
St. Dev		28.02	214	68,229

*Result is not within ± 25% RPD.

B.1.2.8 Flexural Test (ASTM D790). A total of 15 specimens were prepared for ASTM D790 flexure tests. The prepared specimens and test setup are shown in Figures B-10 and B-11.

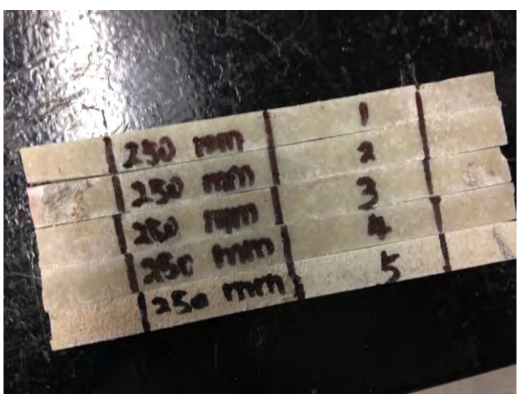

Figure B-10. Five Specimens (left) and 10 More Specimens (right) for Flexural Testing

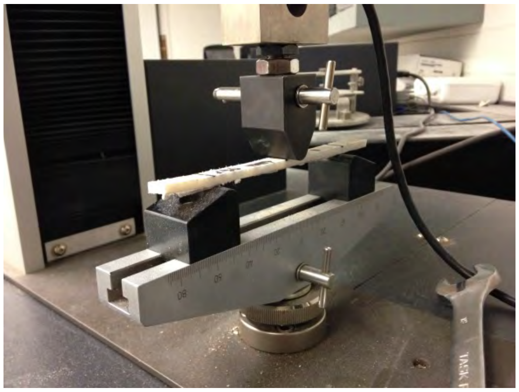
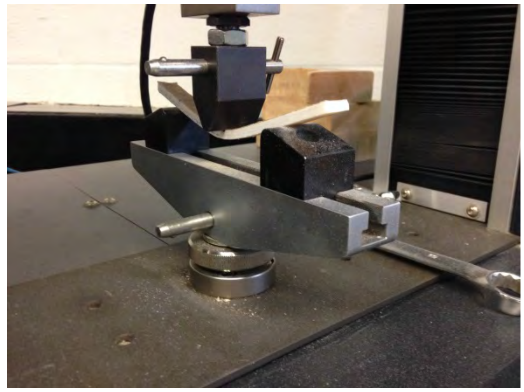

Figure B-11. Flexural Testing in Accordance with ASTM D790 (left) and Samples after Test (right)

The flexure test results are presented in Figure B-12 and Table B-4. The area values were automatically back calculated by the software when the peak load was reached. The average flexural modulus was 331,333 ± 30,354 psi and the average flexure strength was 6,135 ± 535 psi.

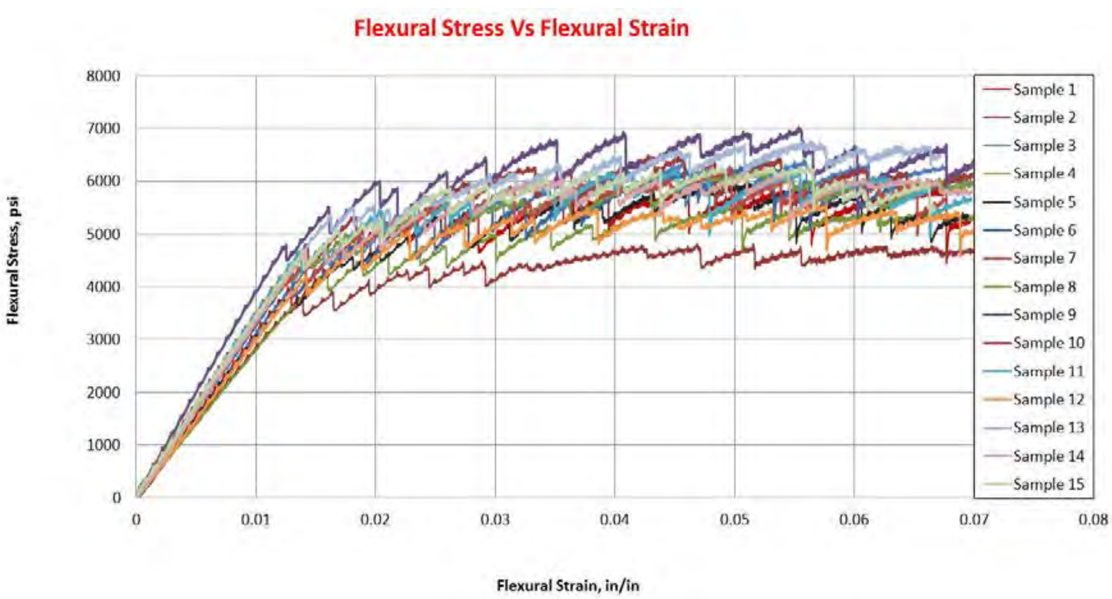

Figure B-12. Edmonton 1: Stress – Strain Curves from Flexural Testing

Table B-4. Edmonton 1: Flexural Test Results

Sample ID	Area ($in.^2$)	Peak Load (lb)	Peak Stress (psi)	Flexural Modulus (psi)
1	0.0028	16.60	5,929	322,781
2	0.0031	14.72	4,748	284,443
3	0.0030	19.27	6,423	314,699
4	0.0031	17.41	5,616	282,367
5	0.0031	18.57	5,990	300,724
6	0.0031	20.04	6,465	323,089
7	0.0034	22.01	6,474	357,066
8	0.0034	20.94	6,159	350,483
9	0.0034	23.61	6,944	392,559
10	0.0031	19.48	6,284	348,759
11	0.0033	20.52	6,218	356,834
12	0.0034	18.90	5,559	304,633
13	0.0034	23.01	6,768	348,563
14	0.0035	21.53	6,151	341,379
15	0.0030	18.89	6,297	341,617
Average		19.70	6,135	331,333
St. Dev		2.39	535	30,354

B.1.2.9 ***Surface Hardness.*** A Shore Type D durometer (ASTM D2240) was used to determine the hardness of the liner samples. The Shore D hardness scale utilizes a weight of 10 lb (4,536 g). The tip diameter and angle are 0.1 mm and 35°, respectively. Samples (1 in. × 1 in.) were cut from the retrieved CIPP liner with a band saw. A total of 400 readings were taken on the inner and outer surfaces of the liner specimens. The average recorded hardness values are shown in Figure B-13. The hardness of the surface exposed to the flow (inner surface) was found to be only slightly lower than that of the protected (outer) surface, suggesting little, if any, softening or erosion of the resin on the inner surface of the tube during its service life. Differences may also be expected due to the initial presence of the sealing layer on the internal surface.

B.1.2.10 ***Short-Term Buckling Test.*** For the short-term buckling test, a 30 in. long piece of full circumference was cut from the sample and housed inside a 12-in. diameter steel tube 30 in. in length. The larger diameter of the steel tube ensured accommodation of any ovality and local curvature of the liner. Two 3/8 in. threaded holes were made on the opposite sides of the steel tube and quick connectors were fixed to the pipe through the holes to allow attachment of the pressure system. Two specially designed, open-ended steel caps were fabricated to keep a uniform 1-in. annular space between the inner wall of the pipe and the outer wall of the liner and these end caps were then sealed. Effective sealing of the annulus under elevated internal annular pressure was essential during the test while the interior of the liner was frequently accessed for observation of liner deformation. The large annular gap for the buckling test makes the buckling test very conservative compared to a liner tightly fitted within the host pipe in the field. However, the test sections also are known to be too short to eliminate end effects (not conservative) because the host pipe configuration and overall testing program did not permit a pipe section with a length of four to six times diameter (32 to 48 in.) to be used.

Figure B-13. Edmonton 1: Shore D Hardness Readings from Inner and Outer Surfaces

Provision was made to apply a high pressure using the TTC's elevated pressure application device (EPAD). First, the test specimen was connected to the EPAD and the EPAD was connected to the water supply line. The annular space between the liner and host pipe plus all the conduits and the accumulator were filled with water. This was ensured by bleeding the air out through the quick connector attached to the steel tube. The accumulator was connected to an N_2 tank and, when pressurized, N_2 was released to the accumulator where it compressed the water inside the accumulator, exerting pressure on the annular space.

The liner collapsed under the supply line water pressure at around 12 psi before the N_2 was released to the accumulator (see Figure B-14). This is equivalent to over 27 ft of water head above the pipe.

Figure B-14. Edmonton 1: Short-Term Buckling Test Setup

B.1.2.11 Glass Transition Temperature. Differential scanning calorimetry (DSC) is used to perform thermal characterization studies on thermosetting resins. As the components in a resin system cure, heat is evolved and measured by the DSC. When no significant heat of cure is observed, then it is assumed that the resin sample is completely or 100% cured. DSC can also be used to measure the glass transition temperature (Tg) or softening temperature of a thermoset resin. Tg represents the temperature region in which the resin transforms from a hard, glassy solid to a viscous liquid. As a thermosetting resin cures, the Tg increases and the heat of cure decreases. These changes can be used to characterize and quantify the degree of cure of the resin system (Perkin-Elmer, 2000).

The Tg determination followed ASTM E1356-08 “Standard Test Method for Assignment of the Glass Transition Temperatures by Differential Scanning Calorimetry.” The calculated Tg values are summarized in Table B-5 for the Edmonton 250 mm CIPP sample. The average Tg for the field samples was 115.48°C (+/- 0.91°C) as measured by ASTM Method E1356-08 with DSC. In general, an increase in the Tg is a function of curing and represents the increase in the molecular weight of the resin system (Perkin-Elmer, 2000).

Table B-5. Edmonton 1: Tg Determination (250 mm CIPP Liner)

Sample	Run	Tg (°C)
Edmonton (250 mm)	1	115.82
Edmonton (250 mm)	2	116.17
Edmonton (250 mm)	3	114.45

B.1.3 Edmonton Sample 2: A 19-Year Old CIPP Liner in an 8 in. (200 mm) Clay Tile Pipe.

Edmonton Sample 2 was retrieved from 119 St. and 109A Ave. in Edmonton, Canada on June 21, 2013. The liner had been installed in 1994 by Insituform Technologies. The clay tile host pipe had originally been installed in 1955. The location was a sag location and therefore was always filled with wastewater to at least 80%. The exposure was considered severe in terms of possible H_2S generation. Significant difficulties were encountered in recovering the CIPP liner. The city had to call for a vacuum truck to empty the line and used jetting equipment to flush the line and remove a downstream blockage that hindered flow and prevented the pipe from draining. Thus, measurement of annular space or pipe thickness was not possible for the remaining host pipe due to the challenging working conditions. However, these measurements were made from the exhumed CIPP and host pipe sample. The host pipe and liner information are shown in Table B-6. The host pipe was at a depth of approximately 3.1 m (10.2 ft) below ground level.

Table B-6. Edmonton 2: Host Pipe and Liner Information

Host pipe	Clay tile pipe, 8 in. (200 mm) in diameter
Liner Thickness	4.76 mm (laboratory measurement)
Resin	Information not available
Primary Catalyst	Information not available
Secondary Catalyst	Information not available
Felt	Information not available
Seal	Information not available
Year of Installation	1994
Liner Vendor	Insituform Technologies
Resin Supplier	Camtron or Ashland

The retrieval process and the retrieved sample are shown in Figure B-15. The sample was received at the TTC South Campus Facility on July 23, 2013.

Figure B-15. Edmonton 2: Retrieval of the Sample (left) and Received Sample (right)

B.1.3.1 Visual Inspection. The sample was found to be in excellent condition. The polyurea coating (handling layer) was still in place and the thickness of the liner was uniform around the circumference.

B.1.3.2 Annular Gap. The annular gap was measured using a feeler gauge on the exposed ends of the exhumed sample, which were marked as downstream and upstream, respectively. For the downstream end, the liner was found to be tight to the host pipe and no gap was observed. For the upstream end, eight readings were taken on the liner as shown in Table B-7.

Table B-7. Edmonton 2: Field Readings of Annular Gap Using a Feeler Gauge

O' Clock Position	Annular Gap at Downstream End of Sample	Annular Gap at Upstream End of Sample
12:00	Tight	0.078 in. (1.98 mm)
1:30	Tight	0.031 in. (0.79 mm)
3:00	Tight	0.00 in. (0.00 mm)
5:00	Tight	0.031 in. (0.79 mm)
6:00	Tight	0.00 in. (0.00 mm)
7:30	Tight	0.031 in. (0.79 mm)
9:00	Tight	0.031 in. (0.79 mm)
11:00	Tight	0.46 . (1.17 mm)

B.1.3.3 Environmental Service Conditions. 2 g of waste material was scooped from the outside surface of the sample and mixed in 200 mL of distilled water stored in a bottle. The pH of the water was measured using pH-indicator strips and found to be between 8 and 9. The inside of the liner was found to be clean and hence no material was collected to allow a pH measurement.

B.1.3.4 Ovality. A profile plotter (see Figure B-16) was used to map any deformation inside the liner. The system features a LVDT connected to a motor-gear system that rotates around the inner circumference of the liner. An encoder system provides position information regarding the location around the pipe at which the data are collected.

Figure B-16. Edmonton 2: Profile Plotter Setup (left) and Measurement of Ovality (right)

The liner was placed on a wooden saddle, clamped with the platform, and careful measurements were taken to ensure that the liner center was aligned with the measuring device. Next, the profile plotter was aligned with the center of the CIPP liner tube. Continuous readings were taken around the circumference of three cross-sections spaced 12 in. apart and averaged. The liner was found to be approximately circular with reference to its center (see Figure B-17). The ovality of the liner was found to vary from 4.50% to 5.75%.

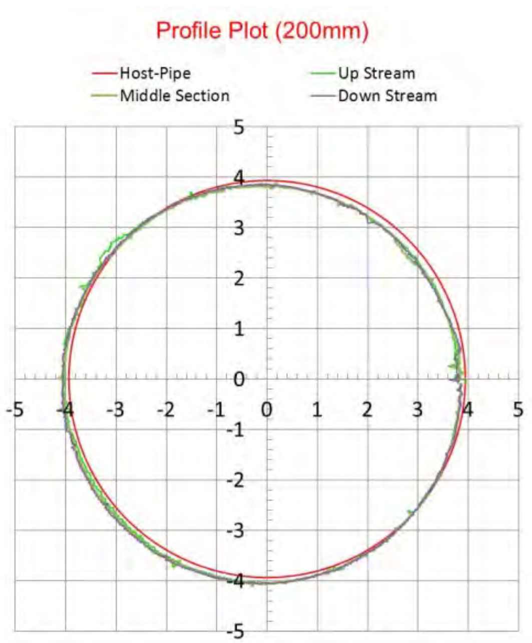

Figure B-17. Edmonton 2: Ovality of the Liner Measured at Three Locations

B.1.3.5 ***Thickness.*** A total of 120 readings were taken on 20 1 in. × 1 in. samples cut from different locations of the specimen. The thickness was measured randomly using a micrometer with a resolution of ± 0.0025 mm. The average thickness was found to be 4.76 mm ± 0.21 mm as shown in Figure B-18. The design thickness was not available.

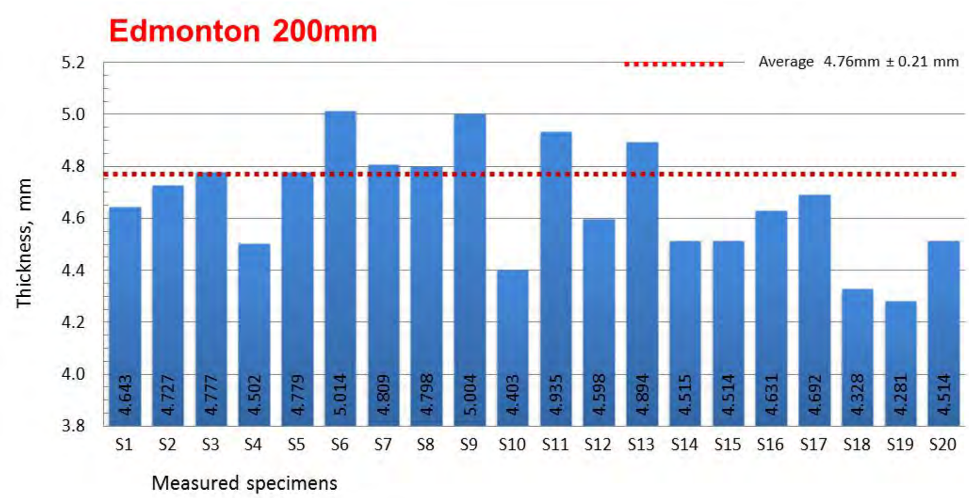

Figure B-18. Edmonton 2: Average Thickness of the Sample

B.1.3.6 ***Specific Gravity.*** The specific gravity of the liner was measured on 20 1 in. × 1 in. samples in accordance with the ASTM D792 standard. The test procedure was the same as for the 250 mm sample test.

The specific gravity values from the sample are shown in Figure B-19. The obtained values were between 1.12 and 1.33. The average specific gravity was 1.25.

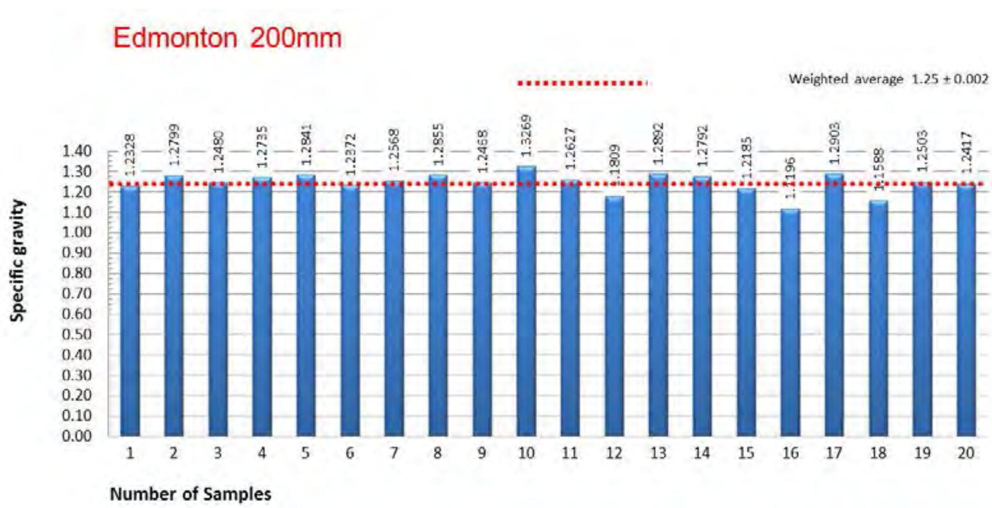

Figure B-19. Edmonton 2: ASTM D792 Measured Specific Gravity

B.1.3.7 Tensile Test (ASTM D638). Specimens, as described in ASTM D638, were cut from the liner using a table saw and a band saw. The Type II specimen dimension was used for the ASTM D638 tensile test. The sides of the specimens were smoothed using a grinder. A total of 15 specimens were prepared and tested. The tensile test results are presented in Figure B-20 and Table B-8. The average tensile strength was 3,652 ± 283 psi and the average tensile modulus was 510,132 ± 44,227 psi.

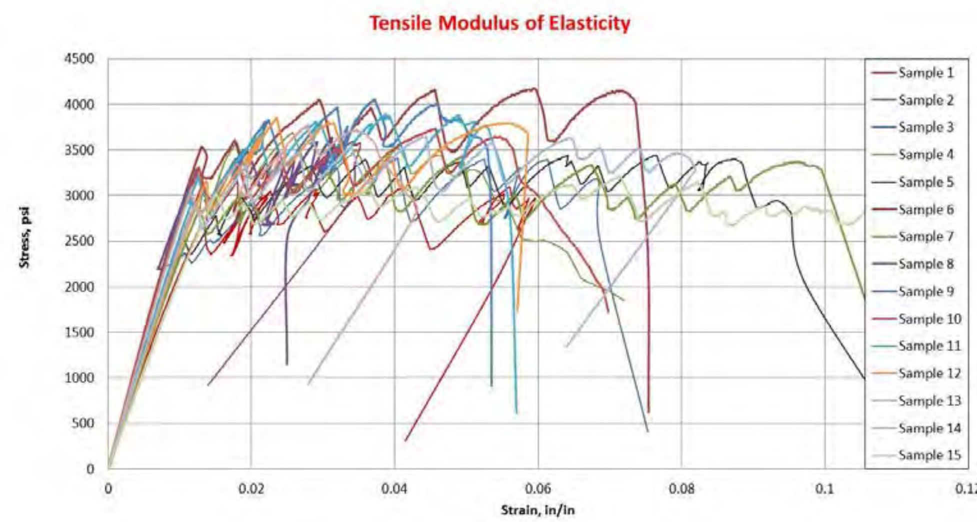

Figure B-20. Edmonton 2: Stress – Strain Curves from Tensile Testing

Table B-8. Edmonton 2: Tensile Test Results

Sample ID	Area (in.^{2})	Peak Load (lb)	Peak Stress (psi)	Tensile Modulus (psi)
1	0.097	299.64	3,095	452,964
2	0.092	330.04	3,603	517,501
3	0.087	296.84	3,412	489,893
4	0.091	336.83	3,693	494,339
5	0.097	332.25	3,443	496,788
6	0.083	346.02	4,179	587,463
7	0.088	302.73	3,432	485,838
8	0.094	341.92	3,637	503,237
9	0.085	346.22	4,054	562,930
10	0.087	322.74	3,735	575,307
11	0.085	330.32	3,895	517,573
12	0.085	326.07	3,850	488,958
13	0.093	337.42	3,648	502,801
14	0.086	325.50	3,772	551,644
15	0.090	301.58	3,340	424,749
Average		325.07	3,653	510,132
St. Dev		17.04	283	44,227

B.1.3.8 Flexural Test (ASTM D790). A total of 15 specimens were prepared for the ASTM D790 flexure tests. The flexure test results are presented in Figure B-21 and Table B-9. The area values were automatically back calculated by the software when the peak load was reached. The average flexural modulus was 364,788 ± 41,344 psi and the average flexure strength was 6,816 ± 942 psi.

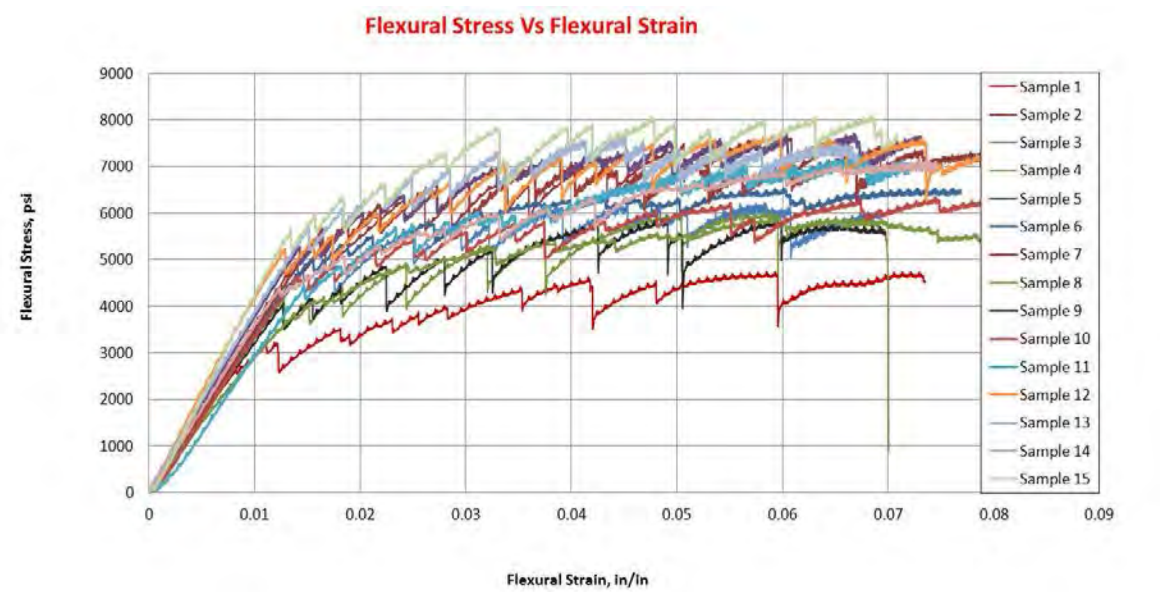

Figure B-21. Edmonton 2: Stress – Strain Curves from Flexural Testing

Table B-9. Edmonton 2: Flexural Test Results

Sample ID	Area (in.^{2})	Peak Load (lb)	Peak Stress (psi)	Flexural Modulus (psi)
1	0.0032	15.41	4,816	321,708
2	0.0038	29.33	7,718	369,676
3	0.0029	17.97	6,197	339,927
4	0.0029	17.59	6,066	337,929
5	0.0029	16.90	5,828	330,974
6	0.0038	24.94	6,563	358,769
7	0.0031	22.36	7,213	367,341
8	0.0043	25.39	5,905	305,892
9	0.0035	27.11	7,746	397,898
10	0.0043	27.15	6,314	361,953
11	0.0034	24.38	7,171	331,949
12	0.0043	32.84	7,637	438,531
13	0.0029	22.53	7,769	389,619
14	0.0036	25.90	7,194	366,456
15	0.0033	26.76	8,109	453,201
Average		23.77	6,816	364,788
St. Dev.		4.97	942	41,344

B.1.3.9 Surface Hardness. A Shore Type D durometer (ASTM D2240) was used to determine the hardness of the liner samples. Samples (1 in. × 1 in.) were cut from the retrieved CIPP liner with a band saw. A total of 400 readings were taken on the inner and outer surfaces of the liner specimens. The average recorded hardness values are shown in Figure B-22. The hardness of the surface exposed to the flow (inner surface) was found to be only slightly lower than that of the protected (outer) surface, suggesting little, if any, softening or erosion of the resin on the inner surface of the tube during its service life. Differences may also be expected due to the initial presence of the sealing layer on the internal surface.

Figure B-22. Edmonton 2: Shore D Hardness Readings from Inner and Outer Surfaces

B.1.3.10 Short-Term Buckling Test. For the short-term buckling test, a 30 in. long piece of full circumference was cut from the sample and housed inside a 10 in. diameter steel tube 30 in. in length with a similar test configuration to that described for the Edmonton 10 in. (250 mm) sample.

Provision was made to apply a high pressure using the TTC's EPAD but the liner collapsed under the supply line water pressure at around 20 psi before the N_2 was released to the accumulator (see Figure B-23). This pressure is equivalent to approximately a 46 ft head of water above the pipe.

Figure B-23. Edmonton 2: Short-Term Buckling Test Setup

B.1.3.11 Glass Transition Temperature. The calculated Tg values are summarized in Table B-10 for the Edmonton 200 mm CIPP sample. The average Tg for the field samples was 112.91°C (+/- 1.95°C) as measured by ASTM Method E1356-08 with DSC.

Table B-10. Edmonton 2: Tg Determination (200 mm CIPP Liner)

Sample	Run	Tg (°C)
Edmonton (200 mm)	1	112.59
Edmonton (200 mm)	2	111.13
Edmonton (200 mm)	3	115.00

B.2 City of Houston

In this section, the test results performed on 21 in. and 18 in. diameter CIPP liners exhumed near Riverview and Blue Willow Drive, Houston, Texas are presented.

B.2.1 Houston Sample 1: A 16- to 17-Year Old CIPP Liner in a 21 in. Concrete Pipe. The sample was retrieved from near Riverview and Blue Willow Drive, Houston, Texas, on May 6, 2013. The lined section of pipe was being replaced in an ongoing contract and it was not possible to retrieve the liner within the host pipe as an intact sample. The depth from the ground surface to the flow line of the pipe was approximately 10.1 ft. The information on the host pipe and liner is shown in Table B-11.

Table B-11. Houston 1: Host Pipe and Liner Information

Host pipe	Concrete pipe, 21 in. diameter
Liner Thickness	10.65 mm (laboratory measurement)
Resin	Not available
Primary Catalyst	Not available
Secondary Catalyst	Not available
Felt	Not available
Seal	Not available
Year of Installation	1996 to 1997
Liner Vendor	Not available
Resin Supplier	Not available

The retrieval process and the retrieved sample are shown in Figure B-24. The specimens were received at the TTC South Campus Lab Facility on May 16, 2013.

B.2.1.1 Visual Inspection. In the field, the sample was observed to be brittle and uneven with visible fibers, but it was not clear to what extent this was observed due to the sample removal process from the host pipe. When received at the TTC, the sample was found to be in good condition relative to the other CIPP samples retrieved. As indicated below, the test results were in the normal range.

B.2.1.2 Annular Gap. Only a sample of the liner was recovered and no annular gap data were obtained for this sample.

Figure B-24. Houston 1: Retrieval of the Sample (left) and Received Sample (right)

B.2.1.3 Environmental Service Conditions. 2 g of waste material was scooped from the inside and outside surfaces of the sample and mixed in 200 mL of distilled water stored in a bottle. The pH was measured separately using pH-indicator strips. The pH of the outside sample was found to be 5, whereas the pH of the inside sample was between 4 and 5.

B.2.1.4 Ovality. A profile plotter was used to accurately map any deformation inside the liner. Continuous readings were taken around the circumference of three cross-sections spaced 2 in. apart and averaged. The liner was found to be approximately circular with reference to its center (see Figure B-25). The ovality of the liner was found to be around 1.4%.

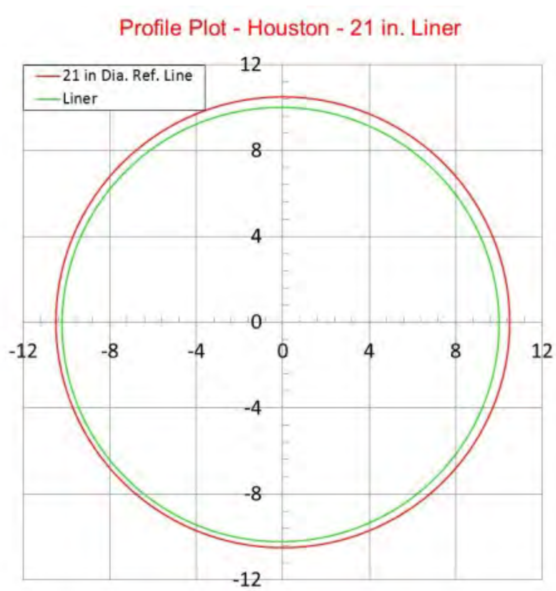

Figure B-25. Houston 1: Ovality of the Liner

B.2.1.5 ***Thickness.*** A total of 60 readings were taken on 10 1 in. × 1 in. samples cut from different locations of the liner specimen. The thickness was measured randomly using a micrometer with a resolution of ± 0.0025 mm. The average thickness was found to be 10.65 mm ± 0.35 mm as shown in Figure B-26. The design thickness was not available.

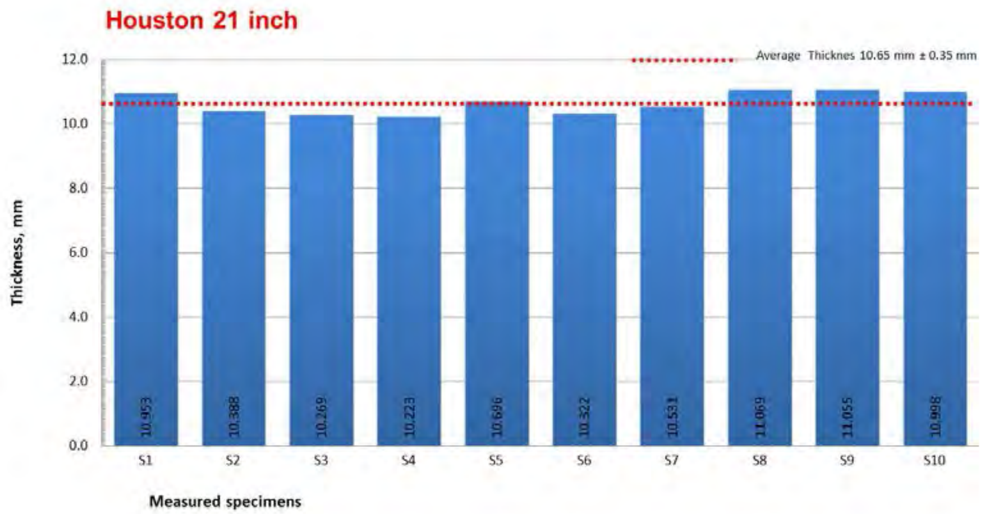

Figure B-26. Houston 1: Average Thickness of the Sample

B.2.1.6 ***Specific Gravity.*** The specific gravity of the liner was measured on 10 1 in. ×1 in. samples in accordance with the ASTM D792 standard. The specific gravity values from the sample are shown in Figure B-27. The obtained values were between 1.15 and 1.19. The average specific gravity was 1.17.

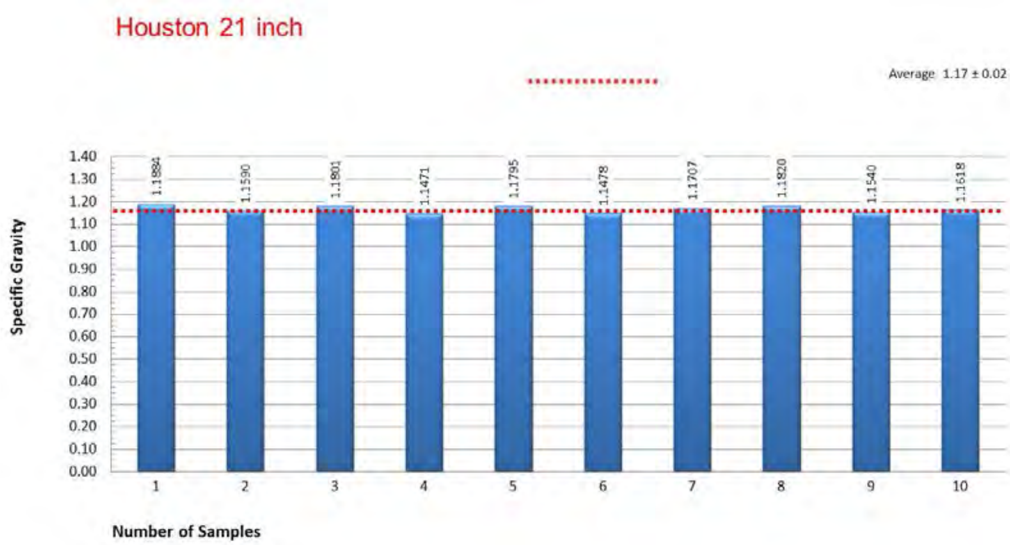

Figure B-27. Houston 1: Measured Specific Gravity

B.2.1.7 ***Tensile Test (ASTM D638).*** Specimens, as described in ASTM D638, were cut from the liner using a table saw and a band saw. The type II specimen dimensions were used for the ASTM D638 tensile test. The sides of the specimens were smoothed using a grinder. A total of 15 specimens were prepared and tested. The tensile test results are presented in Figure B-28 and Table B-12. The average tensile strength was 3,409 ± 405 psi. The average tensile modulus was calculated to be 465,321 ± 56,119 psi.

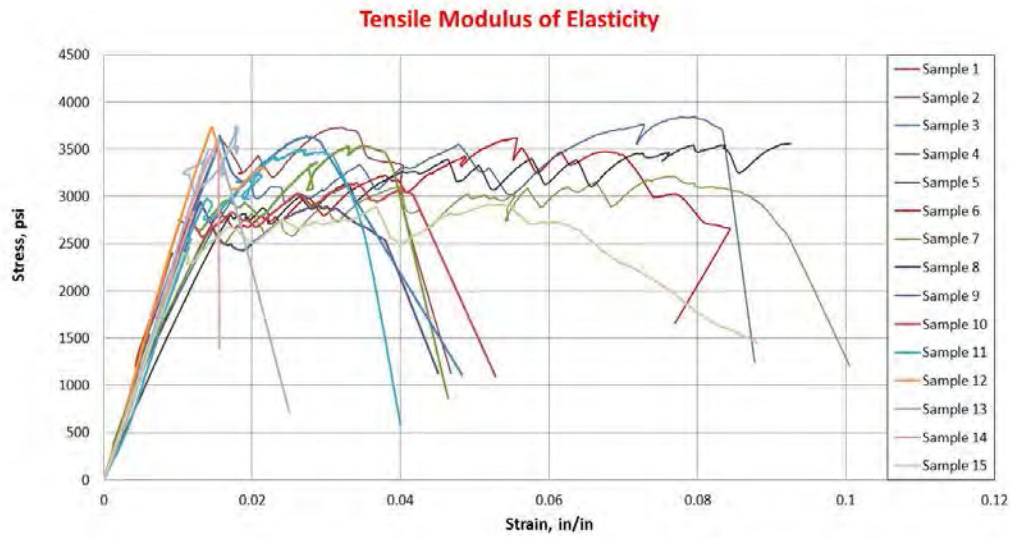

Figure B-28. Houston 1: Stress – Strain Curves from Tensile Testing

Table B-12. Houston 1: Tensile Test Results

Sample ID	Area (in.^{2})	Peak Load (lb)	Peak Stress (psi)	Tensile Modulus (psi)
1	0.2133	772.52	3,622	448,935
2	0.1906	711.13	3,731	442,826
3	0.2074	796.81	3,842	438,923
4	0.1975	634.73	3,214	541,844
5	0.2040	727.52	3,566	347,069*
6	0.2255	540.45	2,397*	546,300
7	0.2407	850.97	3,535	558,187
8	0.2249	661.95	2,943	450,182
9	0.2393	870.90	3,639	469,616
10	0.2021	635.53	3,145	465,297
11	0.2432	848.50	3,489	388,252
12	0.2287	854.63	3,737	463,445
13	0.2218	830.99	3,747	497,816
14	0.2176	787.05	3,617	472,955
15	0.1971	574.79	2,916	448,177
Average		739.90	3,409	465,322
St. Dev		108.67	405	56,119

*Result is not within ± 25% RPD.

B.2.1.8 Flexural Test (ASTM D790). A total of 15 specimens were prepared for ASTM D790 flexure tests. The flexural test results are presented in Figure B-29 and Table B-13. The area values were automatically back calculated by the software when the peak load was reached. The average flexural modulus was 337,638 ± 50,522 psi and the average flexure strength was 6,893 ± 842 psi.

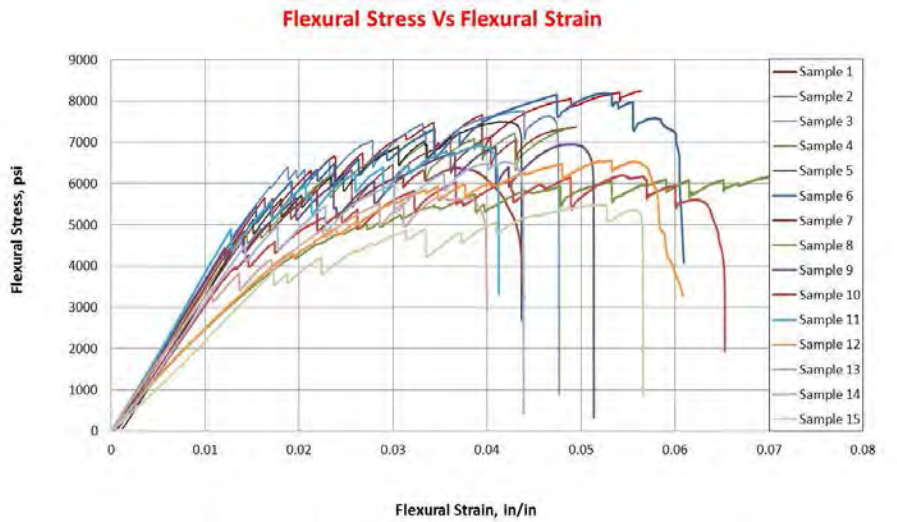

Figure B-29. Houston 1: Stress – Strain Curves from Flexural Testing

Table B-13. Houston 1: Flexural Test Results

Sample ID	Area (in.^{2})	Peak Load (lb)	Peak Stress (psi)	Flexural Modulus (psi)
1	0.0168	138.46	8,242	368,480
2	0.0131	96.82	7,391	349,728
3	0.0121	93.88	7,759	402,052
4	0.0126	92.66	7,354	353,994
5	0.0152	114.30	7,520	370,726
6	0.0277	226.59	8,180	370,281
7	0.0205	130.92	6,386	369,185
8	0.0201	124.38	6,188	266,826
9	0.0208	145.03	6,973	367,612
10	0.0189	117.30	6,206	321,064
11	0.0190	131.39	6,915	382,892
12	0.0190	124.68	6,562	264,659
13	0.0225	146.44	6,508	326,680
14	0.0251	143.53	5,718	328,048
15	0.0326	179.00	5,491	222,348*
Average		133.69	6,893	337,638
St. Dev.		34.38	842	50,522

*Result is not within ± 25% RPD.

B.2.1.9 Surface Hardness. A Shore Type D durometer (ASTM D2240) was used to determine the hardness of the liner samples. A total of 200 readings were taken on the inner and outer surfaces of the liner specimens. The average recorded hardness values are shown in Figure B-30. The hardness of the surface exposed to the flow (inner surface) was found to be almost the same as that of the protected (outer) surface. However, the standard deviation of the recorded data was found to be large compared to the test results for other liners, especially for the outer surface. Differences may also be expected due to the initial presence of the sealing layer on the internal surface.

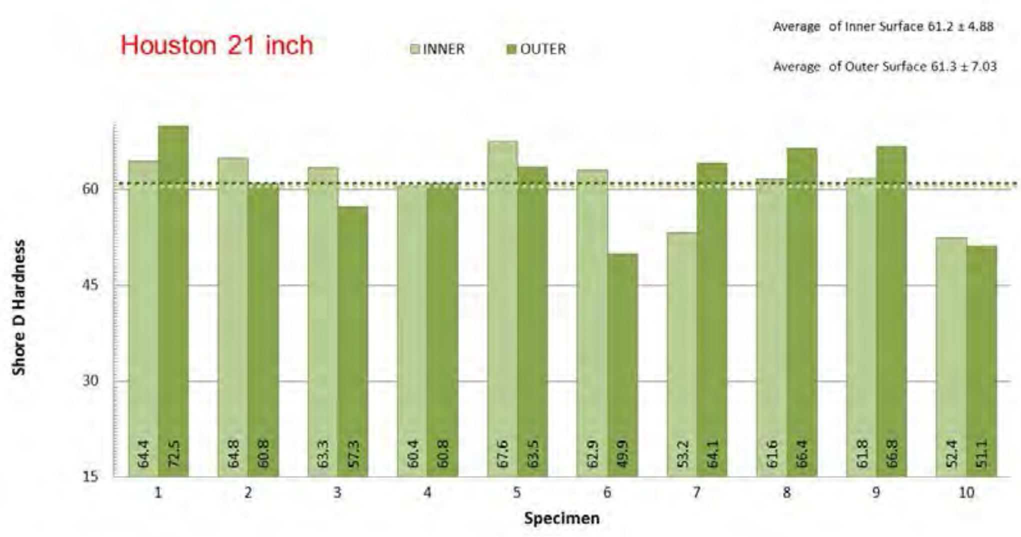

Figure B-30. Houston 1: Shore D Hardness Readings from Inner and Outer Surfaces

B.2.1.10 Glass Transition Temperature. The calculated Tg values are summarized in Table B-14 for the Houston 21 in. CIPP sample. The average Tg for the field samples was 119.91°C (+/- 1.91°C) as measured by ASTM Method E1356-08 with DSC.

Table B-14. Houston 1: Tg Determination (21 in. CIPP Liner)

Sample	Run	Tg (°C)
Houston (21 in.)	1	117.71
Houston (21 in.)	2	121.14
Houston (21 in.)	3	120.87

B.2.2 Houston Sample 2: A 16- to 17-Year Old CIPP Liner in an 18 in. Concrete Pipe. The sample was retrieved from near Riverview and Blue Willow Drive, Houston, TX on May 10, 2013. The lined section of pipe was being replaced in an ongoing contract and it was not possible to retrieve the liner and host as an intact sample. The depth from the ground surface to the flow line of the pipe was approximately 11.5 ft. The information on the host pipe and liner is shown in Table B-15.

The sample was retrieved from the same manhole as the Houston 21 in. CIPP sample and the retrieved sample is shown in Figure B-31. The specimens were received at the TTC South Campus Lab Facility on May 16, 2013.

Table B-15. Houston 2: Host Pipe and Liner Information

Host pipe	Concrete pipe, 18 in. diameter

Liner Thickness	10.95 mm (laboratory measurement)
Resin	Not available
Primary Catalyst	Not available
Secondary Catalyst	Not available
Felt	Not available
Seal	Not available
Year of Installation	1996 to 1997
Liner Vendor	Not available
Resin Supplier	Not available

Figure B-31. Houston 2: Received 18 in. CIPP Sample

B.2.2.1 ***Visual Inspection.*** In the field, the sample was observed to be brittle and uneven with visible fibers, but it was not clear to what extent this was observed due to the sample removal process from the host pipe. When received at the TTC, the sample was found to be in good condition relative to the other CIPP samples retrieved. As indicated below, the test results were in the normal range.

B.2.2.2 ***Annular Gap.*** Only a sample of the liner was recovered and no annular gap data were obtained for this sample.

B.2.2.3 ***Environmental Service Conditions.*** 2 g of waste material was collected from the inner and outer surfaces of the sample and mixed with 200 mL of distilled water stored in a bottle. The pH of the water was measured separately using pH-indicator strips and it was found that the pH of the outside sample was between 4 and 5 while the pH of the inside sample was found to be 6 to 7.

B.2.2.4 ***Ovality.*** A profile plotter was used to accurately map any deformation inside the liner. The system features a LVDT connected to a motor-gear system that rotates around the inner circumference of the liner. An encoder system provides position information regarding the location around the pipe at which the data are taken. The liner was found to be approximately circular with reference to its center (see Figure B-32). The ovality of the liner was found to be around 1.7%.

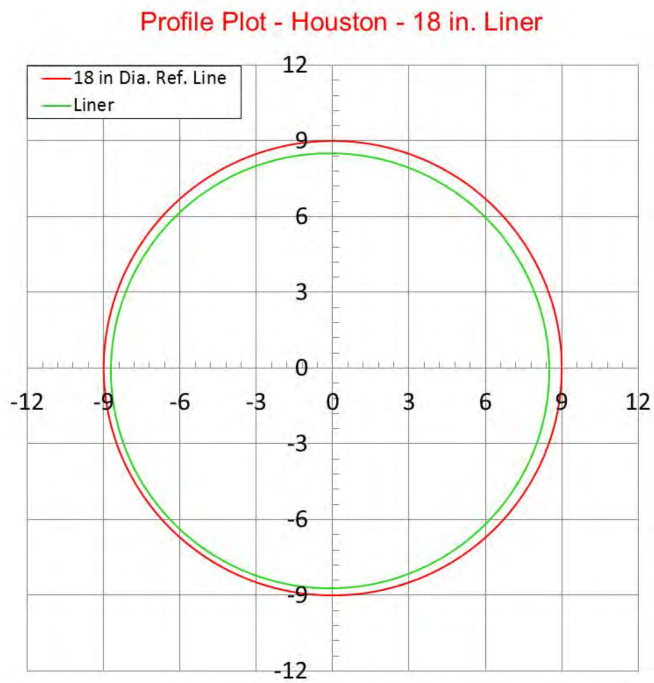

Figure B-32. Houston 2: Ovality of the Liner

B.2.2.5 ***Thickness.*** A total of 120 readings were taken on 20 1 in. × 1 in. samples cut from different locations of the specimen. The thickness was measured randomly using a micrometer with a resolution of ±0.0025 mm. The average thickness was found to be 10.95 mm ± 0.23 mm as shown in Figure B-33. The design thickness was not available.

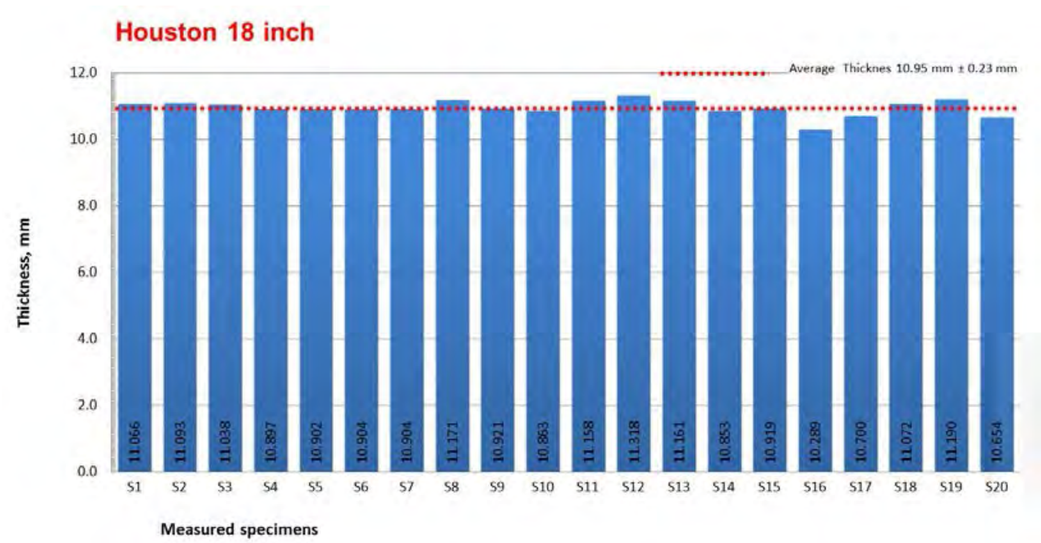

Figure B-33. Houston 2: Average Thickness of the Sample

B.2.2.6 ***Specific Gravity.*** The specific gravity of the liner was measured on 20 1 in. × 1 in. samples in accordance with the ASTM D792 standard. The specific gravity values from the sample are shown in Figure B-34. The obtained values were between 1.15 and 1.19. The average specific gravity was 1.18.

Figure B-34. Houston 2: Measured Specific Gravity of the Liner

B.2.2.7 ***Tensile Test (ASTM D638).*** Specimens, as described in ASTM D638, were cut from the liner using a table saw and a band saw. The Type II specimen dimension was used for the ASTM D638 tensile test. The sides of the specimens were smoothed using a grinder. A total of 15 specimens were prepared and tested.

The tensile test results are presented in Figure B-35 and Table B-16. The average tensile strength was 3,252 ± 456 psi and the average tensile modulus was 450,985 ± 62,184 psi. Data for Specimen 2 were not obtained due to premature failure of the sample which was thought to be from the misalignment of the specimen along the pneumatic grips.

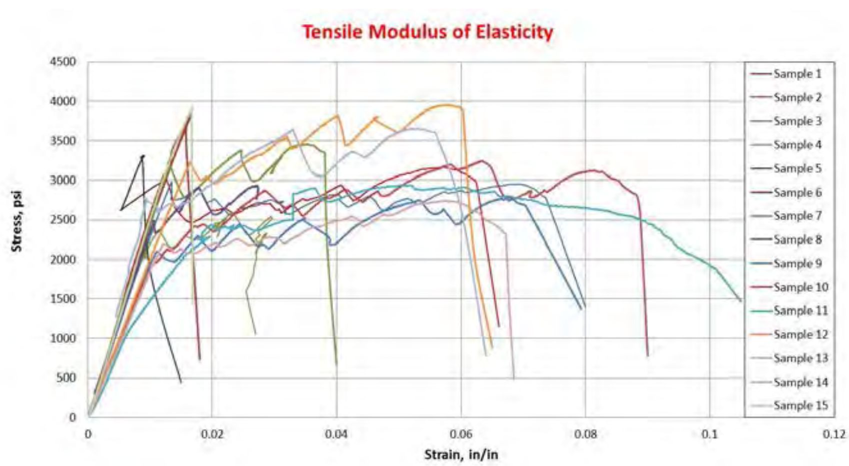

Figure B-35. Houston 2: Stress – Strain Curves from Tensile Testing

Table B-16. Houston 2: Tensile Test Results

Sample ID	Area (in.^{2})	Peak Load (lb)	Peak Stress (psi)	Tensile Modulus (psi)
1	0.2090	661.87	3,167	489,680
2	No data due to machine error			
3	0.2249	670.40	2,981	467,179
4	0.2713	705.36	2,600	520,625
5	0.2151	712.68	3,313	489,362
6	0.2124	815.80	3,841	491,600
7	0.2500	864.89	3,460	522,812
8	0.2262	663.37	2,933	475,687
9	0.2642	731.87	2,770	388,706
10	0.2581	838.19	3,248	389,415
11	0.2451	720.01	2,938	323,123*
12	0.2508	991.97	3,955	408,373
13	0.2296	839.41	3,656	462,991
14	0.2404	659.62	2,744	370,489
15	0.2240	878.97	3,924	513,751
Average		768.17	3,252	450,985
St. Dev		103.12	456	62,184

*Result is not within ± 25% RPD.

B.2.2.8 Flexural Test (ASTM D790). A total of 15 specimens were prepared for ASTM D790 flexure tests. The flexure test results are presented in Figure B-36 and in Table B-17. The area values were automatically back calculated by the software when the peak load was reached. The average flexural modulus was 338,565 ± 26,467 psi and the average flexure strength was 7,204 ± 532 psi. Data were not included in the table for both Samples 6 and 10. For Sample 6, there was a mistake in the input for the span length and, for Sample 10, there was a problem with the machine grip.

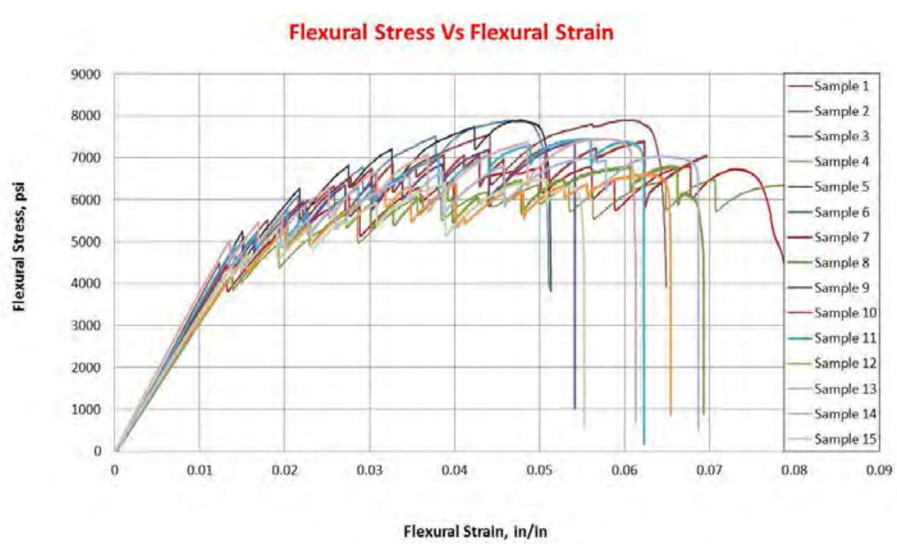

Figure B-36. Houston 2: Stress – Strain Curves from Flexural Testing

Table B-17. Houston 2: Flexural Test Results

Sample ID	Area (in.^{2})	Peak Load (lb)	Peak Stress (psi)	Flexural Modulus (psi)
1	0.0162	110.20	6,802	305,529
2	0.0151	119.37	7,905	366,794
3	0.0155	122.78	7,921	336,622
4	0.0163	105.70	6,485	307,590
5	0.0157	123.91	7,892	360,625
6	Not included due to wrong data input			
7	0.0201	148.39	7,383	342,912
8	0.0212	144.39	6,811	306,866
9	0.0191	141.16	7,391	360,154
10	No data due to machine error			
11	0.0199	148.13	7,444	364,462
12	0.0220	145.30	6,605	310,968
13	0.0209	147.40	7,053	329,906
14	0.0197	147.22	7,473	382,436
15	0.0211	136.96	6,491	326,484
Average		133.92	7,204	338,565
St. Dev		15.45	532	26,467

B.2.2.9 Surface Hardness. A Shore Type D durometer (ASTM D2240) was used to determine the hardness of the liner samples. A total of 400 readings were taken on the inner and outer surfaces of the liner specimens. The average recorded hardness values are shown in Figure B-37. The hardness of the surface exposed to the flow (inner surface) was found to be only slightly lower than that of the protected (outer) surface, suggesting little, if any, softening or erosion of the resin on the inner surface of the tube during its service life. Differences may also be expected due to the initial presence of the sealing layer on the internal surface.

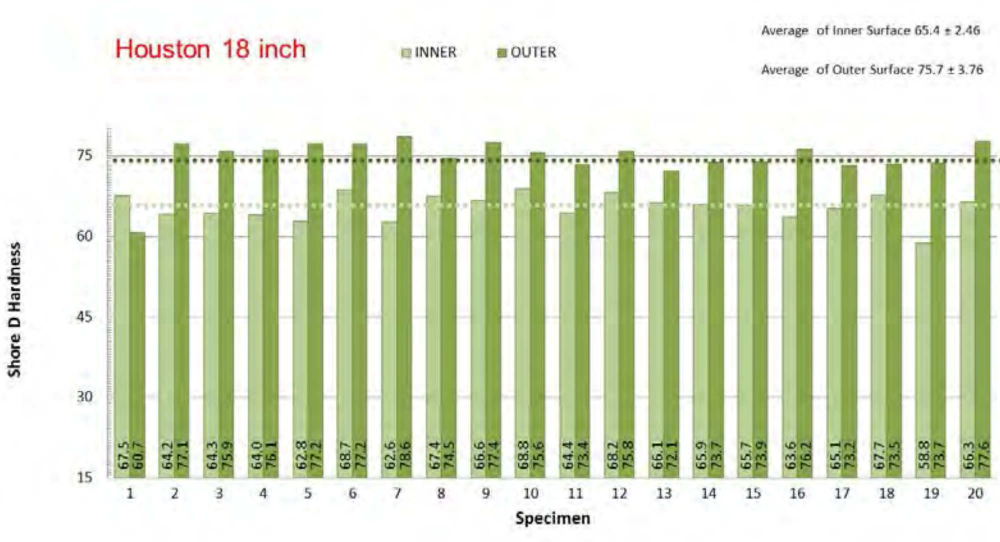

Figure B-37. Houston 2: Shore D Hardness Readings from Inner and Outer Surfaces

B.2.2.10 Glass Transition Temperature. The calculated Tg values are summarized in Table B-18 for the Houston 18 in. CIPP sample. The average Tg for the field samples was 119.69°C (+/- 1.80°C) as measured by ASTM Method E1356-08 with DSC.

Table B-18. Sample Tg Determination (18 in. CIPP Liner)

Sample	Run	Tg (°C)
Houston (18 in.)	1	121.71
Houston (18 in.)	2	118.27
Houston (18 in.)	3	119.10

B.3 City of Indianapolis

B.3.1 Indianapolis: An Approximately 25-Year Old CIPP Liner in a 42-in. Brick Sewer. This report contains the test results performed on a liner exhumed from the intersection of N. Illinois St. and W. Vermont St. in Indianapolis, Indiana (approximate street address: 343 North Illinois Street, Indianapolis, IN 46204) on April 29, 2013. The sample was collected from a lined host pipe of 42-in. diameter. The liner was installed in approximately 1986-1989 by Insituform for the City of Indianapolis.

The host pipe runs beneath Illinois St. from Washington St. in the south to 16th St. in the north, approximately 5,000 lf. This combined sewer has periods of low flow which leads to high odors. The backfill in the area of the pipe is typically sand and the groundwater depth is anticipated to be 10 to 12 ft below grade. The host pipe invert was at a depth of approximately 20 ft below ground level. The host pipe and liner information are shown in Table B-19.

The sample was originally going to be cut from above the spring line, however fiber optic conduits were found inside the sewer pipe at the 10 o'clock and 2 o'clock positions in the pipe on the north side of the manhole (towards Vermont Street). The samples were cut as 25-in. by 25-in. samples (Insituform would also collect a sample of the same size downstream of the Battelle sample for its own use), but it was not possible to lift this size of sample to the surface through the manhole. Hence, each original sample was cut into two 12.5-in. by 25-in. pieces. All sample pieces were successfully raised to the surface. The exhumed samples are shown in Figure B-38. The specimens were received at the TTC South Campus Lab Facility on Monday, October 22, 2012.

Table B-19. Indianapolis: Host Pipe and Liner Information

Host pipe	Brick sewer 42-in. diameter
Liner Thickness	Information not available
Resin	Information not available
Primary Catalyst	Information not available
Secondary Catalyst	Information not available
Felt	Information not available
Seal	Information not available
Year of Installation	1986-1989
Liner Vendor	Insituform Technologies
Resin Supplier	Information not available

Figure B-38. Indianapolis: Retrieval of the Sample (left) and Received Sample (right)

B.3.1.1 ***Visual Inspection.*** The two panels received were in good condition (see Figure B-39).

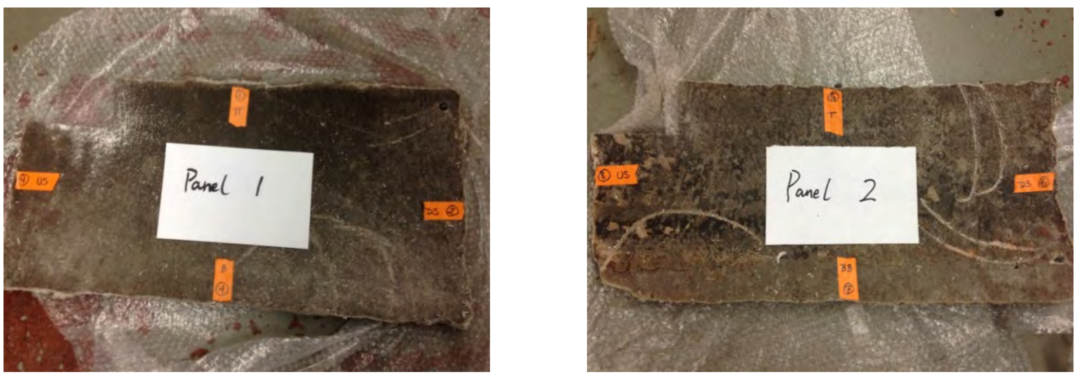

Figure B-39. Indianapolis: Panel 1 of the CIPP Liner (left) and Panel 2 of the CIPP Liner (right)

B.3.1.2 ***Annular Gap.*** The liner in the field was found to be close-fitted to the host pipe with an annular gap no more than 0.406 mm (0.016 in.).

B.3.1.3 ***Environmental Service Conditions.*** 2 g of waste material was collected from the inner and outer surfaces of the sample and mixed with 200 mL of distilled water stored in a bottle. The pH was measured separately using pH-indicator strips. For Panel 1, the pH inside the liner was 5 and outside was 6 to 7. For Panel 2, the pH of the inside and outside was more similar, both around 6 to 7.

B.3.1.4 ***Ovality.*** The sample received was a curved plate (a portion of the liner from the 3 o'clock to 5 o'clock positions of the circumference in the field) and therefore an ovality test was not applicable.

B.3.1.5 ***Thickness.*** A total of 180 readings were taken on 30 1 in. × 1 in. samples (15 specimens from Panel 1 and the other 15 from Panel 2) cut from different locations of the specimen. The thickness was measured randomly using a micrometer with a resolution of ±0.0025 mm.

The average thickness of Panel 1 was found to be 22.4 mm ± 0.21 mm (see Figure B-40) and the average thickness of Panel 2 was 21.9 mm ± 0.21 mm (see Figure B-41). The design thickness was not available and therefore no comparison was made.

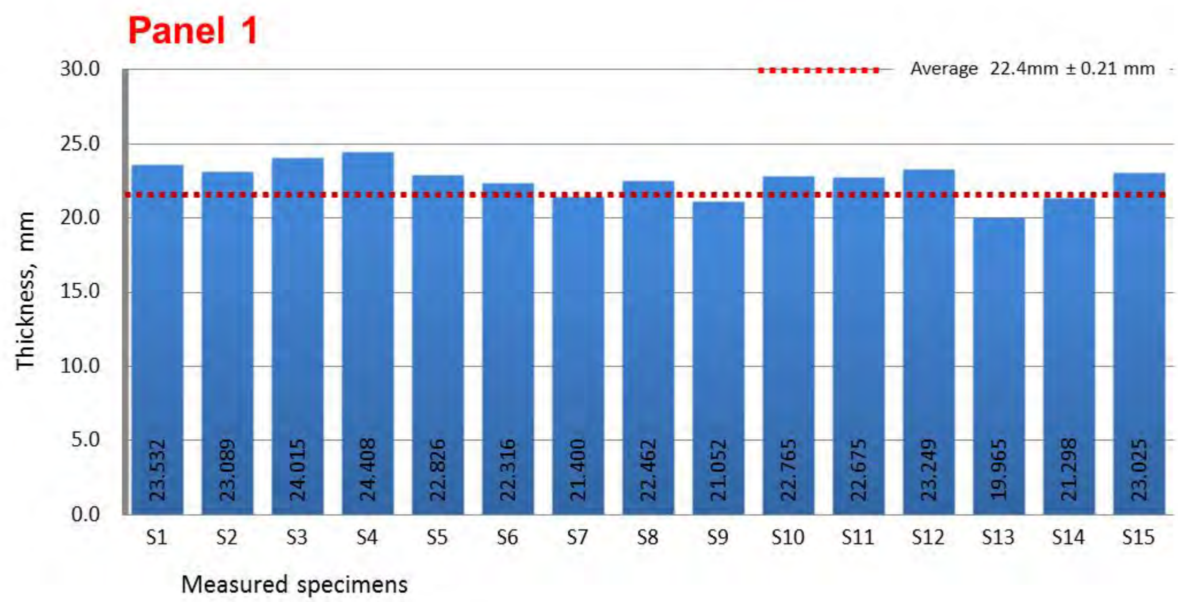

Figure B-40. Indianapolis: Average Thickness of Panel 1

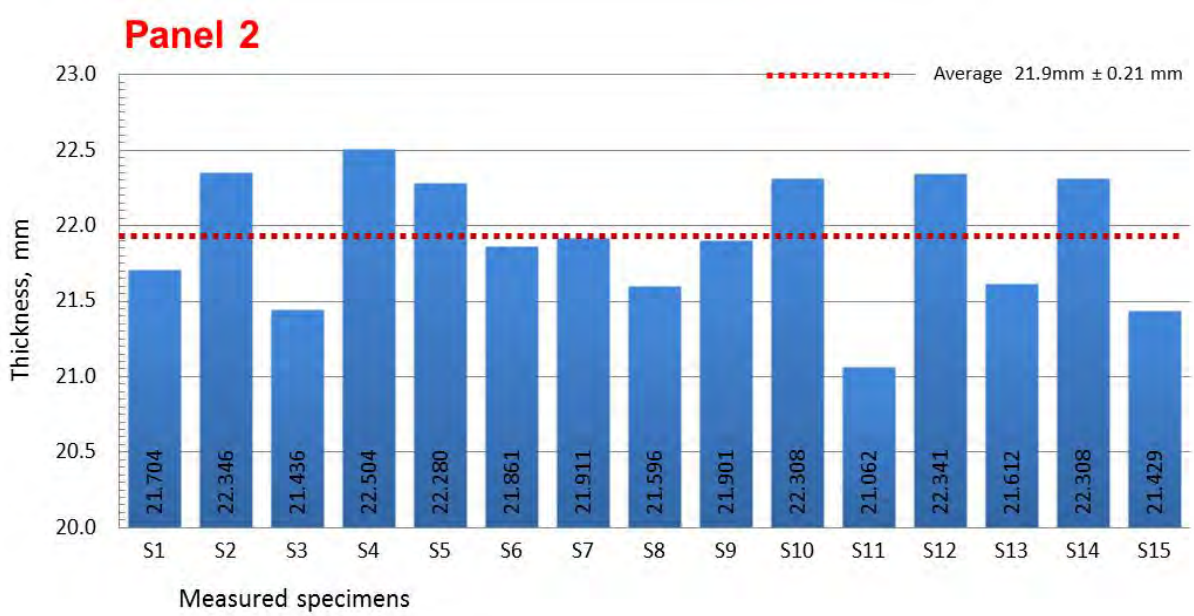

Figure B-41. Indianapolis: Average Thickness of Panel 2

B.3.1.6 ***Specific Gravity.*** The specific gravity of the liner was measured on 30 1 in. × 1 in. samples (15 from Panel 1 and 15 from Panel 2) in accordance with ASTM D792. The specific gravity values from Panel 1 and Panel 2 are shown in Figures B-42 and B-43. The obtained values were between 1.05 and 1.11. The average specific gravity of Panel 1 was 1.07 and Panel 2 was 1.08.

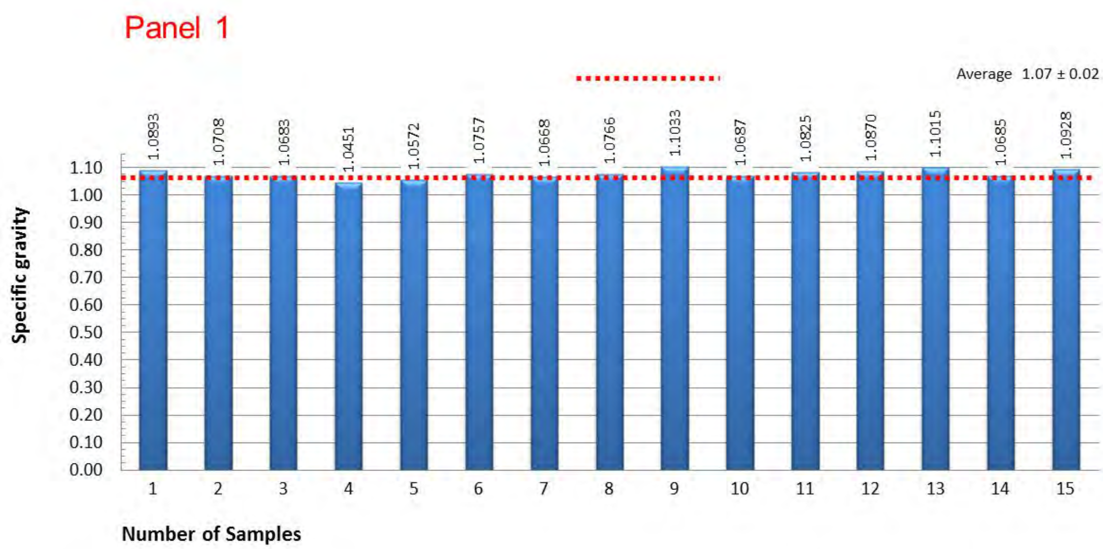

Figure B-42. Indianapolis: Measured Specific Gravity of Panel 1

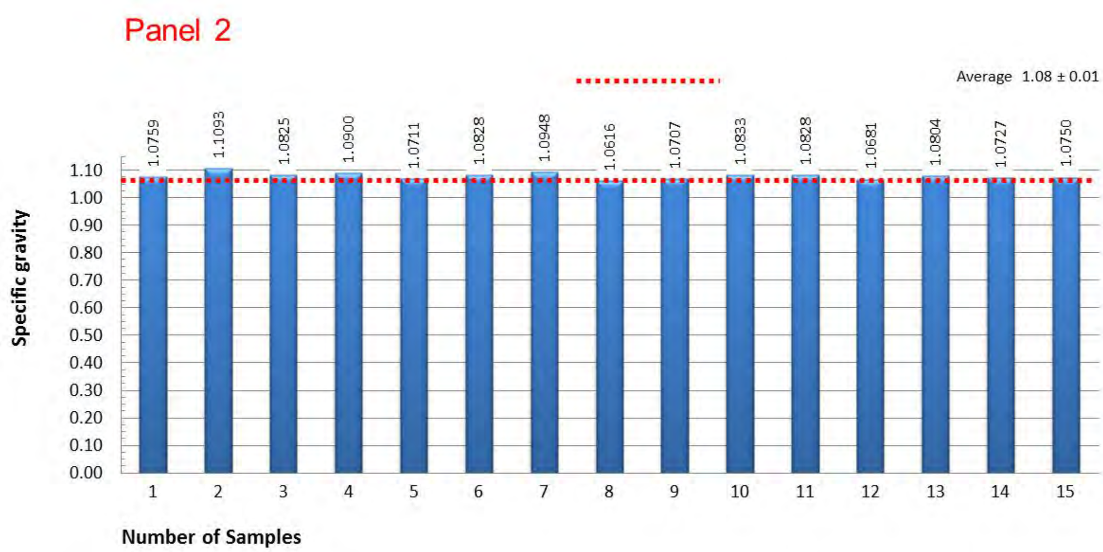

Figure B-43. Indianapolis: Measured Specific Gravity of Panel 2

B.3.1.7 ***Tensile Test (ASTM D638).*** Specimens, as described in ASTM D638, were cut from the retrieved CIPP liner using a table saw and a band saw. Due to the high thickness value of the sample, the Type III specimen dimensions from the standard were used. Tensile specimens were machined to 0.55 in. to meet the limit provided by ASTM D638 (see Figure B-44). The tensile test setup is shown in Figure B-45.

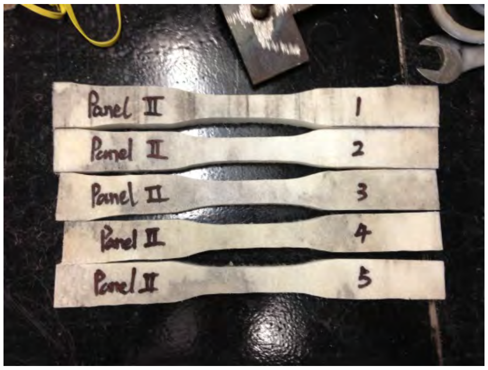

Figure B-44. Indianapolis: Five Panel 1 Specimens (left) and Five Panel 2 Specimens (right) Prepared for Tensile Testing

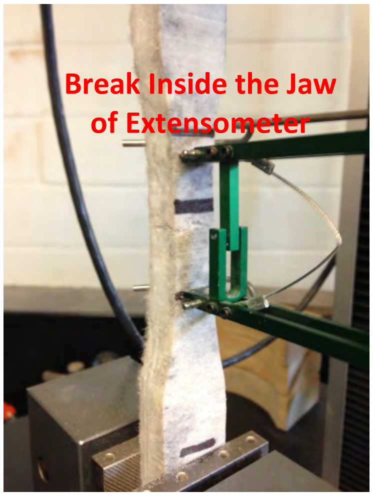

Figure B-45. Indianapolis: Tensile Testing in Accordance with ASTM D638 (left) and Samples after Test (right)

The tensile test results are presented in Figures B-46 and B-47 and Tables B-20 and B-21. The average tensile strength for Panel 1 was 2,826 ± 296 psi and, for Panel 2, was 2,611 ± 241 psi. The average tensile moduli were 356,783 ± 37,515 psi and 345,805 ± 67,528 psi, respectively. A visible crack was observed early in the test of Sample 5 from Panel 2, but the tensile strength and modulus properties still tested in the range of the other samples.

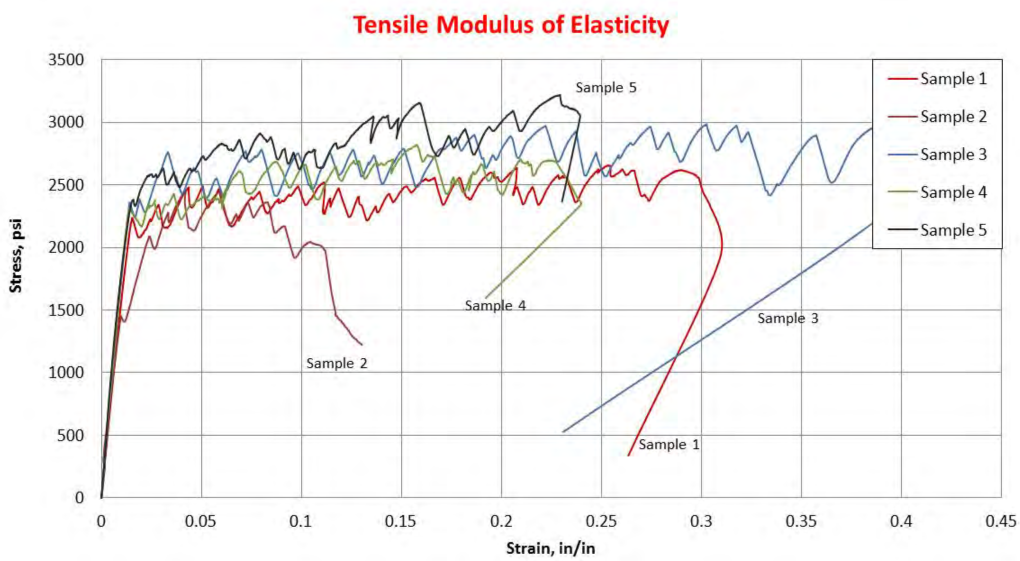

Figure B-46. Indianapolis: Stress – Strain Curves from Tensile Testing of Panel 1

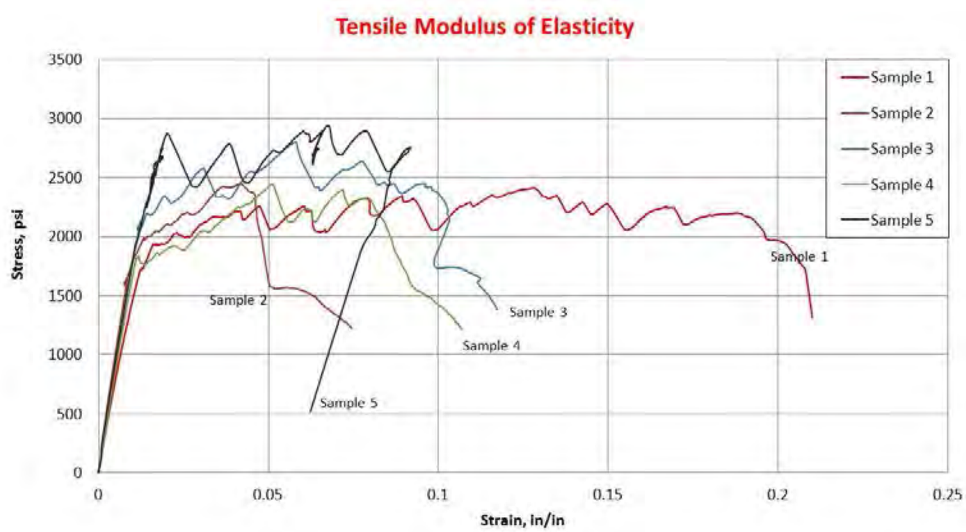

Figure B-47. Indianapolis: Stress – Strain Curves from Tensile Testing of Panel 2

Table B-20. Indianapolis: Tensile Test Results (Panel 1)

Sample ID	Area (in.^{2})	Peak Load (lb)	Peak Stress (psi)	Tensile Modulus (psi)
1	0.4068	1,081.02	2,657	320,584
2	0.3940	964.65	2,448	325,000
3	0.4027	1,201.72	2,985	361,417
4	0.4172	1,176.31	2,820	363,148
5	0.3853	1,239.83	3,218	413,766
Average		1,132.71	2,826	356,783
St. Dev		110.74	296	37,515

Table B-21. Indianapolis: Tensile Test Results (Panel 2)

Sample ID	Area (in.^{2})	Peak Load (lb)	Peak Stress (psi)	Tensile Modulus (psi)
1	0.4341	1,048.61	2,416	312,560
2	0.3795	931.33	2,454	436,579
3	0.3800	1,065.00	2,803	378,849
4	0.3804	930.55	2,446	343,537
5	0.3629	1,065.02	2,935	257,500*
Average		1,008.10	2,611	345,805
St. Dev		70.76	241	67,528

*Result is not within ± 25% RPD.

B.3.1.8 Flexural Test (ASTM D790). The flexural specimens were cut shorter than the required length mentioned in ASTM D790 due to the inadequate sample geometry. The specimens prepared from Panel 1 were 11 in. long while for Panel 2 they were 13 in. long. The sides of the specimens were smoothed using a grinder. The flexure test results are presented in Figures B-48 and B-49 and Tables B-22 and B-23.

The area values shown in the tables are the area back calculated by the software when the load reached its peak. The average flexural moduli of Panel 1 and Panel 2 were found to be 236,254 ± 23,169 psi and 238,273 ± 38,439 psi, respectively. The average flexural strengths for Panel 1 and Panel 2 were found to be 4,892 ± 408 psi and 4,531 ± 339 psi.

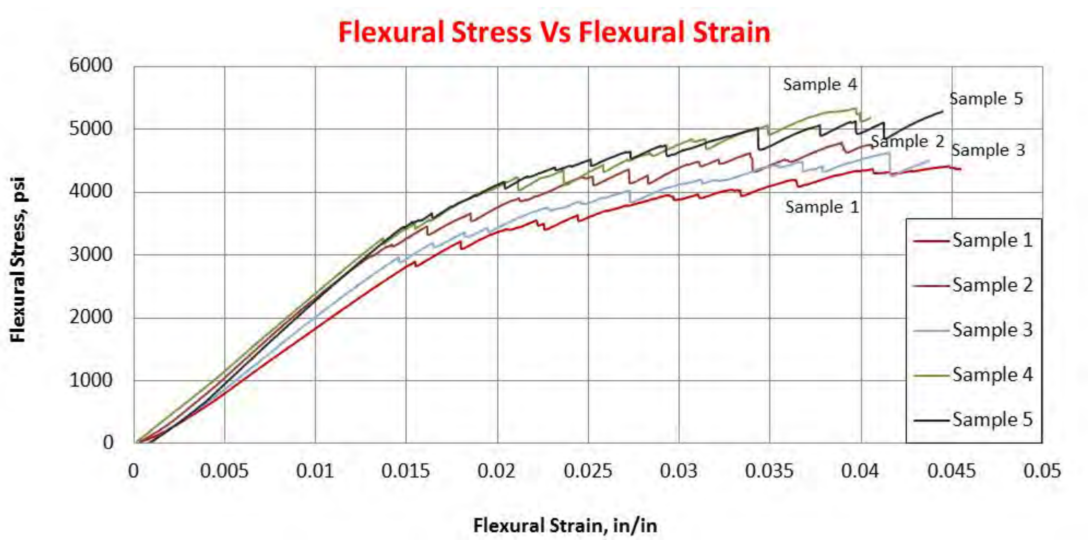

Figure B-48. Indianapolis: Stress – Strain Curves from Flexural Testing of Panel 1

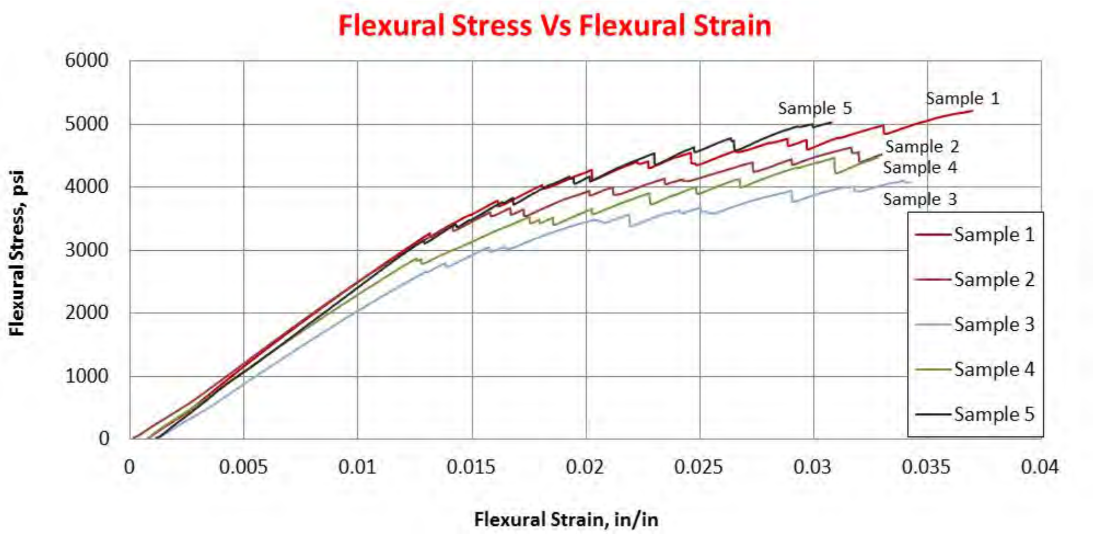

Figure B-49. Indianapolis: Stress – Strain Curves from Flexural Testing of Panel 2

Table B-22. Indianapolis: Flexural Test Results (Panel 1)

Sample ID	Area (in.^{2})	Peak Load (lb)	Peak Stress (psi)	Flexural Modulus (psi)
1	0.0336	148.59	4,422	202,890
2	0.0271	129.64	4,784	249,791
3	0.0313	144.71	4,623	224,674
4	0.0270	144.19	5,340	241,390
5	0.0376	199.00	5.293	262,527
Average		153.23	4,892	236,254
St. Dev		26.59	408	23,169

Table B-23. Indianapolis: Flexural Test Results (Panel 2)

Sample ID	Area (in.^{2})	Peak Load (lb)	Peak Stress (psi)	Flexural Modulus (psi)
1	0.0670	295.55	4,411	172,925*
2	0.0420	194.64	4,634	260,129
3	0.0499	204.96	4,107	236,399
4	0.0430	192.24	4,471	252,906
5	0.0404	203.32	5,033	269,006
Average		218.14	4,531	238,273
St. Dev		43.61	339	38,439

*Result is not within ± 25% RPD.

B.3.1.9 Surface Hardness. A Shore Type D durometer (ASTM D2240) was used to determine the hardness of the liner samples. A total of 400 readings were taken on the inner and outer surfaces of the liner specimens. The average recorded hardness values are shown in Figures B-50 and B-51. It can be seen that Panel 1 and Panel 2 show differences in the comparative hardness results between the inner and outer surfaces. The average outer surface hardness is similar, but the average inner surface hardness for Panel 2 is noticeably lower than for Panel 1.

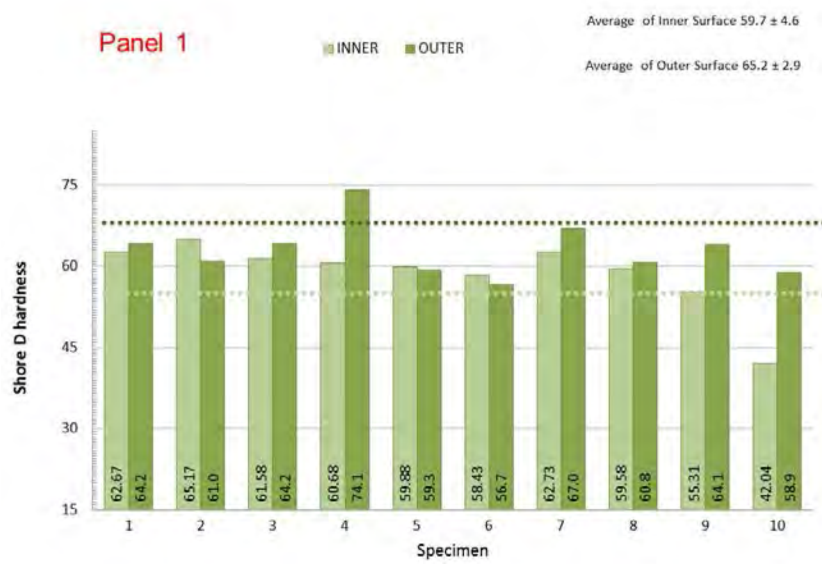

Figure B-50. Indianapolis: Shore D Hardness Readings for Panel 1 Inner and Outer Surfaces

Figure B-51. Indianapolis: Shore D Hardness Readings for Panel 2 Inner and Outer Surfaces

B.3.1.10 Glass Transition Temperature. The calculated Tg values are summarized in Table B-24 for the Indianapolis samples (Panel 1 and Panel 2). The average Tg for both of the field samples was 125.23°C (+/- 5.36°C) as measured by ASTM Method E1356-08 with DSC.

Table B-24. Indianapolis Tg Determination (Panels 1 and 2 CIPP Liner)

Sample	Run	Tg (°C)
Indianapolis Panel 1	1	120.48
Indianapolis Panel 1	2	117.88
Indianapolis Panel 1	3	126.09
Indianapolis Panel 2	1	131.31
Indianapolis Panel 2	2	130.62
Indianapolis Panel 2	3	125.02

B.4 City of Nashville

This section contains the test results performed on two liners exhumed from the City of Nashville, Tennessee.

B.4.1 Nashville Sample 1: A 19-Year Old CIPP Liner Installed in an 8 in. Concrete Pipe. The first sample was retrieved from 625 Dunston Drive, Nashville, Tennessee on September 21, 2013. The host pipe was at a depth of 4 ft to 5 ft below the ground surface. The host pipe and liner information are provided in Table B-25.

Table B-25. Nashville 1: Host Pipe and Liner Information

Host pipe	Concrete pipe, 8 in. diameter
Liner Thickness	5.6 mm (measured in laboratory)
Resin	Information not available
Primary Catalyst	Information not available
Secondary Catalyst	Information not available
Felt	Information not available
Seal	Information not available
Year of Installation	1994
Liner Vendor	Mid-South Partners (Insituform Technologies Inc.)
Resin Supplier	Information not available

The retrieval process and the retrieved sample are shown in Figure B-52. The specimens were received at the TTC South Campus Lab Facility on October 9, 2013.

B.4.1.1 Visual Inspection. The sample was found to be in excellent condition and closely fit inside the host pipe.

B.4.1.2 Annular Gap. The annular gap was measured using a feeler gauge. Eight readings were taken of the annular gap on the remaining host pipe and are shown in Table B-26.

 

Figure B-52. Nashville 1: Retrieval of the Sample (left) and Measuring Annular Gap on the Received Sample (right)

Table B-26. Nashville 1: Reading of Feeler Gauge on the "Remaining Host Pipe"

Position	Gap Measured
12:00	0.016 in. (0.41 mm)
1:30	0.016 in. (0.41 mm)
3:00	0.016 in. (0.41 mm)
5:00	0.000 in. (0.000 mm)
6:00	0.000 in. (0.000 mm)
7:30	0.000 in. (0.000 mm)
9:00	0.031 in. (0.79 mm)
11:00	0.0 . (0.000 mm)

B.4.1.3 Environmental Service Conditions. 20 g of waste material on the inside of the sample was collected and stored in a bottle filled with 200 mL of distilled water. The distilled water was stirred and pH was measured separately using pH-indicator strips. The pH was found to be between 10 and 11.

B.4.1.4 Ovality. A profile plotter was used to accurately map any deformation inside the liner. The liner was found to be approximately circular with reference to its center (see Figure B-53). The ovality of the liner was found to be 3.7%.

B.4.1.5 Thickness. A total of 120 readings were taken on 20 1 in. × 1 in. samples cut from different locations of the liner specimen. The thickness was measured randomly using a micrometer with a resolution of ±0.0025 mm. The average thickness was found to be 5.60 mm ± 0.32 mm as shown in Figure B-54. The design thickness was unavailable so no comparison was made.

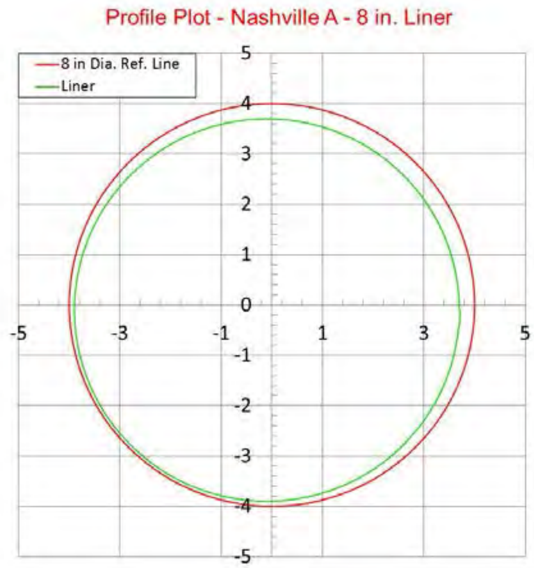

Figure B-53. Nashville 1: Ovality of the Liner

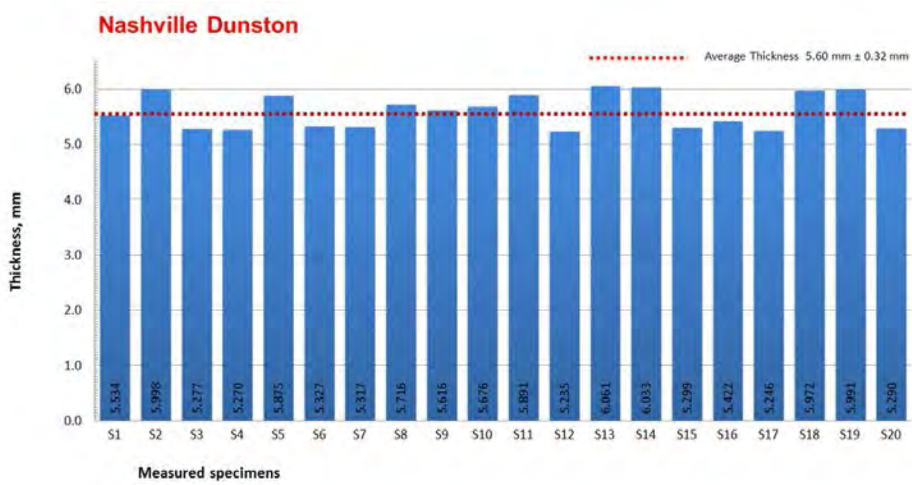

Figure B-54. Nashville 1: Average Thickness of the Sample

B.4.1.6 Specific Gravity. The specific gravity of the liner was measured on 20 1 in. × 1 in. samples in accordance with ASTM D792. The specific gravity values from the sample are shown in Figure B-55. The obtained values were between 1.08 and 1.17. The average specific gravity of the liner was 1.14.

B.4.1.7 Tensile Test (ASTM D638). Specimens, as described in ASTM D638, were cut from the liner using a table saw and a band saw. The Type II specimen dimension was used for the ASTM D638 tensile test. The sides of the specimens were smoothed using a grinder. A total of 15 specimens were prepared and tested. The tensile test results are presented in Figure B-56 and Table B-27. The average tensile strength was 3,436 ± 274 psi. The average tensile modulus was calculated to be 375,807 ± 48,729 psi.

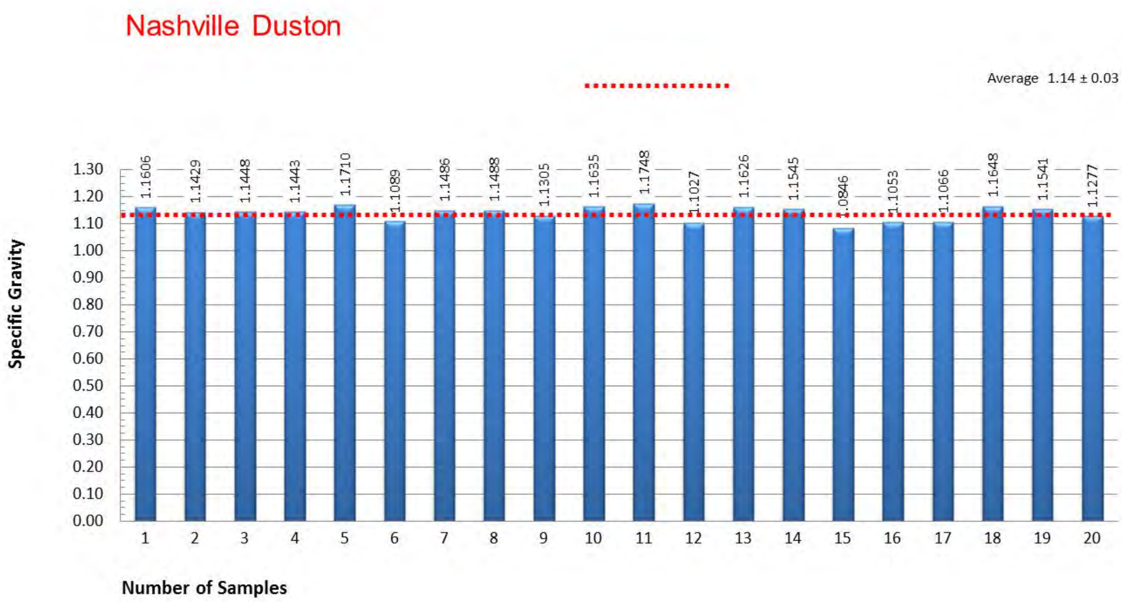

Figure B-55. Nashville 1: Measured Specific Gravity of the Liner

Table B-27. Nashville 1: Tensile Test Results

Sample ID	Area (in.^{2})	Peak Load (lb)	Peak Stress (psi)	Tensile Modulus (psi)
1	0.1025	376.41	3,672	391,267
2	0.1061	325.39	3,067	439,783
3	0.1059	393.01	3,711	432,223
4	0.0965	326.24	3,381	287,329
5	0.1002	349.03	3,483	350,412
6	0.1163	404.54	3,478	385,196
7	0.1101	367.00	3,333	343,115
8	0.1111	380.20	3,422	420,735
9	0.1185	469.79	3,964	427,424
10	0.0976	339.33	3,477	284,745
11	0.1085	316.35	2,916	361,284
12	0.1186	418.99	3,533	413,245
13	0.1049	382.88	3,650	353,638
14	0.1297	393.42	3,033	395,794
15	0.0992	339.15	3,419	350,909
Average		372.11	3,436	375,807
St. Dev		41.40	274	48,729

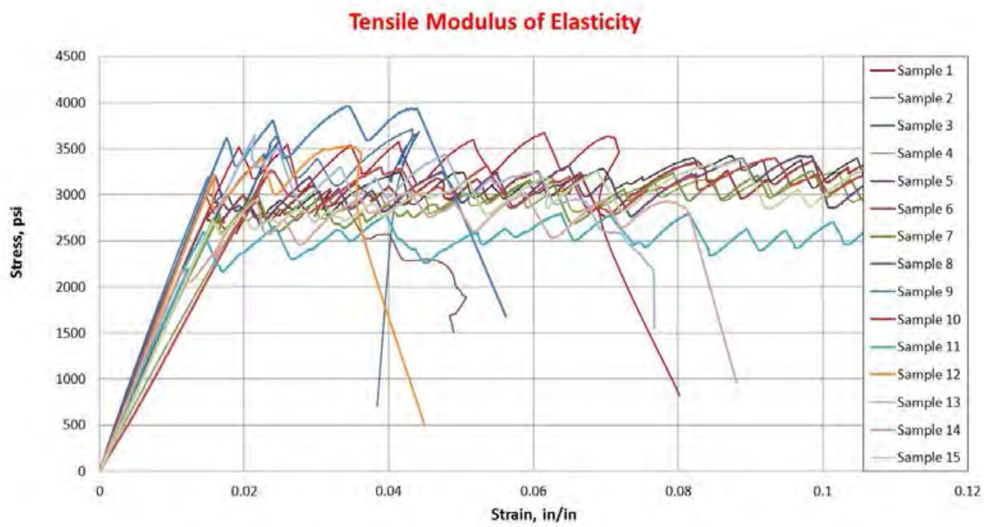

Figure B-56. Nashville 1: Stress – Strain Curves from Tensile Testing

B.4.1.8 Flexural Test (ASTM D790). A total of 15 specimens were prepared for ASTM D790 flexure tests. The flexure test results are presented in Figure B-57 and Table B-28. The area values were automatically back calculated by the software when the peak load was reached. The average flexural modulus was 301,724 ± 42,399 psi and the average flexure strength was 6,832 ± 864 psi.

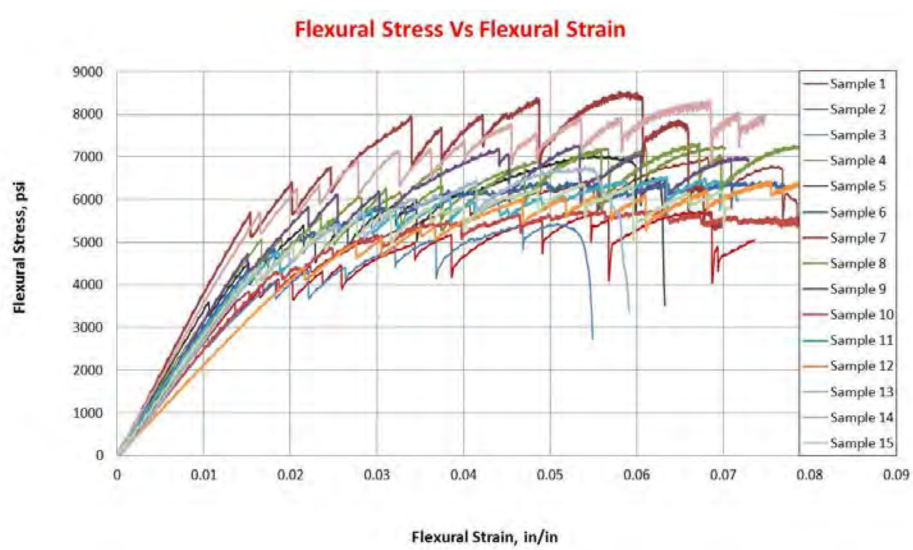

Figure B-57. Nashville 1: Stress – Strain Curves from Flexural Testing

B.4.1.9 Surface Hardness. A Shore Type D durometer (ASTM D2240) was used to determine the hardness of the liner samples. Samples (1 in. × 1 in.) were cut from the retrieved CIPP liner with a band saw. A total of 400 readings were taken on the inner and outer surfaces of the liner specimens. The average recorded hardness values are shown in Figure B-58. The hardness of the surface exposed to the flow (inner surface) was found to be only slightly lower than that of the protected (outer) surface, suggesting little, if any, softening or erosion of the resin on the inner surface of the tube during its service life. Differences may also be expected due to the initial presence of the sealing layer on the internal surface.

Table B-28. Nashville 1: Flexural Test Results

Sample ID	Area (in.^{2})	Peak Load (lb)	Peak Stress (psi)	Flexural Modulus (psi)
1	0.0044	25.44	5,782	263,620
2	0.0043	30.22	7,028	315,296
3	0.0043	23.52	5,470	276,162
4	0.0041	29.52	7,200	311,503
5	0.0037	26.13	7,062	338,642
6	0.0037	23.86	6,449	308,482
7	0.0049	41.88	8,547	386,728
8	0.0060	43.98	7,330	294,335
9	0.0051	36.96	7,247	334,861
10	0.0044	25.19	5,725	258,893
11	0.0056	36.53	6,523	291,689
12	0.0071	47.58	6,701	214,178*
13	0.0046	31.29	6,802	288,000
14	0.0056	46.49	8,302	356,428
15	0.0053	33.53	6,326	287,057
Average		33.47	6,832	301,724
St. Dev		8.37	864	42,399

*Result is not within ± 25% RPD.

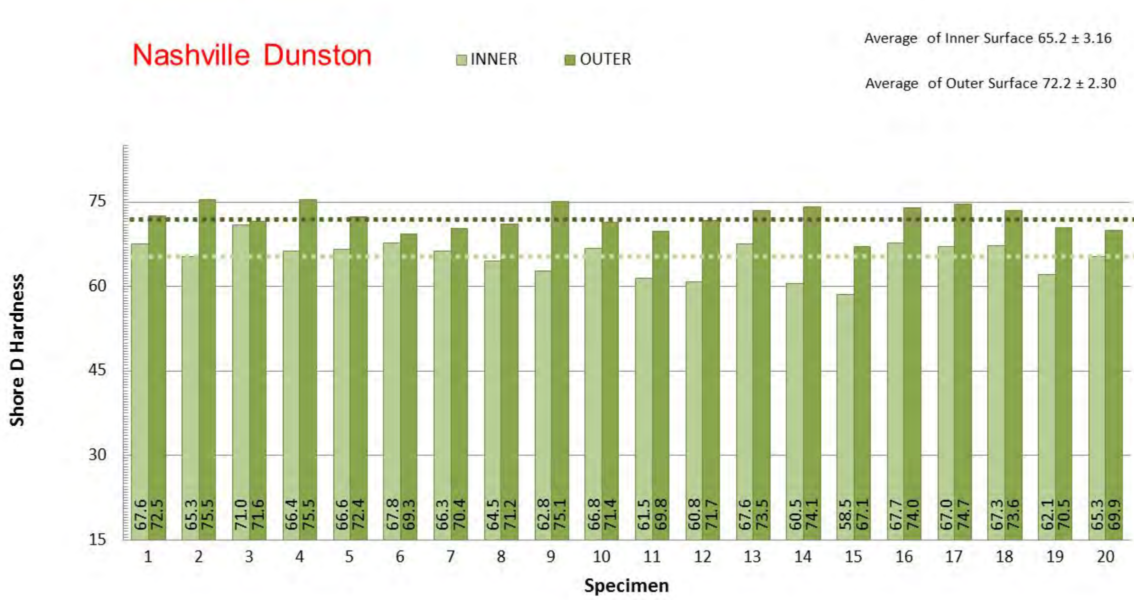

Figure B-58. Nashville 1: Shore D Hardness Readings from Inner and Outer Surfaces

B.4.1.10 Glass Transition Temperature. The calculated Tg values are summarized in Table B-29 for the Nashville (Dunston) CIPP sample. The average Tg for the field samples was 120.37°C (+/- 2.14°C) as measured by ASTM Method E1356-08 with DSC.

Table B-29. Nashville 1: Tg Determination (Dunston CIPP Liner)

Sample	Run	Tg (°C)
Nashville (Dunston)	1	121.79
Nashville (Dunston)	2	121.42
Nashville (Dunston)	3	117.91

B.4.2 Nashville 2: A 9-Year Old CIPP Liner in an 8 in. Non-reinforced Concrete Pipe. The liner sample was retrieved from 5100 Wyoming Avenue, Nashville, Tennessee on September 21, 2013. The host pipe was at 4 ft to 5 ft below the ground surface. The host pipe and liner information are shown in B-30.

Table B-30. Nashville 2: Host Pipe and Liner Information

Host pipe	Concrete pipe, 8 in. diameter
Liner Thickness	7.05 mm (laboratory measurement)
Resin	Information not available
Primary Catalyst	Information not available
Secondary Catalyst	Information not available
Felt	Information not available
Seal	Information not available
Year of Installation	2004
Liner Vendor	Miller Pipeline
Resin Supplier	Information not available

The retrieval process and the retrieved sample are shown in Figure B-59. The sample was received at TTC South Campus Facility on October 9, 2013.

B.4.2.1 Visual Inspection. The sample was found to be in excellent condition.

B.4.2.2 Annular Gap. The annular gap was measured using a feeler gauge on the remaining host pipe. Eight readings were taken and are shown in Table B-31.

B.4.2.3 Environmental Service Conditions. 20 g of waste material was collected from the inside of the sample and mixed with 200 mL of distilled water. The pH of the water was measured using pH-indicator strips and found to be between 9 and 10. The pH also was measured in a similar manner on the collected soil sample and the value obtained was found between 6 and 7.

B.4.2.4 Ovality. A profile plotter was used to accurately map any deformation inside the liner. The liner was found to be approximately circular with reference to its center (see Figure B-60). The ovality of the liner was found to be 3.6%.

Figure B-59. Nashville 2: Retrieval of the Sample (left) and Received Sample (right)

Table B-31. Nashville 2: Reading of Feeler Gauge on the "Remaining Host Pipe"

Position	Gap Measured
12:00	0.046 in. (1.17 mm)
1:30	0.000 in. (0.000 mm)
3:00	0.000 in. (0.000 mm)
5:00	0.016 in. (0.41 mm)
6:00	0.016 in. (0.41 mm)
7:30	0.000 in. (0.000 mm)
9:00	0.000 in. (0.000 mm)
11:00	0.016 in. (0.41 mm)

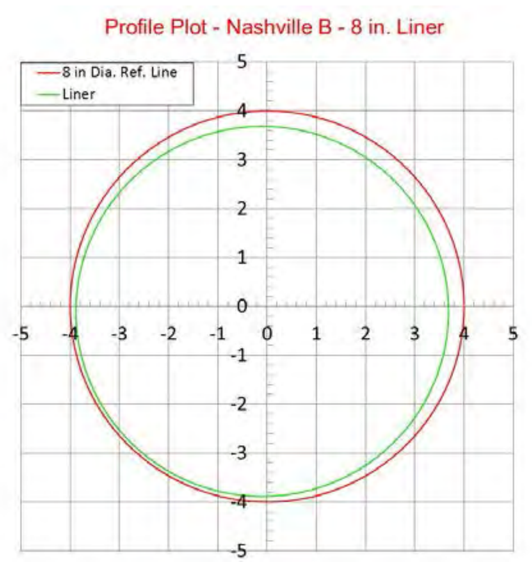

Figure B-60. Nashville 2: Ovality of the Liner

B.4.2.5 ***Thickness.*** A total of 120 readings were taken on 20 1 in. × 1 in. samples cut from different locations of the specimen. The thickness was measured randomly using a micrometer with a resolution of ±0.0025 mm. The average thickness was found to be 7.05 mm ± 0.28 mm as shown in Figure B-61. The design thickness was not available.

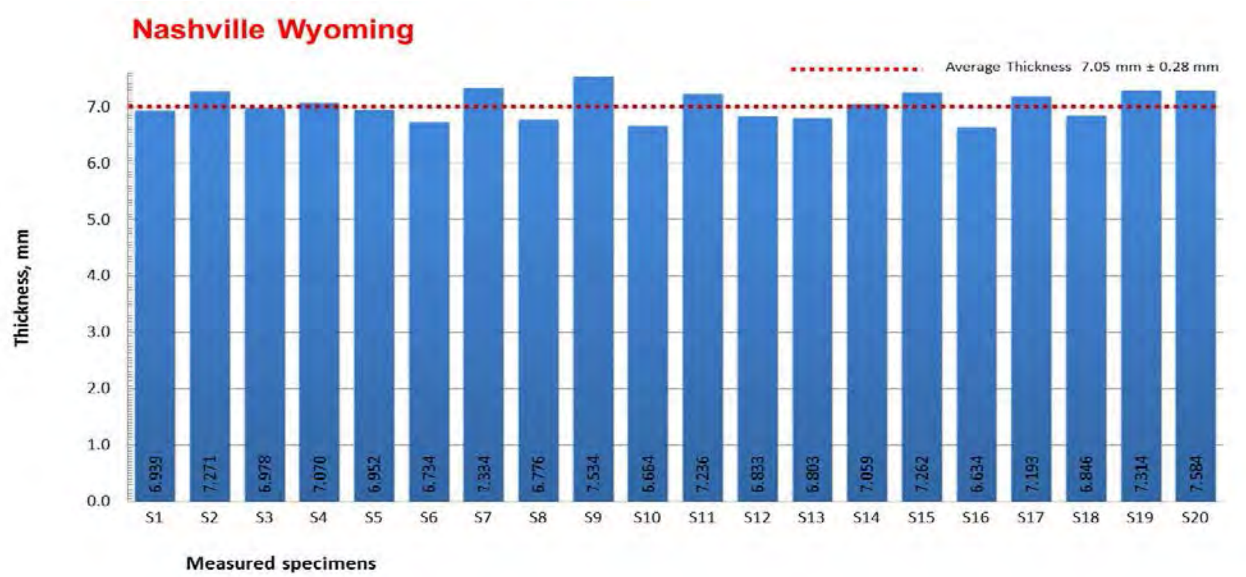

Figure B-61. Nashville 2: Average Thickness of the Sample

B.4.2.6 ***Specific Gravity.*** The specific gravity of the liner was measured on 20 1 in. × 1 in. samples in accordance with ASTM D792. The specific gravity values from the sample are shown in Figure B-62. The obtained values were between 1.15 and 1.25. The average specific gravity of the liner was 1.21.

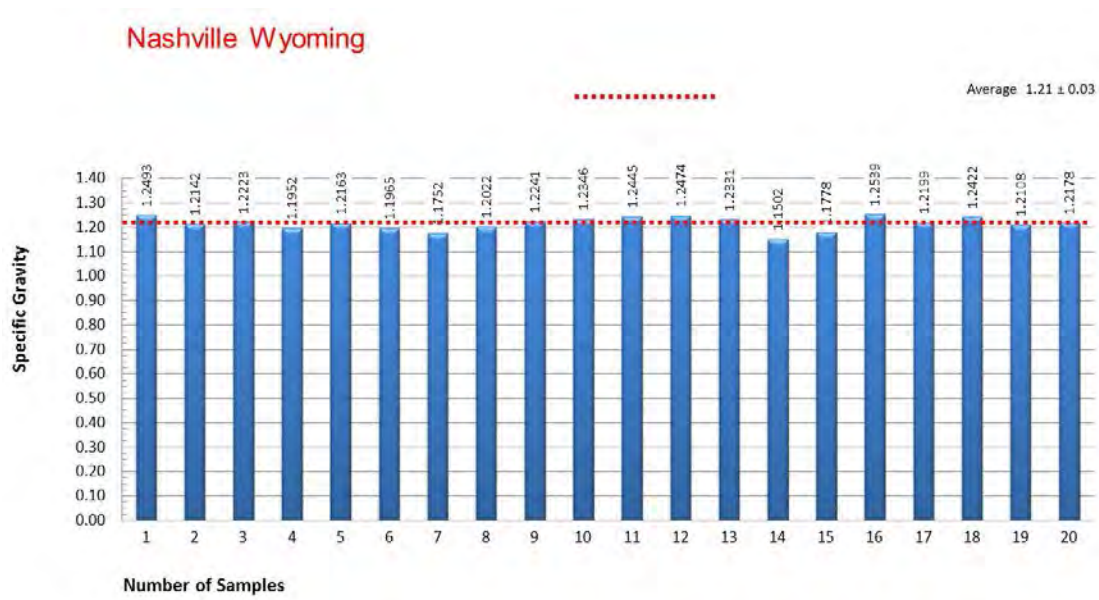

Figure B-62. Nashville 2: Measured Specific Gravity of Liner

B.4.2.7 Tensile Test (ASTM D638). Specimens, as described in ASTM D638, were cut from the liner using a table saw and a band saw. The Type II specimen dimension was used for the ASTM D638 tensile test. The sides of the specimens were smoothed using a grinder. A total of 15 specimens were prepared and tested. The tensile test results are presented in Figure B-63 and Table B-32. The average tensile strength was 2,672 ± 425 psi and the average tensile modulus was 400,926 ± 79,773 psi.

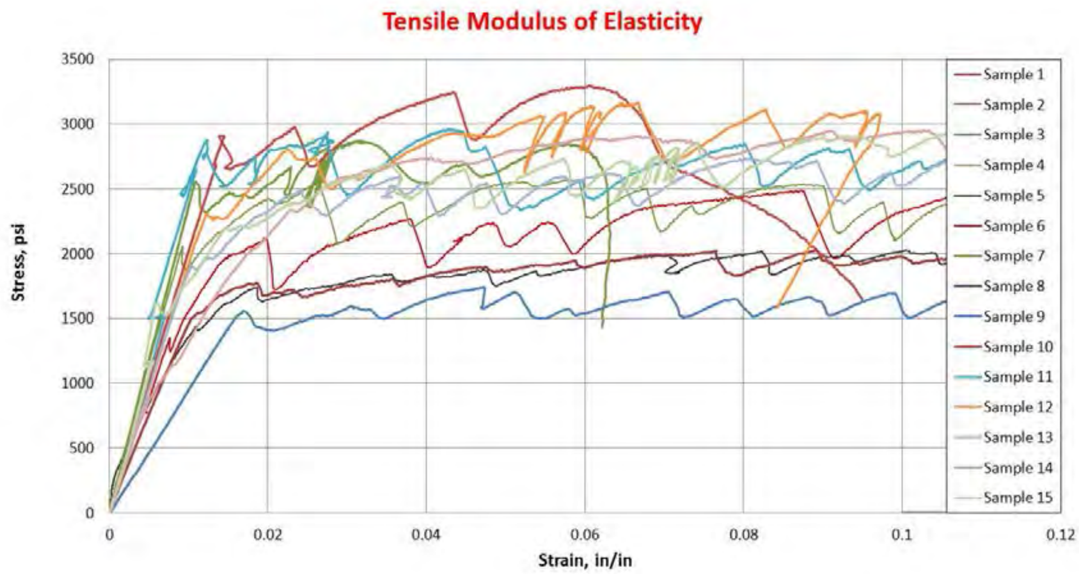

Figure B-63. Nashville 2: Stress – Strain Curves from Tensile Testing

Table B-32. Nashville 2: Tensile Test Results

Sample ID	Area (in.^{2})	Peak Load (lb)	Peak Stress (psi)	Tensile Modulus (psi)
1	0.1816	454.98	2,505	409,234
2	0.1387	372.21	2,684	499,595
3	0.1336	361.91	2,709	452,010
4	0.1403	360.52	2,570	468,111
5	0.1382	292.40	2,116	483,333
6	0.1447	334.75	2,315	300,738
7	0.1403	402.67	2,870	468,814
8	0.1455	318.25	2,187	328,964
9	0.2136	384.84	1,793*	191,123*
10	0.1760	580.20	3,297	408,346
11	0.1558	461.51	2,962	429,530
12	0.1445	457.51	3,166	395,000
13	0.1520	436.64	2,873	381,617
14	0.1628	503.65	3,094	387,788
15	0.1481	435.78	2,942	409,693
Average		410.52	2,672	400,926
St. Dev		75.98	425	79,773

* Result is not within ± 25% RPD.

B.4.2.8 Flexural Test (ASTM D790). A total of 15 specimens were prepared for ASTM D790 flexure tests. The flexure test results are presented in Figure B-64 and Table B-33. The area values were automatically back calculated by the software when the peak load was reached. The average flexural modulus was 282,460 ± 50,774 psi and the average flexure strength was 5,497 ± 916 psi. The bending modulus values for Samples 1 to 5 were found to be noticeably lower than the other samples cut from a different location of the same specimen. The flexural strength for Sample 10 was also noticeably lower in value (see Figure B-64). This is attributed to a localized variation in liner properties either from the time of installation or due to subsequent deterioration.

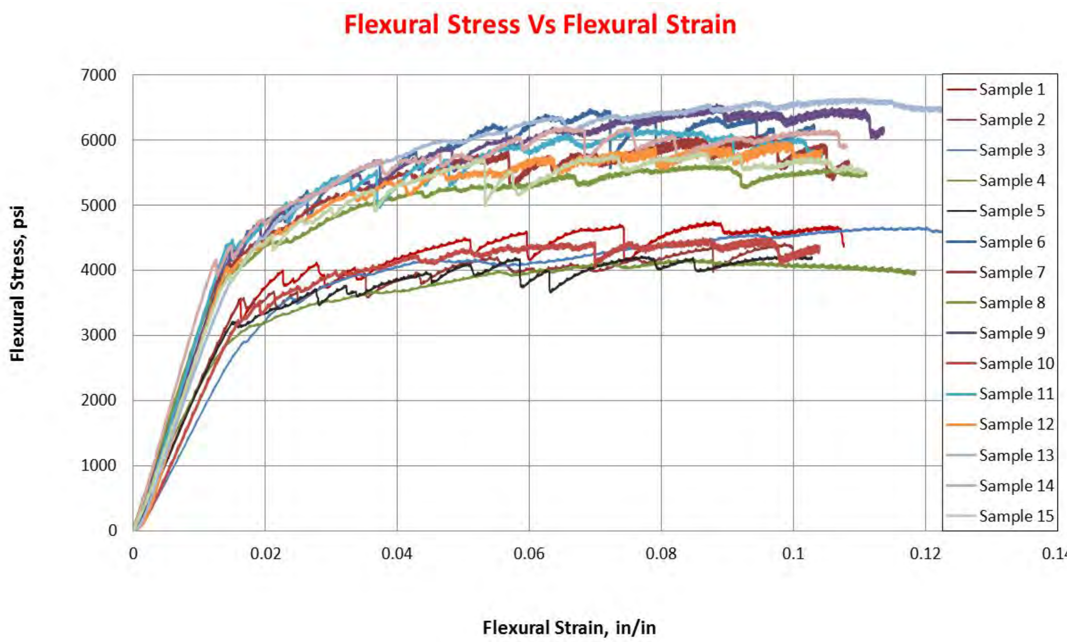

Figure B-64. Nashville 2: Stress – Strain Curves from Flexural Testing

B.4.2.9 Surface Hardness. A Shore Type D durometer (ASTM D2240) was used to determine the hardness of the liner samples. Samples (1 in. × 1 in.) were cut from the retrieved CIPP liner with a band saw. A total of 400 readings were taken on the inner and outer surfaces of the liner specimens. The average recorded hardness values are shown in Figure B-65. The hardness of the surface exposed to the flow (inner surface) was found to be only slightly lower than that of the protected (outer) surface, suggesting little, if any, softening or erosion of the resin on the inner surface of the tube during its service life. Differences may also be expected due to the initial presence of the sealing layer on the internal surface.

B.4.2.10 Glass Transition Temperature. The calculated Tg values are summarized in Table B-34 for the Nashville (Wyoming Avenue) sample. The average Tg for the field samples was 109.43°C (± 3.79°C) as measured by ASTM Method E1356-08 with DSC.

Table B-33. Nashville 2: Flexural Test Results

Sample ID	Area (in.^{2})	Peak Load (lb)	Peak Stress (psi)	Flexural Modulus (psi)
1	0.0070	33.45	4,779	236,019
2	0.0063	27.88	4,425	241,460
3	0.0094	43.85	4,665	189,627*
4	0.0085	35.65	4,194	237,897
5	0.0063	26.77	4,249	229,241
6	0.0067	43.59	6,506	340,971
7	0.0074	45.16	6,103	315,721
8	0.0078	43.85	5,622	312,206
9	0.0082	53.37	6,509	306,335
10	0.0069	30.96	4,487	226,103
11	0.0070	42.92	6,131	328,685
12	0.0070	42.92	6,131	328,685
13	0.0103	68.35	6,636	297,954
14	0.0074	45.75	6,182	353,472
15	0.0077	44.90	5,831	292,528
Average		41.96	5,497	282,460
St. Dev		10.46	916	50,774

* Result is not within ± 25% RPD.

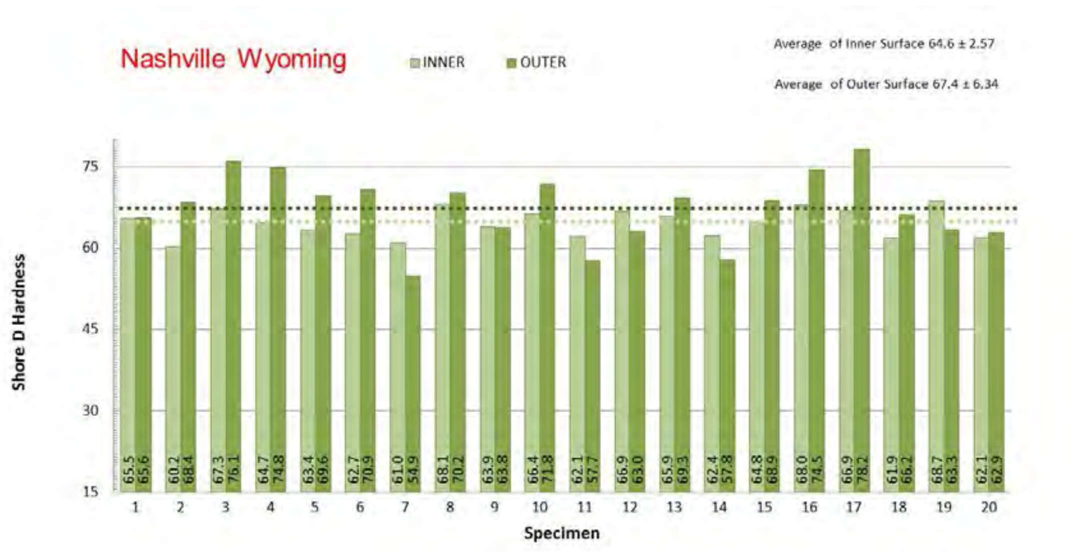

Figure B-65. Nashville 2: Shore D Hardness Readings from Inner and Outer Surfaces

Table B-34. Nashville 2: Tg Determination (Wyoming Avenue 8 in. CIPP Liner)

Sample	Run	Tg (°C)
Nashville (Wyoming)	1	112.81
Nashville (Wyoming)	2	105.34
Nashville (Wyoming)	3	110.15

B.5 City of New York

This report contains the test results performed on three liners exhumed from 3rd Street and Willoughby Street in New York City. The sample locations were selected by the city based on the age of the CIPP installation and accessibility. Sample 1 was defective, and therefore was subjected to visual examination, but not to physical testing.

B.5.1 New York Sample 1: A 24-Year Old CIPP Liner in a 12 in. Clay or Concrete Pipe. At this location at 630A 3rd Street, Brooklyn, New York, a sample was recovered on October 16, 2012 by cutting a liner sample from within the host pipe adjacent to an existing manhole (Figure B-66). The depth to the invert of the host pipe at the sample location was 11.6 ft. However, the sample recovered was not suitable for testing. The sample consisted mostly of uncured felt with very little resin. This could have been due to significant infiltration of groundwater near the manhole, which washed away the impregnated resin before it could be cured and hardened or due to a lack of resin saturation during the wet out process. It was expected that mechanical testing of this soft sample would have been unlikely to produce meaningful data, and therefore no testing was carried out.

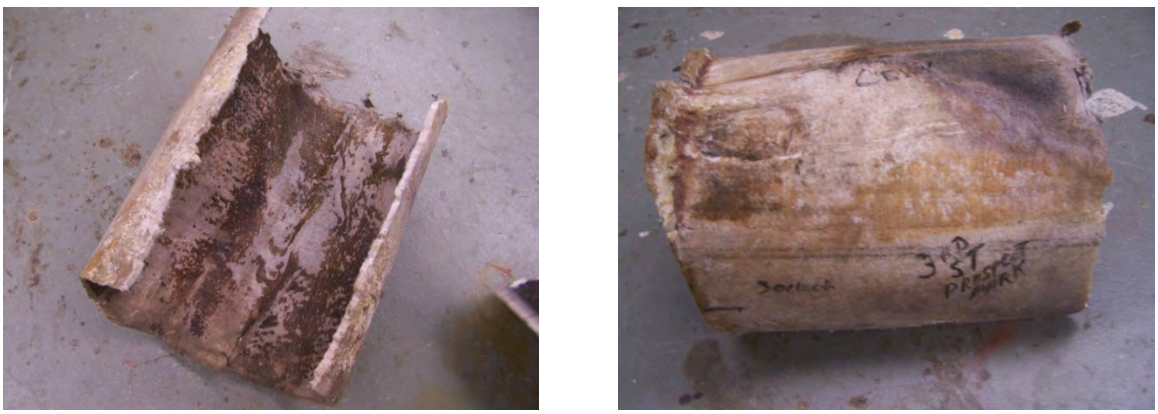

Figure B-66. New York 1: Defective Sample Retrieved from 3rd Street

B.5.2 New York Sample 2: A 23-Year Old CIPP Liner in a 15-in. Clay Pipe. The sample was recovered at 141 Willoughby Street, Brooklyn, New York on October 16, 2012. The host pipe and liner information are shown in Table B-35. The invert of the host pipe was at a depth of approximately 12 ft below ground level and the groundwater conditions could not be observed due to the sample retrieval via a manhole.

B.5.2.1 Visual Inspection. The liner sample was removed fairly easily compared to the previous site containing the defective liner. The bottom half of the liner was inaccessible for removal. The liner appeared to be in good condition. However, the interior polyurethane coating seemed to have hydrolyzed or eroded away. The retrieval process and the retrieved sample are shown in Figures B-67 and B-68.

Table B-35. New York 2: Host Pipe and Liner Information

Host pipe	Extra Strength Vitrified Clay Pipe 15 in.
Liner Thickness	@ 3:00 o'clock 6.8 mm and @ 9:00 o'clock 7.05 mm
Resin	AOC 7-5810-PM
Primary Catalyst	Esperox 570P
Secondary Catalyst	Esperox 10
Felt	Unwoven fabric (similar to products used today)
Seal	Polyurethane, 0.015 in. thick (today CIPP liners use polyethylene coating)
Year of Installation	1989-1991
Liner Vendor	Insituform
Resin Supplier	AOC LLC

Figure B-67. New York 2: Retrieval of the Sample (left) and Retrieved Sample in the Field (right)

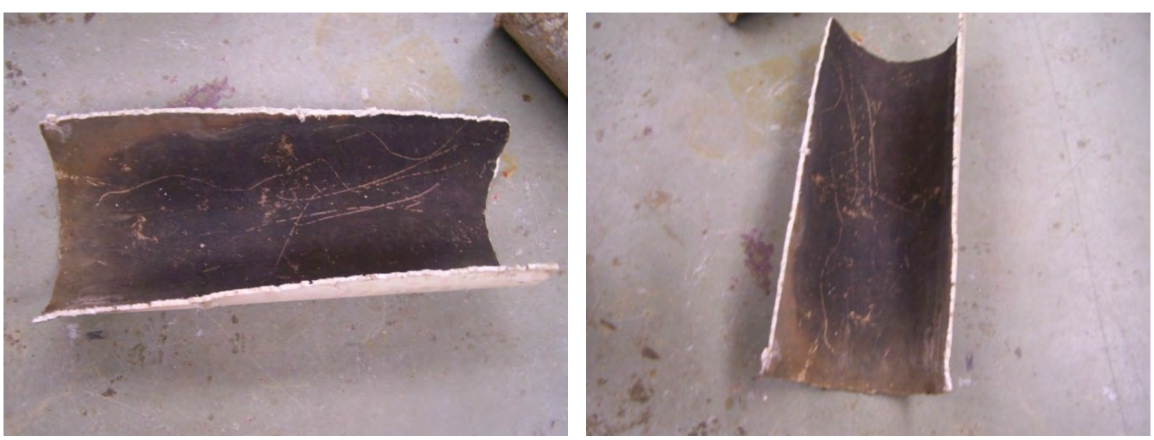

Figure B-68. New York 2: Images of the Inner Surface of the 23-Year Old, 36-in. Long CIPP Liner Section Prior to Testing

B.5.2.2 Annular Gap. The liner was observed to be tight to the invert of the pipe (below the 9:00 o'clock to 3:00 o'clock positions) with no annular gap. However, a small annular gap (around 0.007 in. [0.18 mm]) was measured in the field from the 9:00 o'clock to the 3:00 o'clock positions.

B.5.2.3 Environmental Service Conditions. Not applicable due to method of removal described above where only the top half of the liner was removed. No soil samples were collected because of sample removal through the manhole.

B.5.2.4 Thickness. A total of 120 readings were taken on 20 1 in. × 1 in. samples cut from different locations of the specimen. The thickness was measured randomly using a micrometer with a resolution of ±0.0025 mm. The average thickness of the liner was found to be 7.27 mm ± 0.26 mm as shown in Figure B-69. The design thickness was unavailable; therefore, no comparison was made.

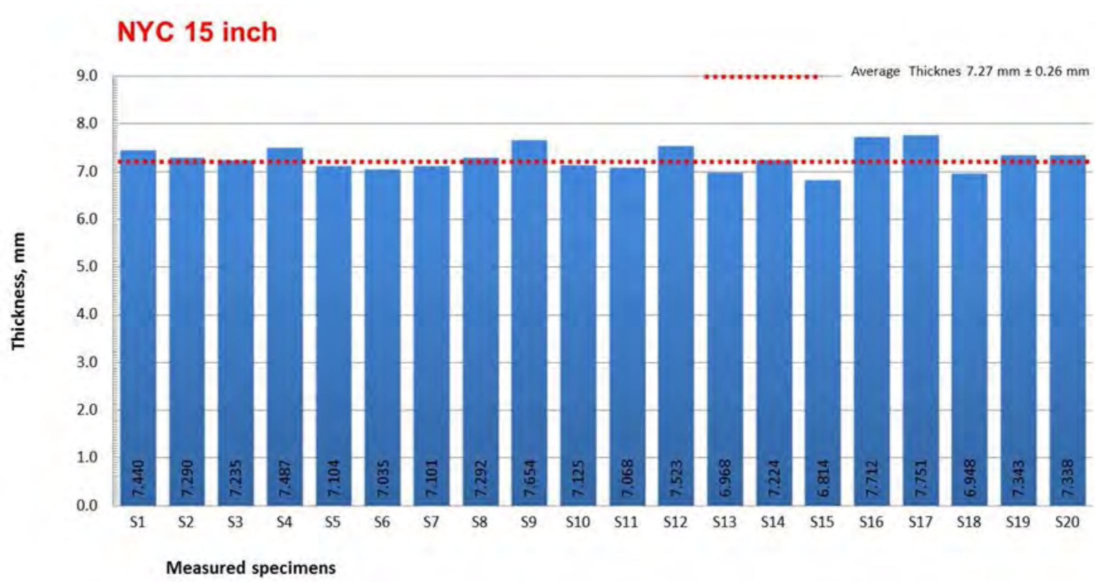

Figure B-69. New York 2: Average Thickness of the Liner Sample

B.5.2.5 Specific Gravity. The specific gravity of the liner was measured on 20 1 in. × 1 in. samples in accordance with ASTM D792. The specific gravity values are shown in Figure B-70. The obtained values were between 1.26 and 1.35. The average specific gravity was 1.31 ± 0.03.

B.5.2.6 Tensile Test (ASTM D638). Specimens, as described in ASTM D638, were cut from the retrieved CIPP liner using a router and a band saw. A total of 15 specimens were prepared and tested. The sides of the specimens were smoothed using a grinder. A water jet cutter could not be used as the liner was curved and too small to be mounted inside the cutting board. The tensile test results are presented in Figure B-71 and Table B-36. The average tensile strength was 3,729 ± 369 psi and average tensile modulus 554,100 ± 60,863 psi. The elongation at break varied from around 1.5% to 16%.

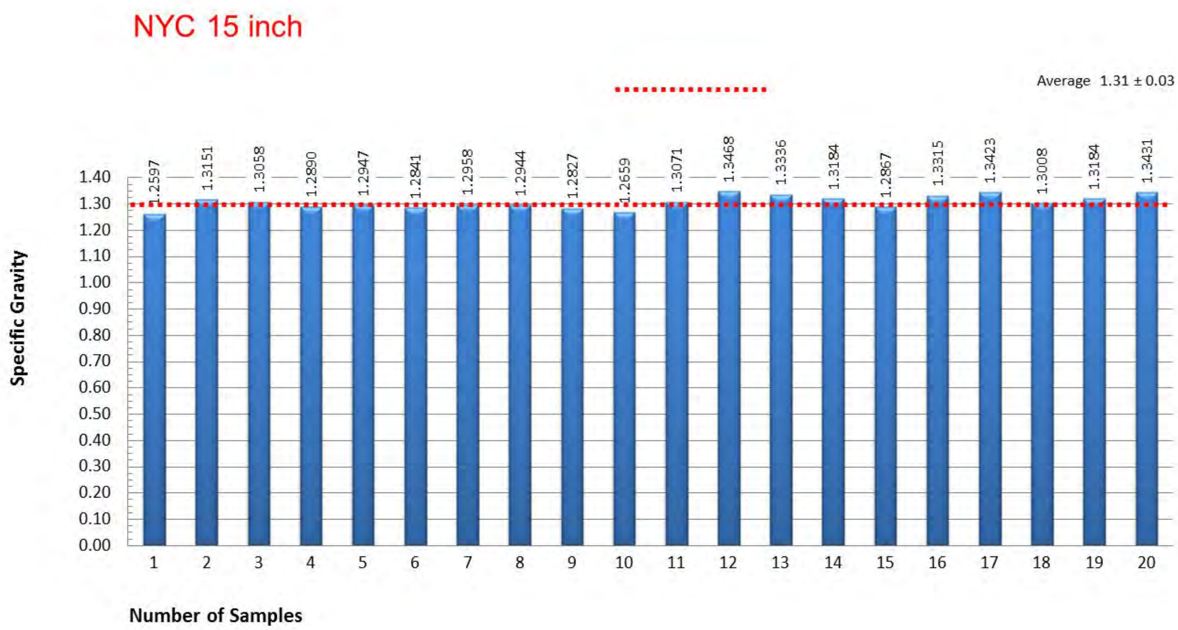

Figure B-70. New York 2: Measured Specific Gravity of the Liner

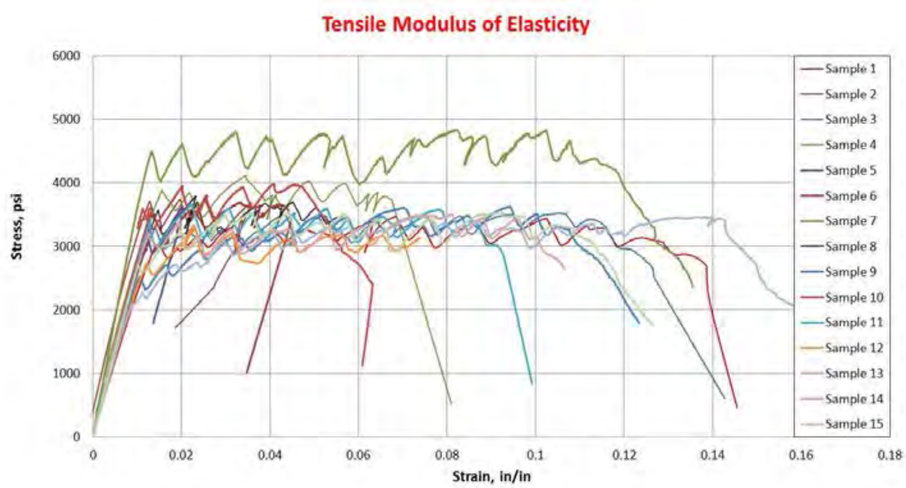

Figure B-71. New York 2: Stress – Strain Curves from Tensile Testing

B.5.2.7 Flexural Test (ASTM D790). Specimens, as described in ASTM D790, were cut from the retrieved CIPP liner using a router and a band saw. A total of 15 specimens were prepared and tested. The sides of the specimens were smoothed using a grinder. A water jet cutter could not be used as the liner was curved and too small to be mounted inside the cutting board.

The flexure test results are presented graphically in Figure B-72 and are listed in Table B-37. The average flexural modulus was 477,609 ± 28,389 psi and average flexural strength was 7,978 ± 654. All the bending stress and bending modulus values were found to be well above the minimum values listed in ASTM F1216 (bending stress 4,500 psi and bending modulus 250,000 psi).

Table B-36. New York 2: Tensile Test Results

Sample ID	Area (in.^{2})	Peak Load (lb)	Peak Stress (psi)	Tensile Modulus (psi)
1	0.1300	450.87	3,471	462,521
2	0.1336	500.33	3,742	605,810
3	0.1321	465.09	3,521	532,143
4	0.1390	572.73	4,120	558,672
5	0.1284	486.89	3,792	533,626
6	0.1250	461.26	3,690	533,729
7	0.0983	475.89	4,841*	732,320*
8	0.1385	502.19	3,626	535,320
9	0.1392	505.65	3,633	567,942
10	0.1455	580.61	3,990	577,666
11	0.1462	535.87	3,665	537,092
12	0.1365	454.18	3,327	495,523
13	0.1345	467.87	3,479	511,923
14	0.1403	491.37	3,502	584,860
15	0.1354	479.19	3,539	542,363
Average		459.33	3,729	554,101
St. Dev		39.92	369	60,853

* Result is not within ± 25% RPD.

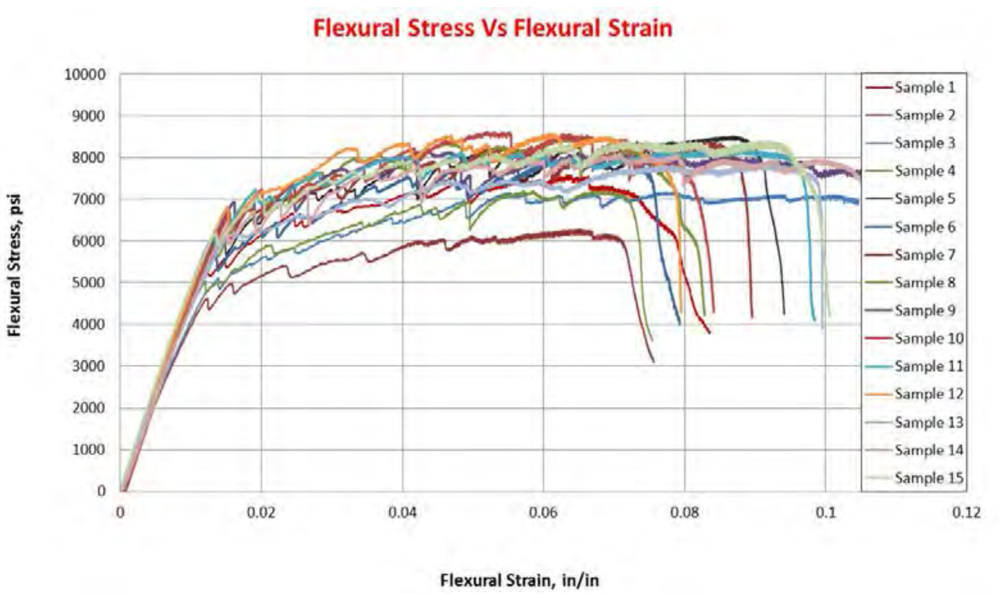

Figure B-72. New York 2: Stress – Strain Curves from Flexural Testing

Table B-37. New York 2: Flexural Test Results

Sample ID	Area (in.^{2})	Peak Load (lb)	Peak Stress (psi)	Flexural Modulus (psi)
1	0.0074	56.17	7,591	475,682
2	0.0060	37.73	6,288	415,252
3	0.0064	46.24	7,225	424,530
4	0.0069	49.56	7,183	463,767
5	0.0071	60.77	8,559	506,677
6	0.0065	52.38	8,058	469,488
7	0.0071	59.70	8,408	494,120
8	0.0073	61.99	8,492	481,669
9	0.0071	57.90	8,155	487,077
10	0.0071	60.93	8,582	501,782
11	0.0072	59.07	8,204	503,308
12	0.0068	58.16	8,553	499,735
13	0.0073	57.39	7,862	459,930
14	0.0069	55.92	8,104	471,710
15	0.0071	59.70	8,408	509,404
Average		55.57	7,978	477,609
St. Dev		6.61	654	28,389

B.5.2.8 Surface Hardness. A Shore Type D durometer (ASTM D2240) was used to determine the hardness of the liner samples. Samples (1 in. × 1 in.) were cut from the retrieved CIPP liner with a band saw. A total of 400 readings were taken on the inner and outer surfaces of the liner specimens. The average recorded hardness values are shown in Figure B-73. The hardness of the surface exposed to the flow (inner surface) was found to be slightly higher than that of the protected (outer) surface, suggesting little, if any, softening or erosion of the resin on the inner surface of the tube during its service life. Note that the inner surface of the liner is the resin beneath the original sealing layer which had eroded or degraded away.

Figure B-73. New York 2: Shore D Hardness Readings for the Liner's Inner and Outer Surfaces

B.5.2.9 Glass Transition Temperature. The calculated Tg values are summarized in Table B-38 for the City of New York (Willoughby) sample. The average Tg for the field samples was 87.28°C (+/- 2.49°C) as measured by ASTM Method E1356-08 with DSC.

Table B-38. New York 2: Tg Determination (Willoughby CIPP Liner)

Sample	Run	Tg (°C)
NYC (Willoughby)	1	84.43
NYC (Willoughby)	2	89.05
NYC (Willoughby)	3	88.36

B.5.3 New York Sample 3: A 24-Year Old CIPP Liner in a 12 in. Extra Strength Vitrified Clay Pipe. The sample was recovered at 3rd Street, Brooklyn, New York on January 29, 2013, on the same street as the location of Sample 1. It represented a replacement sample for the defective Sample 1. The host pipe was at a depth of approximately 11.5 to 12 ft below ground level. Little information was available on the CIPP characteristics for this sample beyond the year of installation which was 1988-1989 and the original installer (see Table B-39).

Table B-39. New York 3: Host Pipe and Liner Information

Host pipe	15 in. Extra Strength Vitrified Clay Pipe
Liner Thickness	7.09 mm (laboratory measurement)
Resin	Not available
Primary Catalyst	Not available
Secondary Catalyst	Not available
Felt	Not available
Seal	Not available
Year of Installation	1988-1989
Liner Vendor	Insituform
Resin Supplier	Not available

B.5.3.1 Visual Inspection. The retrieval process and the retrieved sample are shown in Figure B-74. The second sample was collected from a different manhole on 3rd Street and was found to be fully cured unlike the first defective sample.

B.5.3.2 Annular Gap. Since only the CIPP liner was received, no annular gap measurements were possible.

B.5.3.3 Environmental Service Conditions. No soil samples were collected because of sample removal through the manhole.

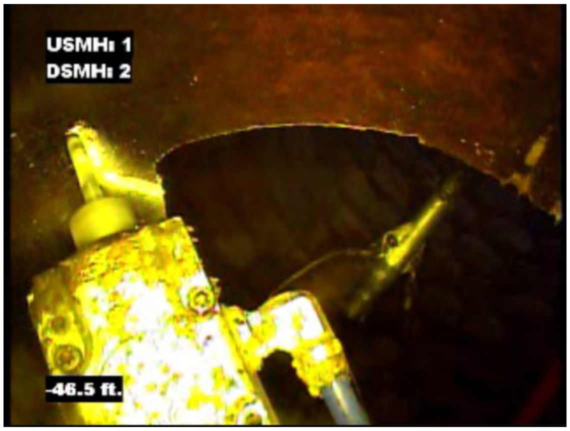

Figure B-74. New York 3: Retrieval of the Sample (left) and Retrieved Sample (right)

B.5.3.4 ***Thickness.*** A total of 120 readings were taken on 20 1 in. × 1 in. samples cut from different locations of the specimen. The average thickness of the liner was found to be 7.09 mm ± 0.27 mm as shown in Figure B-75. The design thickness was unavailable, therefore no comparison was made.

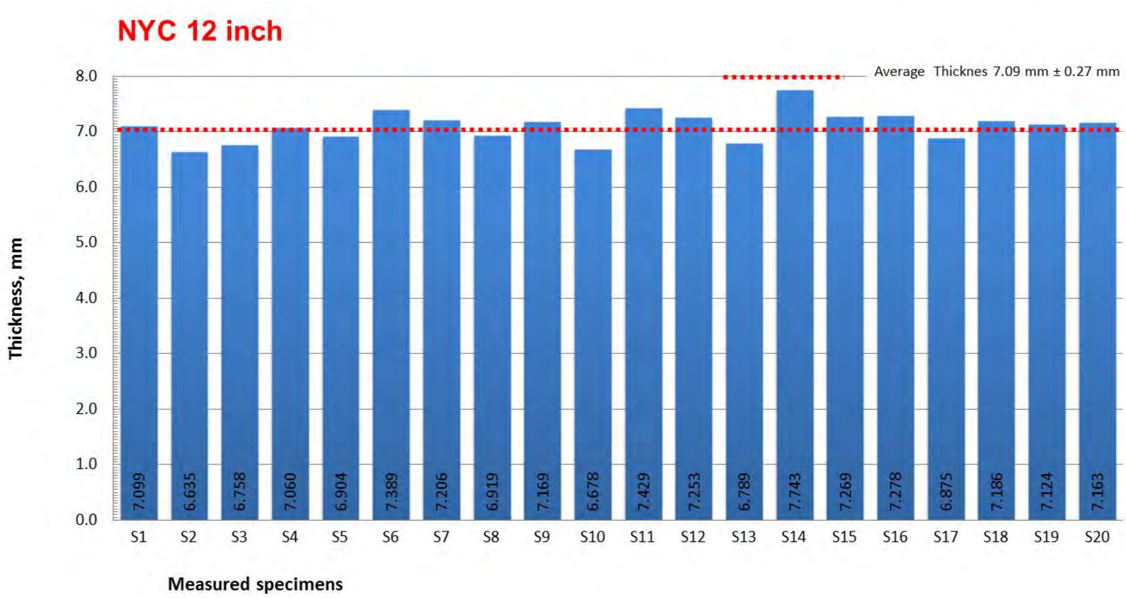

Figure B-75. New York 3: Average Thickness of the Liner Sample

B.5.3.5 ***Specific Gravity.*** The specific gravity of the liner was measured on 20 1 in. × 1 in. samples in accordance with ASTM D 792. The specific gravity results are shown in Figure B-76. The obtained values were between 1.13 and 1.18. The average specific gravity was 1.15 ± 0.01.

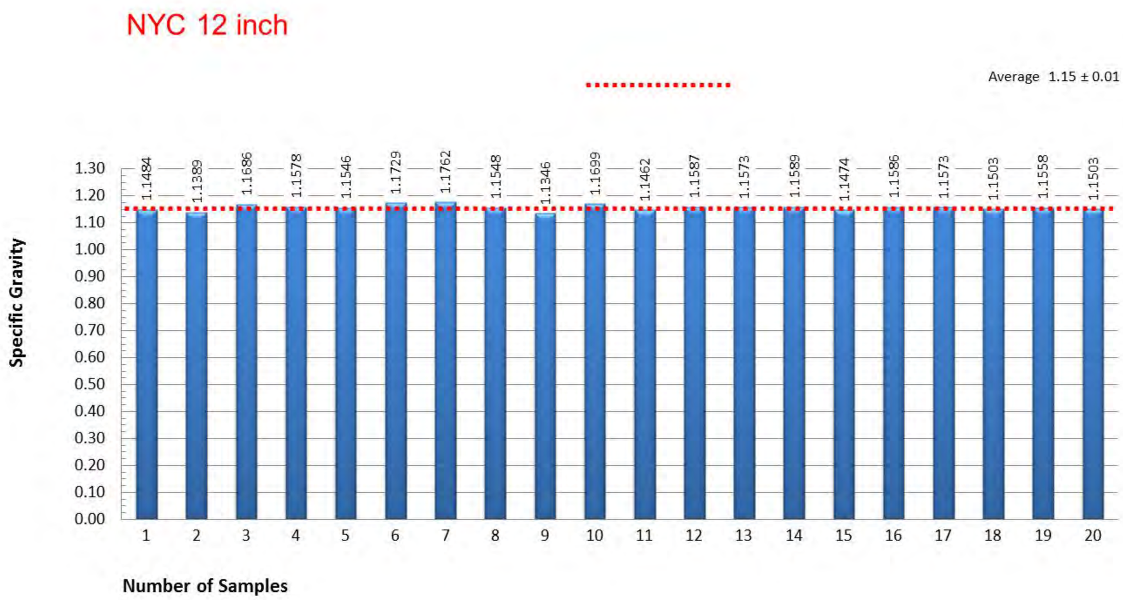

Figure B-76. New York 3: Measured Specific Gravity of the Liner

B.5.3.6 Tensile Test (ASTM D638). Specimens, as described in ASTM D638, were cut from the retrieved CIPP liner using a router and a band saw. A total of 15 specimens were prepared and tested. The sides of the specimens were smoothed using a grinder. A water jet cutter could not be used as the liner was curved and too small to be safely secured inside the cutting board.

Tensile test results are presented in Figure B-77 and Table B-40. The average tensile strength was 3,275 ± 262 psi and the average tensile modulus was 324,406 ± 54,913 psi. The tensile elongation at break varied from about 3.0% to 12%.

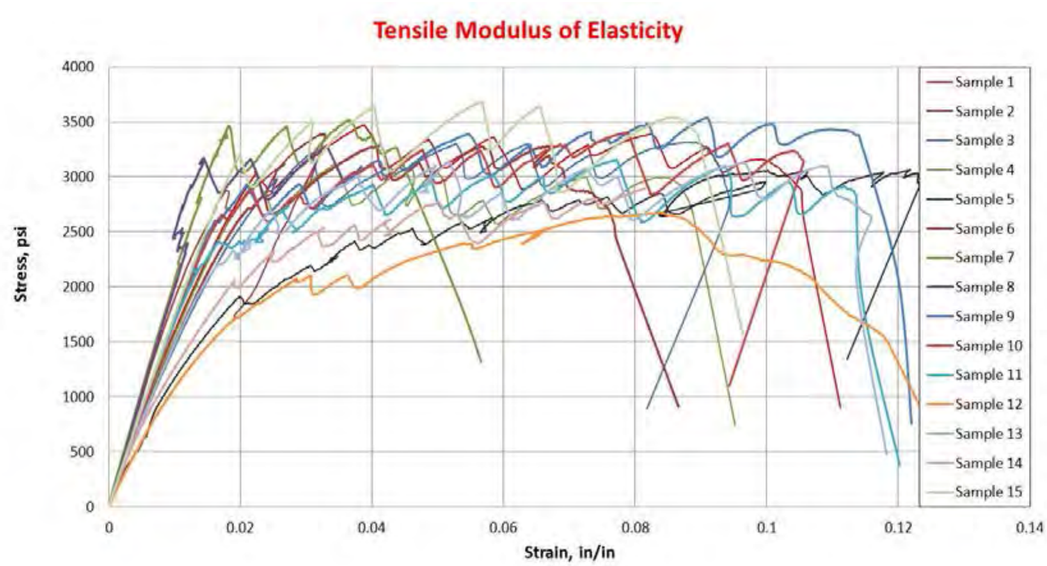

Figure B-77. New York 3: Stress – Strain Curves from Tensile Testing

Table B-40. New York 3: Tensile Test Results

Sample ID	Area (in.^{2})	Peak Load (lb)	Peak Stress (psi)	Tensile Modulus (psi)
1	0.1396	485.38	3,477	322,496
2	0.1200	407.23	3,394	320,125
3	0.1331	441.56	3,318	291,114
4	0.1304	406.87	3,120	335,792
5	0.1363	417.86	3,066	199,967*
6	0.1237	407.24	3,292	317,206
7	0.1321	465.08	3,521	411,721
8	0.1410	476.59	3,380	407,646
9	0.1397	494.85	3,542	351,886
10	0.1422	485.13	3,412	340,811
11	0.1326	429.94	3,157	369,757
12	0.1287	344.60	2,678	243,429
13	0.1308	410.90	3,141	305,713
14	0.1368	401.84	2,937	303,246
15	0.1352	498.34	3,686	345,178
Average		438.23	3,275	324,406
St. Dev		44.46	262	54,913

* Result is not within ± 25% RPD.

B.5.3.7 Flexural Test (ASTM D790). Specimens, as described in ASTM D790, were cut from the retrieved CIPP liner using a router and a band saw. A total of 15 specimens were prepared and tested. The sides of the specimens were smoothed using a grinder. A water jet cutter could not be used as the liner was curved and too small to be safely secured inside the cutting board.

Flexure test results are presented in Figure B-78 and Table B-41. All the bending stress values were found to be above the values prescribed in ASTM F1216 (bending stress 4,500 psi). The average flexural strength was 7,200 ± 997 psi. For the flexural modulus, the values ranged from approximately 200,000 to 373,000 psi with an average of 285,177 ± 49,221 psi, which is higher than the minimum prescribed by ASTM F1216 (250,000 psi).

B.5.3.8 Surface Hardness. A Shore Type D durometer (ASTM D2240) was used to determine the hardness of the liner samples. Samples (1 in. × 1 in.) were cut from the retrieved CIPP liner with a band saw. A total of 400 readings were taken on the inner and outer sides of the samples. The average recorded values are shown in Figure B-79. The data suggest that the hardness values of the liner's inner and outer surfaces are very similar, indicating minimal degradation of the surface exposed to the flow (i.e., inner surface) compared with the surface which was protected from the flow (outer surface). The variation is slightly higher than for the Willoughby Street sample, but with a similar standard deviation for both the inner and outer surfaces.

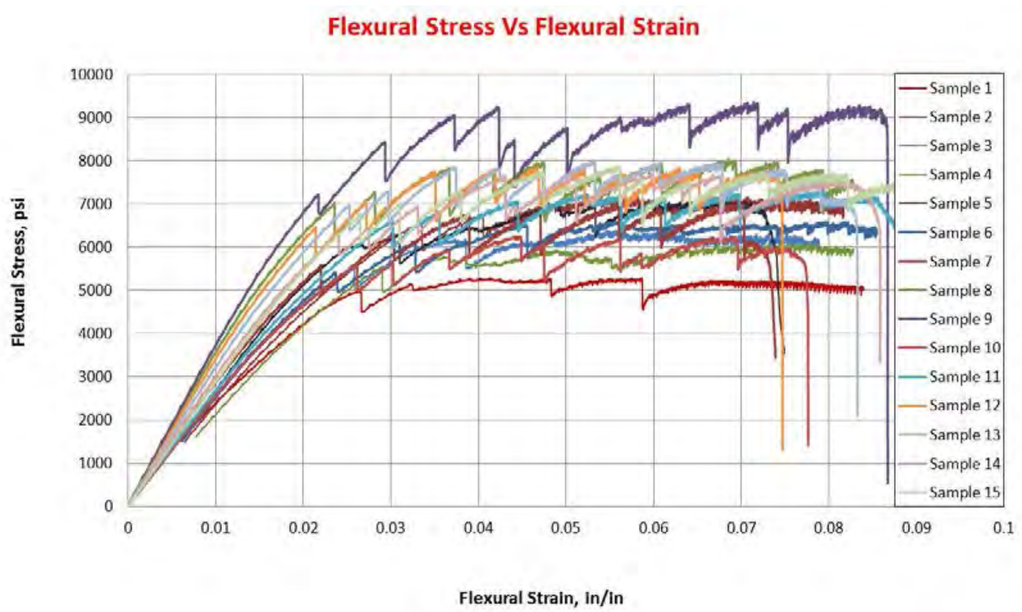

Figure B-78. New York 3: Stress – Strain Curves from Flexural Testing

Table B-41. New York 3: Flexural Test Results

Sample ID	Area (in.^{2})	Peak Load (lb)	Peak Stress (psi)	Flexural Modulus (psi)
1	0.0069	36.28	5,258*	199,529*
2	0.0067	48.23	7,199	246,671
3	0.0058	37.05	6,388	249,418
4	0.0062	37.89	6,111	229,737
5	0.0065	46.56	7,163	284,773
6	0.0066	43.36	6,570	260,699
7	0.0064	44.83	7,005	286,030
8	0.0059	47.51	8,053	361,610
9	0.0060	55.86	9,310*	373,328
10	0.0069	43.09	6,245	258,034
11	0.0063	45.96	7,295	266,628
12	0.0062	48.47	7,818	345,924
13	0.0064	51.59	8,061	322,962
14	0.0066	50.56	7,661	303,025
15	0.0070	55.03	7,861	289,286
Average		46.15	7,200	285,177
St. Dev		5.98	997	49,221

* Result is not within ± 25% RPD

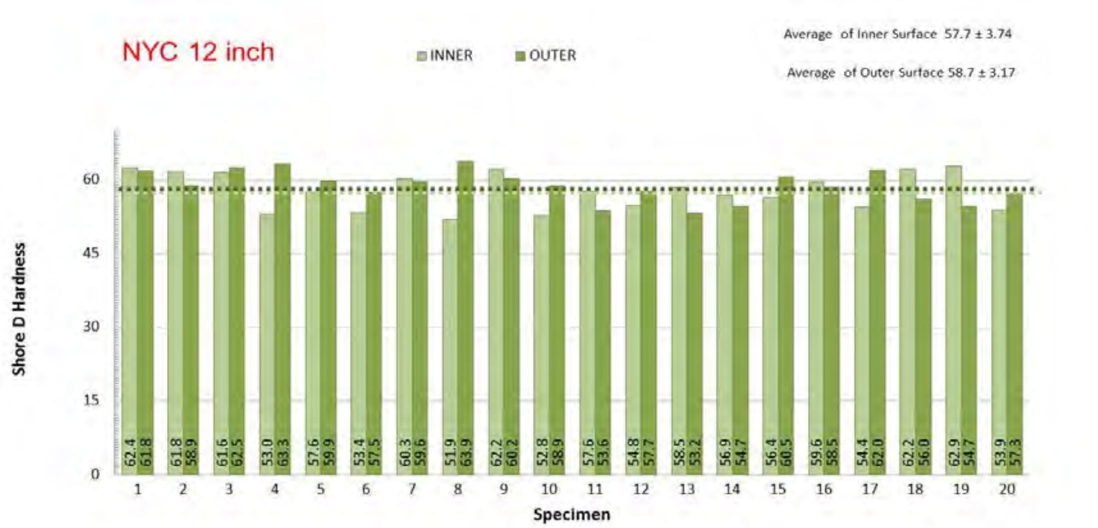

Figure B-79. New York 3: Shore D Hardness Readings for Inner and Outer Surfaces

B.5.3.9 Glass Transition Temperature. The calculated Tg values are summarized in Table B-42 for the City of New York (3rd Street) sample. The average Tg for the field samples was 90.10°C (± 4.10°C) as measured by ASTM Method E1356-08 with DSC.

Table B-42. New York 3: Tg Determination (3rd Street CIPP Liner)

Sample	Run	Tg (°C)
NYC (3rd)	1	88.36
NYC (3rd)	2	87.54
NYC (3rd)	3	88.26
NYC (3rd)	4	96.22

B.6 City of Northbrook

This section contains the test results performed on a 12 in. diameter liner exhumed from 990 Skokie Boulevard, Northbrook, Illinois. This particular CIPP liner had been installed as part of a research and demonstration project jointly undertaken by the Village of Northbrook and EPA between 1979 and 1981 (Driver and Olson, 1983). The actual installation of the CIPP liner took place in October 1979. The host pipe to be rehabilitated was a 12 in. sanitary sewer installed in 1962 by a private contractor. The ground conditions were reported to be from clay to silty loam with a frequently high water table. The average water table was reportedly consistently 6 in. above the pipe. The depth of the host pipe was approximately 9 ft. Prior to the CIPP lining, the line was witnessed to have considerable surcharging events following precipitation. Also, prior to relining, the pipe was seen to have many offset and pulled joints with visible infiltration, as well as radial and longitudinal cracks in many locations. Some sections were considered to be structurally unstable (with sections no longer circular). The deterioration was linked to the lack of construction inspection by the city at the time of the installation and the poor ground conditions and high water table leading to possibly inadequate bedding of the pipe at the time of construction. Comparisons of pre- and post-lining infiltration and flow characteristics showed significant improvement in performance with no surcharging during wet weather events.

The physical properties of the CIPP liner material were tested by an independent laboratory and are summarized in Table B-43. However, it should be noted that the samples tested were *"…flat samples of the cured liner material which, by statement from the manufacturer (Appendix A), were of identical materials and thickness and cured in the same manner as the Northbrook test section …"* (Driver and Olson, 1983).

The testing of resistance to reagents comprised testing of the tensile and compressive properties of the liner (five test samples for each reagent) after 168 hr of immersion in the following nine reagents: acetic acid, ammonia, brine, calcium hydroxide, diesel fuel, hydrochloric acid, gasoline, nickel plating solution and sulfuric acid. The highest average loss of tensile strength was for diesel fuel with a loss of 21% in tensile strength. The highest average loss of compressive strength was for nickel plating solution with a loss of 24%. Full results and solution strengths are provided in the referenced report.

In addition to the above laboratory testing, a 12 ft section of the lined pipe was dug up and removed for further testing of the as-installed liner. A 5 ft long test section of the liner alone was cut from the removed sample and installed in a new host pipe to allow external pressure testing. Liner deformation in the form of local buckling was noted at around 50 psi in the test with the liner returning to its original cross-section after the pressure was removed.

A follow-up visual inspection was carried out on March 24, 1980 with no evidence of deterioration, infiltration, or buildup of material in the invert of the pipe noted.

Table B-43. Northbrook: Test Results at Installation

Property	ASTM Test Method	Insituform CIPP
Tensile strength	D-638	5,420 psi
Tensile Modulus	D-638	475,000 psi
Flexural Strength	D-790	9,320 psi
Flexural Modulus	D-790	403,000 psi
Compressive Strength	D-695	15,500 psi
Compressive Modulus*	D-695	325,000 psi
Coefficient of Thermal Expansion	D-696	5.96×10^{-5} in./in./°C
Shear Strength	D-732	8,150 psi
Deformation under Load (800 psi, 158°F, 24 hr)	D-621	0.149%
Deflection Temperature	D-648	106°C @ 66 psi 92.5°C @ 264 psi
Flexural Fatigue Endurance Limit	D-671	1,360 psi @ 10^7 cycles
Bearing Strength	D-953	3,330 psi @ 4% def. 5,910 psi @ max.
Resistance to Reagents	D-543	Effect of 9 reagents tested

* The summary table in the 1983 report substitutes the strength for this value. The values in this table are taken from the testing company report in the appendix of the Driver and Olson (1983) report in which this value is of the correct order of magnitude.

For the current evaluation, a first attempt was made to retrieve a sample on June 5, 2013. The excavation and pipe section removal were completed, but it was found that this particular location had not been lined. It is possible that this was the same location of the section previously removed after CIPP installation in 1979 as described above, but historic records were not available to confirm this. The line was then videotaped from the upstream manhole to the downstream manhole (total length ~110 ft). The pipe was found to be lined for 32 ft starting at the upstream manhole and for approximately 5 ft starting at the downstream manhole. A CIPP sample was then retrieved on June 11, 2013. Onsite personnel included representatives from the Village of Northbrook and Layla Construction (contractor). A lined 6 ft section of 12 in. clay pipe was collected.

B.6.1 Northbrook Sample 1. The host pipe and liner information are shown in Table B-44 and the site for sample removal is shown in Figure B-80.

The retrieval process and the retrieved sample are shown in Figure B-81. The specimens were received at the TTC South Campus Lab Facility on July 23, 2013.

B.6.1.1 Visual Inspection. The sample was in good condition, with the exception of an approximately 0.5 in. annular gap at the 5 o'clock position of the liner.

Table B-44. Northbrook: Host Pipe and Liner Information

Host pipe	Clay pipe, 12 in. diameter at approximately 9 ft depth
Liner Design Thickness	6 mm (2-3 mm Felt - EPA-BOO/S2-83-064 Sept. 1983)
Resin	Partially polymerized thermosetting resin
Primary Catalyst	Information not available
Secondary Catalyst	Information not available
Felt	Densely needled polyester fiber
Seal	Polyurethane
Year of Installation	October 1979
Liner Vendor	Insituform Technologies
Resin Supplier	Information not available

B.6.1.2 Annular Gap. The south end of the section of pipe removed was where a subsequent point repair had been made, so that the south end of the sample had been connected to the replaced segment with a coupling. The remnants of the connection were left intact and no measurements were made. The north end is the upstream location. Eight readings were taken on the liner within the sample removed (at the north end) and again on the adjacent host pipe that remained in place (see Table B-45).

B.6.1.3 Environmental Service Conditions. Waste material on the inside and outside of the sample was collected and stored in a bottle filled with distilled water. pH was measured separately using pH-indicator strips. pH was found to be between 6 and 7. The pH of the inside and outside was almost the same value.

B.6.1.4 Ovality. A profile plotter was used to map any deformation inside the liner. Continuous readings were taken around the circumference of three cross-sections spaced 8 in. apart and averaged.

The liner was found to be approximately circular with reference to its center (see Figure B-82). The ovality of the liner was found to vary from 0.33% to 0.38%. The ovality curves of all three sections were almost the same and hence are difficult to distinguish in the plot.

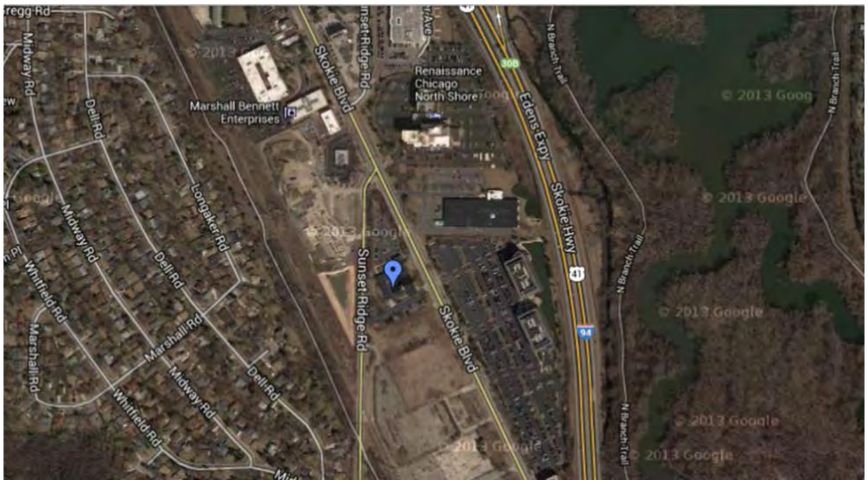

Figure B-80. Northbrook: Sample Retrieval Location

Figure B-81. Northbrook: Retrieval of the Sample (left) and Received Sample (right)

Table B-45. Northbrook Annular Gap Measurements

O'Clock Position	Annular Gap Measured for Remaining Host Pipe (north end of sample)	Annular Gap Measured for Retrieved Host Pipe Sample (north end)
12:00	0.027 in. (0.69 mm)	0.026 in. (0.66 mm)
1:30	0.019 in. (0.48 mm)	0.019 in. (0.48 mm)
3:00	0.011 in. (0.28 mm)	0.010 in. (0.25 mm)
5:00	0.420 in. (10.67 mm)	0.380 in. (9.65 mm)
6:00	0.170 in. (4.32 mm)	0.100 in. (2.54 mm)
7:30	0.008 in. (0.20 mm)	0.008 in. (0.20 mm)
9:00	0.016 in. (0.41 mm)	0.016 in. (0.41 mm)
11:00	0.009 in. (0.23 mm)	0.008 in. (0.20 mm)

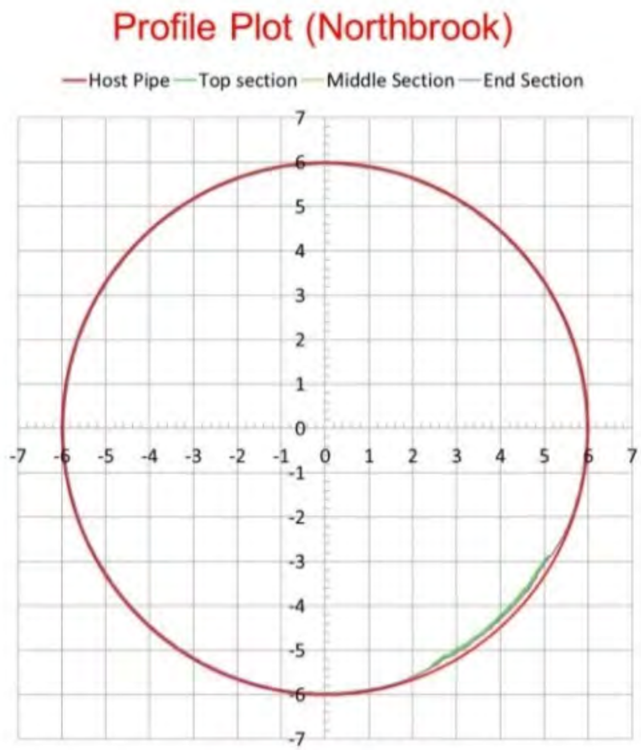

Figure B-82. Northbrook: Ovality of the Liner at Up Stream, Middle Section, and Down Stream

B.6.1.5 ***Thickness.*** A total of 120 readings were taken on 20 1 in. × 1 in. samples cut from different locations of the liner specimen. The thickness was measured randomly using a micrometer with a resolution of ±0.0025 mm. The average thickness was found to be 4.66 mm ± 0.21 mm as shown in Figure B-83. The design thickness was 6 mm.

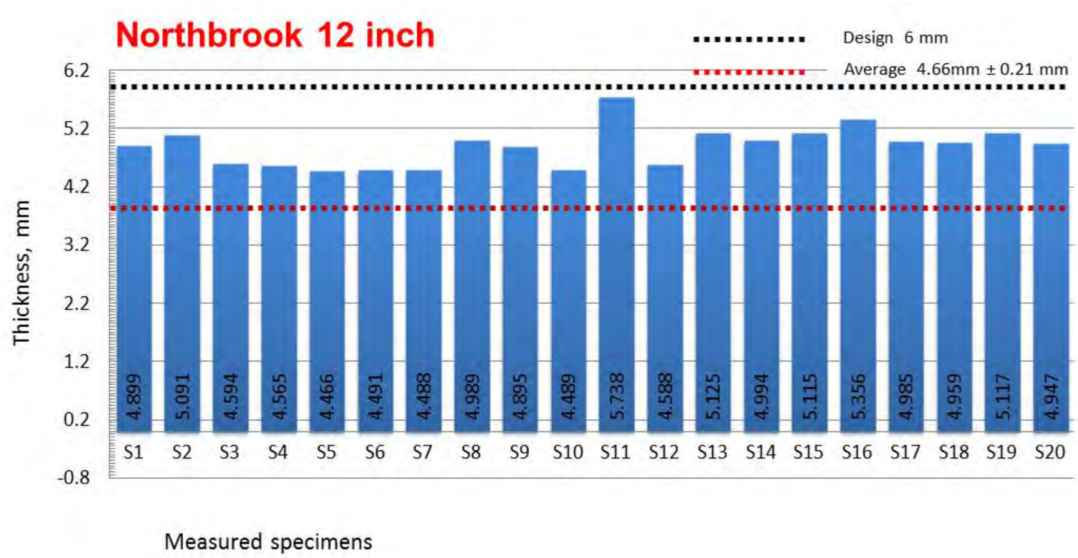

Figure B-83. Northbrook: Average Thickness of the Sample

B.6.1.6 Specific Gravity. The specific gravity of the liner was measured on 20 1 in. × 1 in. samples in accordance with ASTM D792. The specific gravity values from the sample are shown in Figure B-84. The obtained values were between 1.16 and 1.24. The average specific gravity was 1.19.

Figure B-84. Northbrook: Measured Specific Gravity of the CIPP Liner

B.6.1.7 Tensile Test (ASTM D638). Specimens, as described in ASTM D638, were cut from the liner using a table saw and a band saw. Type II specimen dimensions were used for the ASTM D638 tensile test. The sides of the specimens were smoothed using a grinder. A total of 15 specimens were prepared and tested.

The tensile test results are presented in Figure B-85 and Table B-46. The average tensile strength was 4,402 ± 175 psi. The average tensile modulus was calculated to be 433,541 ± 28,506 psi.

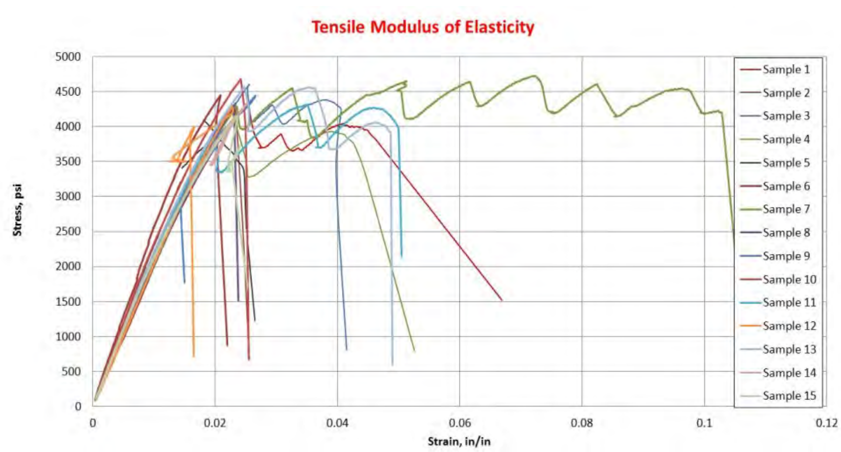

Figure B-85. Northbrook: Stress – Strain Curves from Tensile Testing

Table B-46. Northbrook: Tensile Test Results

Sample ID	Area (in.^{2})	Peak Load (lb)	Peak Stress (psi)	Tensile Modulus (psi)
1	0.0983	427.22	4,346	411,329
2	0.1005	435.80	4,336	402,404
3	0.0990	455.33	4,599	397,254
4	0.0964	408.47	4,237	414,831
5	0.1107	463.64	4,188	458,823
6	0.0094	442.21	4,449	495,270
7	0.1203	567.80	4,724	425,035
8	0.0964	411.35	4,267	418,493
9	0.0907	402.60	4,439	413,592
10	0.0894	418.01	4,676	478,705
11	0.0948	409.38	4,318	442,872
12	0.0962	412.19	4,285	410,866
13	0.0877	400.38	4,565	451,702
14	0.0907	402.64	4,439	437,925
15	0.0828	344.18	4,157	444,023
Average		426.75	4,402	433,541
St. Dev		47.98	175	28,506

B.6.1.8 Flexural Test (ASTM D790). A total of 15 specimens were prepared for ASTM D790 flexure tests. The flexure test results are presented in Figure B-86 and Table B-47. The area values were automatically back calculated by the software when the peak load was reached. The average flexural modulus was 322,360 ± 46,910 psi and the average flexure strength was 7,761 ± 883 psi.

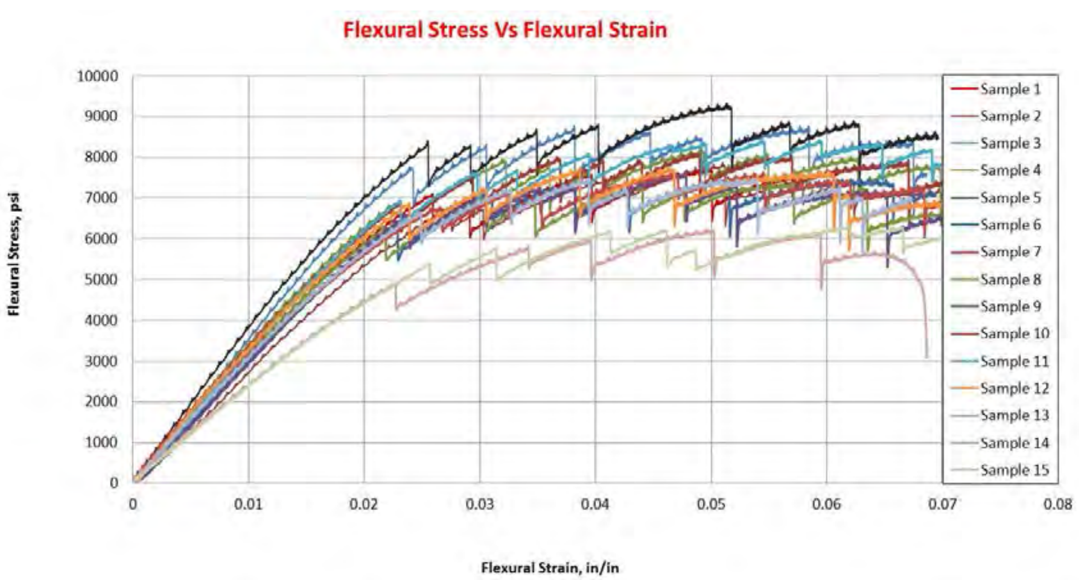

Figure B-86. Northbrook: Stress – Strain Curves from Flexural Testing

Table B-47. Northbrook: Flexural Test Results

Sample ID	Area (in.^{2})	Peak Load (lb)	Peak Stress (psi)	Flexural Modulus (psi)
1	0.0033	25.43	7,706	330,705
2	0.0029	23.14	7,979	284,652
3	0.0028	24.72	8,829	370,383
4	0.0032	26.6	8,312	338,927
5	0.0030	28.07	9,357	383,681
6	0.0029	21.5	7,414	295,071
7	0.0030	24.09	8,030	334,193
8	0.0037	27.08	7,319	327,404
9	0.0030	23.04	7,680	309,646
10	0.0032	24.21	7,566	337,505
11	0.0050	42.26	8,452	336,131
12	0.0029	22.87	7,886	403,957
13	0.0028	20.71	7,396	309,658
14	0.0037	23.05	6,230	237,922*
15	0.0062	38.77	6,253	235,557*
Average		26.37	7,761	322,360
St. Dev		6.12	833	46,910

* Result is not within ± 25% RPD.

B.6.1.9 Surface Hardness. A Shore Type D durometer (ASTM D2240) was used to determine the hardness of the liner samples. Samples (1 in. × 1 in.) were cut from the retrieved CIPP liner with a band saw. A total of 400 readings were taken on the inner and outer surfaces of the liner specimens. The average recorded hardness values are shown in Figure B-87. The hardness of the surface exposed to the flow (inner surface) was found to be only slightly lower than that of the protected (outer) surface, suggesting little, if any, softening or erosion of the resin on the inner surface of the tube during its service life. Differences may also be expected due to the initial presence of the sealing layer on the internal surface.

Figure B-87. Northbrook: Shore D Hardness Readings from Inner and Outer Surfaces

B.6.1.10 Short-Term Buckling Test. For the short-term buckling test, a 30 in. long piece of full circumference was cut from the sample and housed inside a 14-in. diameter steel tube 30 in. in length. The larger diameter of the steel tube ensured accommodation of any ovality and local curvature of the liner. The large annular gap for the buckling test makes the test very conservative compared to a liner tightly fitted within the host pipe in the field. However, the test sections also are known to be too short to eliminate end effects (not conservative) because the host pipe configuration and overall testing program did not permit a pipe section with a length of four to six times diameter (32 to 48 in.) to be used.

Provision was made to apply a high pressure using the TTC's EPAD. However, the liner collapsed at a supply line water pressure of approximately 5 psi before the N_2 was released to the accumulator (see Figure B-88). The liner collapsed at close to the 11 o'clock position in the test setup which mapped to the 5 o'clock position in the liner's original field location.

Figure B-88. Northbrook: Short-Term Buckling Test

B.6.1.11 Glass Transition Temperature. The calculated Tg values are summarized in Table B-48 for the Northbrook CIPP sample. The average Tg for the field samples was 105.74°C (± 1.29°C) as measured by ASTM Method E1356-08 with DSC.

Table B-48. Northbrook: Tg Determination

Sample	Run	Tg (°C)
Northbrook (Skokie)	1	105.58
Northbrook (Skokie)	2	104.54
Northbrook (Skokie)	3	107.11

B.7 City of Winnipeg

This section contains the test results performed on three liner samples obtained from the City of Winnipeg, Manitoba, Canada following its own retrospective evaluation program (see Section 4 in this report and Macey et al., 2012, 2013). Only a limited set of tests were performed at the TTC due to the limited sample size that was available from these previously exhumed samples. This limitation is noted where applicable in the test results presentation below.

B.7.1 Winnipeg Sample 1: A 34-Year Old CIPP Liner in a 30 in. Reinforced Concrete Pipe. This sample was retrieved from Richard Street in the City of Winnipeg, Manitoba on December 8, 2011. It was part of a larger sample that was tested by the City of Winnipeg. The results from that testing as reported by Macey et al. (2012 and 2013) are presented in Sections 4 and 5. The sewer identification location is MA20010001. The host pipe and liner information are shown in Table B-49. The host pipe depth was reported to be 17.7 ft (5.4 m).

Table B-49. Winnipeg 1: Host Pipe and Liner Information

Host pipe	Reinforced concrete pipe, 30 in. diameter
Liner Thickness	Design thickness is 6 mm
Resin	Unfilled isophthalic polyester resin
Primary Catalyst	Information not available
Secondary Catalyst	Information not available
Felt	Information not available
Seal	Information not available
Year of Installation	November 1978
Liner Vendor	A.B.C. Pipe Cleaning Services Limited
Resin Supplier	Information not available

The sample (see Figure B-89) was received at the TTC South Campus Facility on August 2, 2013.

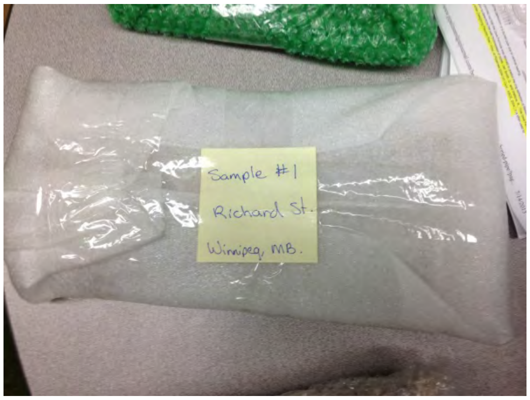

Figure B-89. Winnipeg 1: Received Sample

B.7.1.1 Visual Inspection. The sample as received at the TTC was found to be in excellent condition.

B.7.1.2 Annular Gap. Since only the CIPP liner was received, no annular gap measurements were possible.

B.7.1.3 Environmental Service Conditions. Soil collection was not applicable because the sample was retrieved via a manhole.

B.7.1.4 Thickness. A total of 90 readings were taken on 15 1 in. × 1 in. samples cut from different locations of the liner specimen. The thickness was measured randomly using a micrometer with a resolution of ±0.0025 mm. The average thickness was found to be 6.60 mm ± 0.68 mm as shown in Figure B-90. The design thickness was 6 mm. The average installed thickness at the sample location was 10% greater than the design thickness.

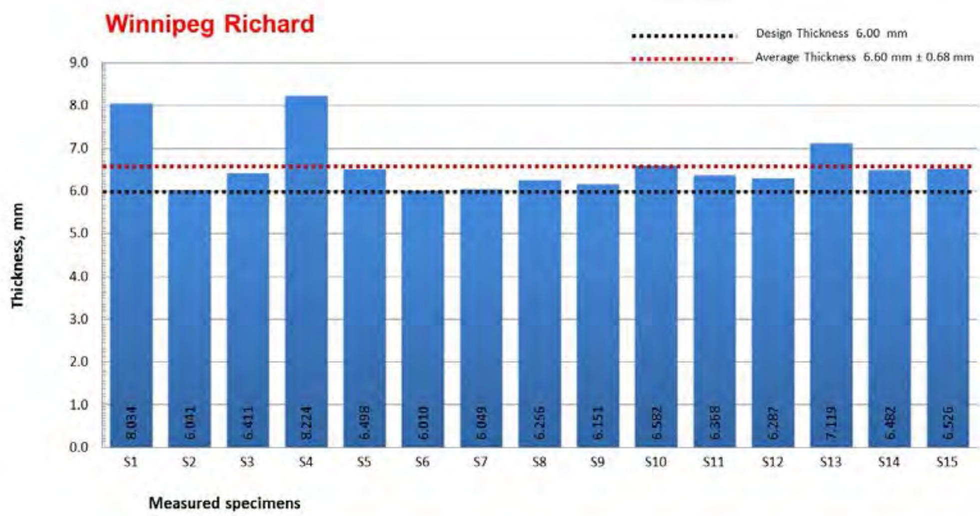

Figure B-90. Winnipeg 1: Average Thickness of the Sample

B.7.1.5 Specific Gravity. The specific gravity of the liner was measured on 15 1 in. × 1 in. samples in accordance with ASTM D792. The specific gravity values from the sample are shown in Figure B-91. The obtained values were between 1.15 and 1.30. The average specific gravity of the liner was 1.21.

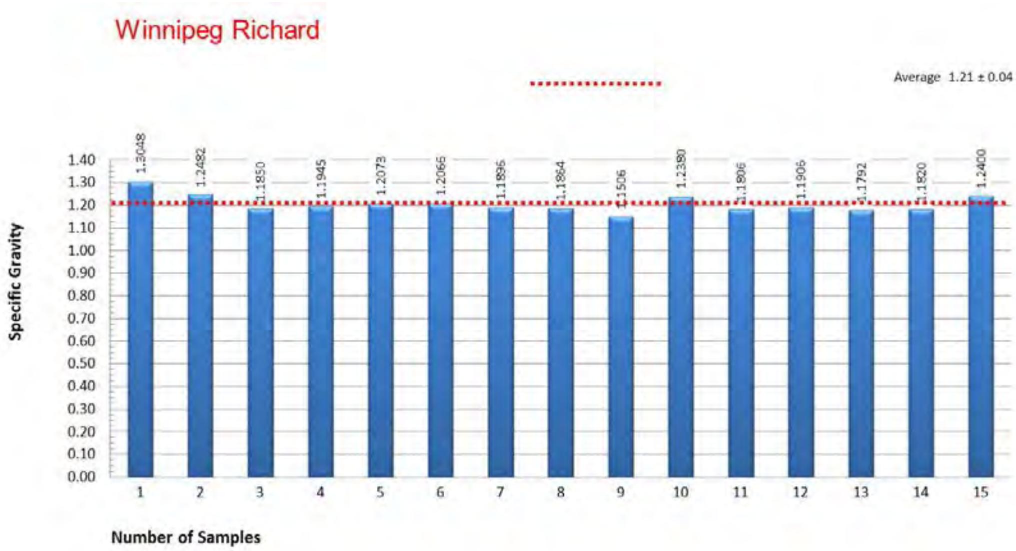

Figure B-91. Winnipeg 1: Measured Specific Gravity of the CIPP Liner

B.7.1.6 Tensile Test (ASTM D638). No tensile testing according to ASTM D638 was possible because of the size of the sample received at the TTC.

B.7.1.7 Flexural Test (ASTM D790). No flexural testing according to ASTM D790 was possible because of the size of the sample received at the TTC. However, data from flexural property testing conducted by the City of Winnipeg were provided. The data for flexural strength and flexural modulus are shown in Table B-50. The calculated average flexural strength from the data provided is 8,592 ± 321 psi and the calculated average flexural modulus is 452,134 ± 17,373 psi. These data are similar to those published in Macey et al. (2013) for the same liner (flexural strength reported to range from 7,252 psi to 8,412 psi and the flexural modulus ranging from 448,457 psi to 455,999 psi).

Table B-50. Winnipeg 1 (Richard): Flexural Test Results

Sample ID	Flexural Strength (psi)	Flexural Modulus (psi)
1	8,455	455,047
2	8,473	427,944
3	8,300	461,276
4	8,591	434,410
5	8,446	453,223
6	9,285	480,741
7	8,592	452,300
Average	8,592	452,134
St. Dev	321	17,373

B.7.1.8 Surface Hardness. A Shore Type D durometer (ASTM D2240) was used to determine the hardness of the liner samples. A total of 300 readings were taken on the inner and outer surfaces of the liner specimens. The average recorded hardness values are shown in Figure B-92. The hardness of the surface exposed to the flow (inner surface) was found to be only slightly lower than that of the protected (outer) surface, suggesting little, if any, softening or erosion of the resin on the inner surface of the tube during its service life. Differences may also be expected due to the initial presence or any continuing presence of the sealing layer on the internal surface.

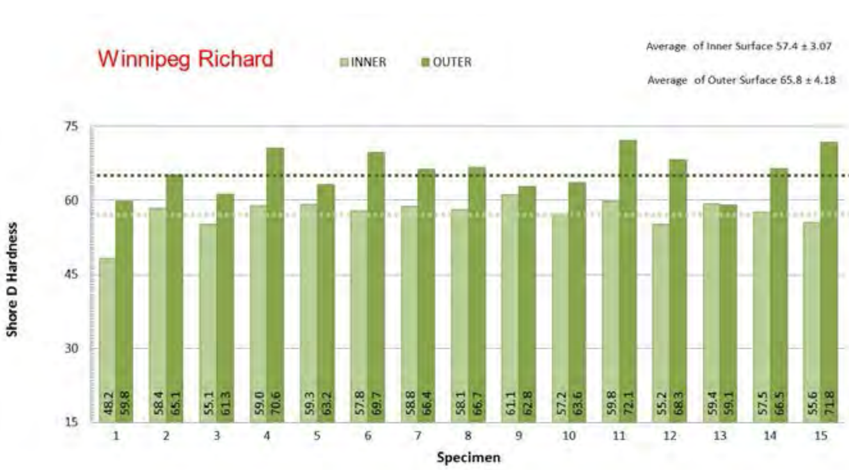

Figure B-92. Winnipeg 1: Shore D Hardness Readings from Inner and Outer Surfaces

B.7.1.9 Glass Transition Temperature. The calculated Tg values are summarized in Table B-51 for the Winnipeg (Richard) sample. The average Tg for the field samples was 122.28°C (± 2.92°C) as measured by ASTM Method E1356-08 with DSC.

Table B-51. Winnipeg 1: Tg Determination (Richard St. CIPP Liner)

Sample	Run	Tg (°C)
Winnipeg (Richard)	1	119.96
Winnipeg (Richard)	2	124.46
Winnipeg (Richard)	3	125.43

B.7.2 Winnipeg Sample 2: A 34-Year Old CIPP Liner in an 18 in. Vitrified Clay Pipe. This sample was retrieved from Kingsway in the City of Winnipeg, Manitoba on December 8, 2011. It was part of a larger sample that was tested by the City of Winnipeg. The results from that testing as published by Macey et al. (2012 and 2013) are presented in Sections 4 and 5. The sewer identification location is MA20010001. The host pipe and liner information are shown in Table B-52. The host pipe depth was reported to be 12.3 ft (3.76 m).

Table B-52. Winnipeg 2: Host Pipe and Liner Information

Host pipe	Vitrified clay tile pipe, 18 in. diameter
Liner Thickness	Design thickness is 6 mm
Resin	Unfilled isophthalic polyester resin
Primary Catalyst	Information not available
Secondary Catalyst	Information not available
Felt	Information not available
Seal	Information not available
Year of Installation	November 1978
Liner Vendor	A.B.C. Pipe Cleaning Services Limited
Resin Supplier	Information not available

The sample (see Figure B-93) was received at the TTC South Campus Facility on August 2, 2013.

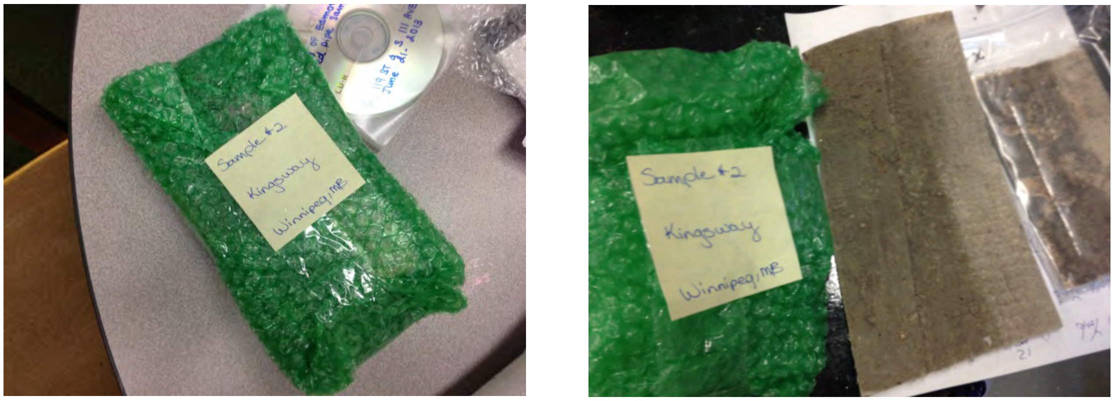

Figure B-93. Winnipeg 2: Received Sample

B.7.2.1 ***Visual Inspection.*** The sample as received at the TTC was found to be in excellent condition. The polyurea coating was still in place and the thickness of the liner was uniform around the circumference.

B.7.2.2 ***Annular Gap.*** Since only the CIPP liner was received, no annular gap measurements were possible.

B.7.2.3 ***Environmental Service Conditions.*** Soil collection was not applicable because the sample was retrieved via a manhole.

B.7.2.4 ***Thickness.*** A total of 120 readings were taken on 20 1 in. × 1 in. samples cut from different locations of the specimen. The thickness was measured randomly using a micrometer with a resolution of ±0.0025 mm. The average thickness was found to be 6.69 mm ± 0.31 mm as shown in Figure B-94. The design thickness was 6 mm. The average installed thickness at the sample location was 11.5% greater than the design thickness.

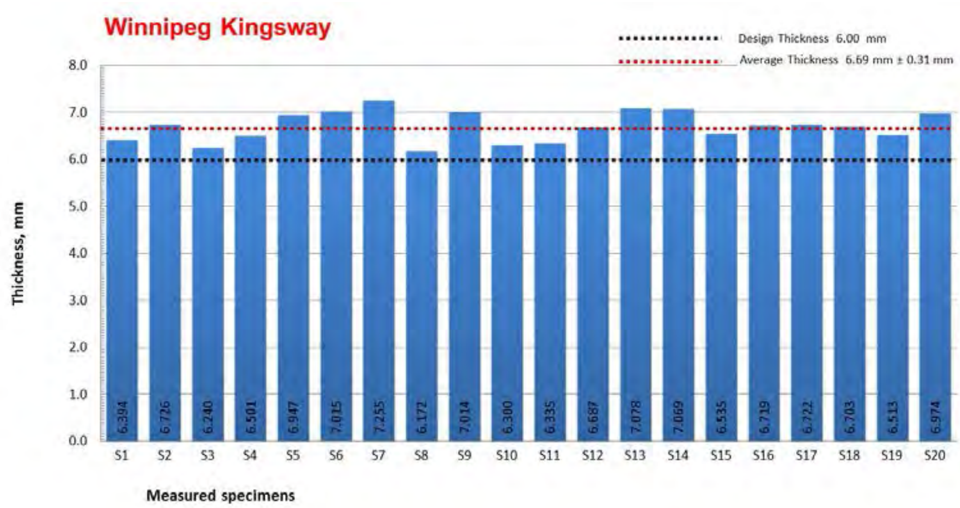

Figure B-94. Winnipeg 2: Average Thickness of the Sample

B.7.2.5 Specific Gravity. The specific gravity of the liner was measured on 20 1 in. × 1 in. samples in accordance with ASTM D792. The specific gravity values from the sample are shown in Figure B-95. The obtained values were between 1.04 and 1.19. The average specific gravity of the liner was 1.14.

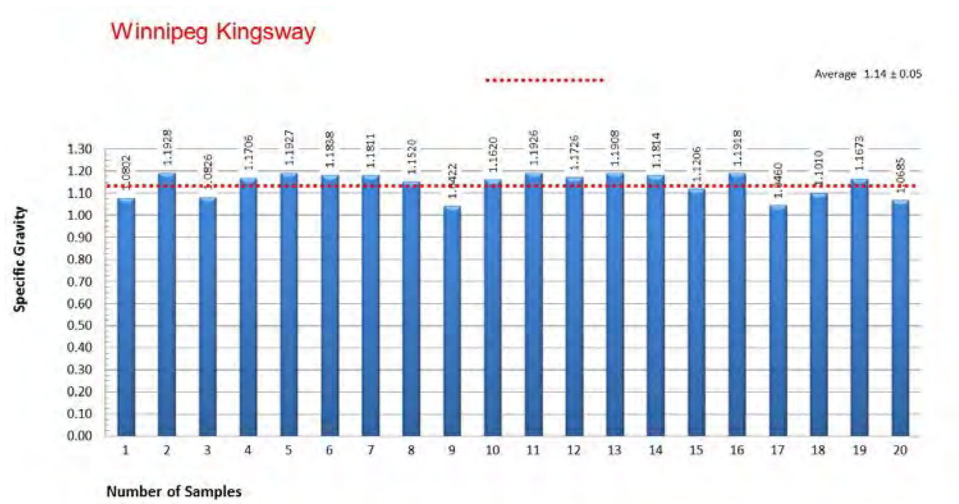

Figure B-95. Winnipeg 2: Measured Specific Gravity of the CIPP Liner

B.7.2.6 Tensile Test (ASTM D638). No tensile testing according to ASTM D638 was possible because of the size of the sample received at the TTC.

B.7.2.7 Flexural Test (ASTM D790). No flexural testing according to ASTM D790 was possible because of the size of the sample received at the TTC. However, data from flexural property testing conducted by the City of Winnipeg were provided. The data for flexural strength and flexural modulus are shown in Table B-53. The calculated average flexural strength from the data provided is 6,779 ± 1,346 psi and the calculated average flexural modulus is 323,930 ± 59,728 psi. These data are similar to those published in Macey et al. (2013) for the same liner (flexural strength reported to range from 5,511 psi to 7,297 psi and the flexural modulus ranging from 272,816 psi to 375,068 psi).

Table B-53. Winnipeg 2 (Kingsway): Flexural Test Results

Sample ID	Flexural Strength (psi)	Flexural Modulus (psi)
1	5,938	277,347
2	6,316	299,458
3	4,856	241,504
4	7,868	381,630
5	6,672	327,520
6	9,027	416,120
7	6,779	323,930
Average	6,779	323,930
St. Dev	1,346	59,728

B.7.2.8 ***Surface Hardness.*** A Shore Type D durometer (ASTM D2240) was used to determine the hardness of the liner samples. A total of 400 readings were taken on the inner and outer surfaces of the liner specimens. The average recorded hardness values are shown in Figure B-96. The hardness of the surface exposed to the flow (inner surface) was found to be only slightly lower than that of the protected (outer) surface, suggesting little, if any, softening or erosion of the resin on the inner surface of the tube during its service life. Differences may also be expected due to the initial presence or any continuing presence of the sealing layer on the internal surface.

Figure B-96. Winnipeg 2: Shore D Hardness Readings from Inner and Outer Surfaces

B.7.2.9 ***Glass Transition Temperature.*** The calculated Tg values are summarized in Table B-54 for the Winnipeg (Kingsway) sample. The average Tg for the field samples was 76.72°C (± 22.63°C) as measured by ASTM Method E1356-08 with DSC.

Table B-54. Winnipeg 2: Sample Tg Determination (Kingsway CIPP Liner)

Sample	Run	Tg (°C)
Winnipeg (Kingsway)	1	65.13
Winnipeg (Kingsway)	2	62.23
Winnipeg (Kingsway)	3	102.80

B.7.3 Winnipeg Sample 3: A 28-Year Old CIPP Liner in a 30 in. Reinforced Concrete Pipe. This sample was retrieved from Mission St. in the City of Winnipeg, Manitoba in January 2013. It was part of a larger sample that was tested by the City of Winnipeg. The host pipe and liner information are shown in Table B-55. The host pipe depth was reported to be 27 ft (8.2 m).

Table B-55. Winnipeg 3 (Mission): Host Pipe and Liner Information

Host pipe	Reinforced concrete pipe, 30 in. diameter

Liner Thickness	About 23 mm as measured on the sample retrieved
Resin	Unfilled isophthalic polyester resin
Primary Catalyst	Information unavailable
Secondary Catalyst	Information unavailable
Felt	Information unavailable
Seal	Information unavailable
Year of Installation	April 1984
Liner Vendor	Information unavailable
Resin Supplier	Information unavailable

The sample (Figure B-97) was received at the TTC south campus facility on August 2, 2013.

Figure B-97. Winnipeg 3: Received Sample

B.7.3.1 Visual Inspection. The sample as received at the TTC was found to be in excellent condition.

B.7.3.2 Annular Gap. Since only the CIPP liner was received, no annular gap measurements were possible.

B.7.3.3 Environmental Service Conditions. Soil collection was not applicable because the sample was retrieved via a manhole.

B.7.3.4 Thickness. A total of 60 readings were taken on 10 1 in. × 1 in. samples cut from different locations of the specimen. The thickness was measured randomly using a micrometer with a resolution of ±0.0025 mm. The average thickness was found to be 22.83 mm ± 3.11 mm as shown in Figure B-98. The design thickness was not available.

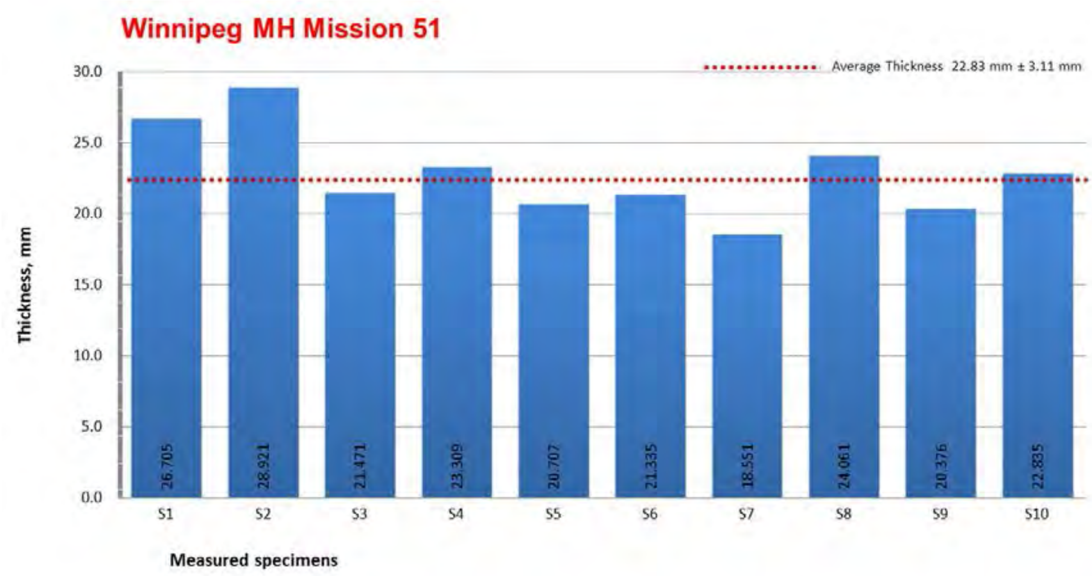

Figure B-98. Winnipeg 3: Average Thickness of the Sample

B.7.3.5 ***Specific Gravity.*** The specific gravity of the liner was measured on 10 1 in. × 1 in. samples in accordance with ASTM D792. The specific gravity values from the sample are shown in Figure B-99. The obtained values were between 1.03 and 1.11. The average specific gravity of the liner was 1.07.

Figure B-99. Winnipeg 3: Measured Specific Gravity of the CIPP Liner

B.7.3.6 ***Tensile Test (ASTM D638).*** No tensile testing according to ASTM D638 was possible because of the size of the sample received at the TTC.

B.7.3.7 Flexural Test (ASTM D790). No flexural testing according to ASTM D790 was possible because of the size of the sample received at the TTC. However, data from flexural property testing conducted by the City of Winnipeg were provided. The data for flexural strength and flexural modulus are shown in Table B-56. The calculated average flexural strength from the data provided is 4,469 ± 807 psi and the calculated average flexural modulus is 245,753 ± 52,540 psi. No other data for this liner could be found in the published material from the Winnipeg testing. Both the average flexural strength and the average flexural modulus are just below the respective current ASTM standards but it is reported in Macey et al. (2013) that the flexural modulus requirement at the time of installation was 240,000 psi and the average flexural modulus test results are above that requirement.

Table B-56. Winnipeg 3 (Mission): Flexural Test Results

Sample ID	Flexural Strength (psi)	Flexural Modulus (psi)
1	5,316	298,135
2	5,774	315,672
3	4,140	258,234
4	5,411	292,587
5	4,913	280,548
6	4,044	231,960
7	3,558	155,492
8	3,774	189,062
9	4,071	234,525
10	3,694	201,315
Average	4,469	245,753
St. Dev	807	52,540

B.7.3.8 Surface Hardness. A Shore Type D durometer (ASTM D2240) was used to determine the hardness of the liner samples. A total of 200 readings were taken on the inner and outer surfaces of the liner specimens. The average recorded hardness values are shown in Figure B-100. The hardness of the surface exposed to the flow (inner surface) was found to be only slightly lower than that of the protected (outer) surface, suggesting little, if any, softening or erosion of the resin on the inner surface of the tube during its service life. Differences may also be expected due to the initial presence or any continuing presence of the sealing layer on the internal surface.

Figure B-100. Winnipeg 3: Shore D Hardness Readings from Inner and Outer Surfaces

B.7.3.9 Glass Transition Temperature. The calculated Tg values are summarized in Table B-57 for the Winnipeg (Mission) sample. The average Tg for the field samples was 129.24°C (±3.27°C) as measured by ASTM Method E1356-08 with DSC.

Table B-57. Winnipeg 3: Tg Determination (Mission CIPP Liner)

Sample	Run	Tg (°C)
Winnipeg (Mission)	1	129.12
Winnipeg (Mission)	2	132.57
Winnipeg (Mission)	3	126.03

APPENDIX C

STUDIES FOR OTHER REHABILITATION TECHNOLOGIES

C.1 Fold-and-Form (PVC) Samples

C.1.1 Denver Ringsby St. Sample: A 15-Year Old Fold-and-Form PVC Liner in an 8-in. Vitrified Clay Host Pipe. This sample was retrieved on September 24, 2013 from beneath a grassy area in a parking lot at 3333 Ringsby Ct. in Denver, Colorado. The host pipe and liner information are shown in Table C-1. The depth to top of pipe at the upstream (southwest) end was 37 in. and at the downstream (northeast) end was 38 in. There was no evidence of a water table above the top of the pipe at the retrieval.

Table C-1. Denver Ringsby Ct.: Host Pipe and Liner Information

Host pipe	Vitrified clay 8 in. inner diameter (outer diameter 9.75 in.)
Liner Thickness	0.5 cm (using ruler) and 0.46 cm (using caliper) at upstream
Liner Type	PVC
Year of Installation	1998
Liner Vendor/Supplier	Ultraliner

C.1.1.1 Visual Inspection. The PVC sample was retrieved with the host pipe and both were in good condition. The liner fitted the host pipe closely around most of the circumference. The thickness was consistent. No soil accumulation was retained on the sample when it arrived at the TTC laboratory. The retrieved sample in the field and in the laboratory is shown in Figure C-1.


Figure C-1. Denver Ringsby Ct.: PVC Liner and Host Pipe during Retrieval (left) and at the Laboratory (right)

C.1.1.2 Annular Gap. Annular gaps were measured at the site and the measured gaps are shown in Table C-2.

Table C-2. Denver Ringsby Ct.: Annular Gap Results

End	12:00	1:30	3:00	4:30	6:00	7:30	9:00	11:30
Annular Gap in Remaining Host pipe (mm)								
Northeast	0.8	0.7	0.25	0.25	0.8	0	0	0.43
Southwest	0	0	2	0.58	0.8	0	0	0
Annular Gap of Retrieved Sample (mm)								
Northeast	1.0	0.43	0	0	0.88	0.2	0.3	0.25
Southwest	N/A	N/A	0.70	0	0	0	0	0

N/A = Not Available

C.1.1.3 Environmental Service Conditions. Soil samples were not collected. Waste material (2 g) was collected at the inside and outside surfaces of the sample and blended with 200 mL of distilled water. The pH was measured separately using pH-indicator strips. The pH value was found to be between 6 and 7 on both sides.

C.1.1.4 Ovality. The sample's ovality was measured using software named VectorizeIT. First, the shape of the liner was traced on a piece of paper and an image of the traced liner was taken. Next, the image file was converted to a DXF file format using the software. An 8 in. inner diameter circle (as if it were the host-pipe's inner diameter – red line) was drawn and the DXF drawing of the liner (black line) was positioned inside the circle (Figure C-2). Thus, the center of the liner was approximated and diameters were measured on the liner generated using AutoCAD. Based on the maximum diameter measured, the ovality was 1.61%, while the ovality was 1.66% when calculated based on the minimum diameter. The higher ovality value was used as the representative value. The detailed ovality calculation is shown in Table C-3. For all samples in Appendix C, the outer diameter and inner diameter were measured via this method versus ASTM D2122.

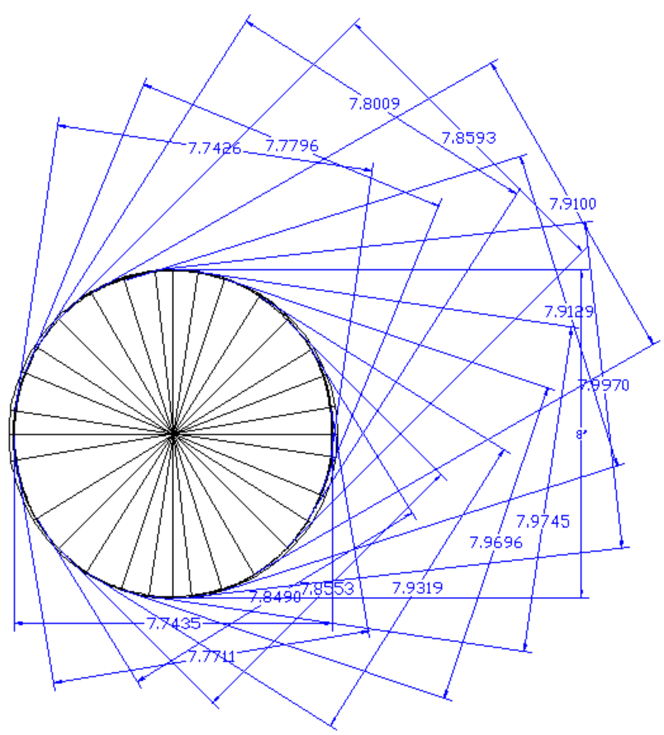

Figure C-2. Denver Ringsby Ct.: Diameter of the Liner

Table C-3. Denver Rigsby Ct. – Ovality Calculation

Measured Diameter (in.)	Diameter (in.)			Ovality (%) Based on	
	Maximum	Minimum	Mean	Max Dia.	Min. Dia.
7.7426	8.0	7.7426	7.7	1.611	1.658
7.7796					
7.8009					
7.8593					
7.9100					
7.9129					
7.9970					
8.0000					
7.9745					
7.9696					
7.9319					
7.8553					
7.8490					
7.7435					
7.7711					

C.1.1.5 ***Thickness.*** A total of 120 readings were taken on 20 1 in. × 1 in. samples cut from different locations of the specimen. The thickness on the samples was measured randomly using a micrometer with a resolution of ±0.0025 mm. The average thickness of the liner was found to be 4.17 mm ± 0.05 mm as shown in Figure C-3. The design thickness was not available and therefore, no comparison was made.

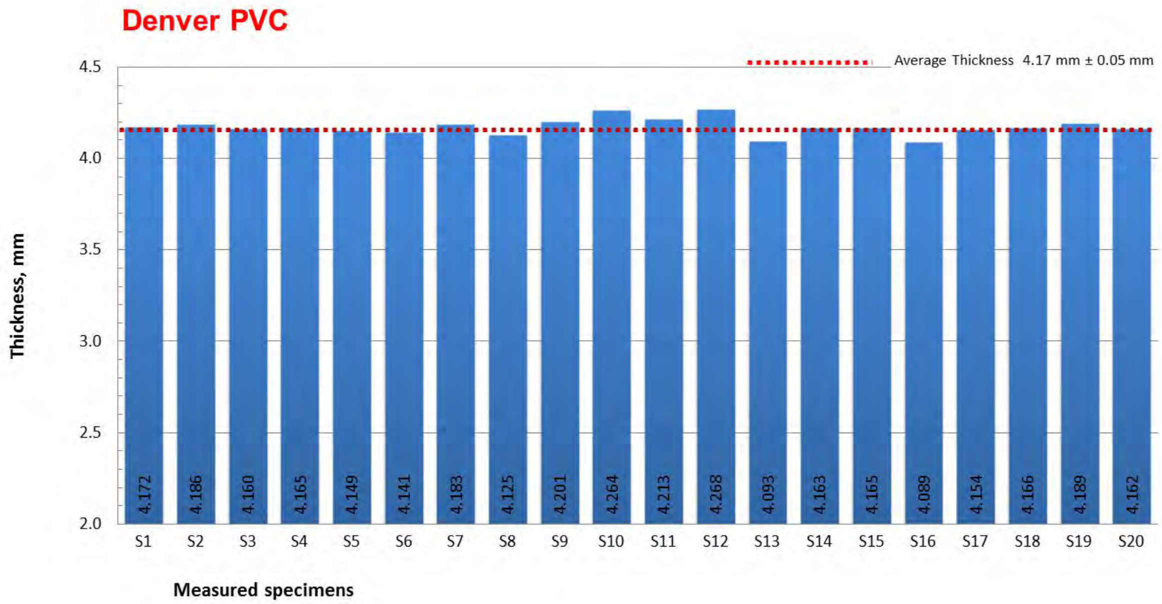

Figure C-3. Denver Ringsby Ct.: Average Thickness of the Liner Sample

C.1.1.6 Specific Gravity. The specific gravity of the liner was measured on 20 1 in. × 1 in. samples in accordance with ASTM D792. The specific gravity values are shown in Figure C-4. The obtained values were between 1.31 and 1.35, and average specific gravity was 1.32 ± 0.01.

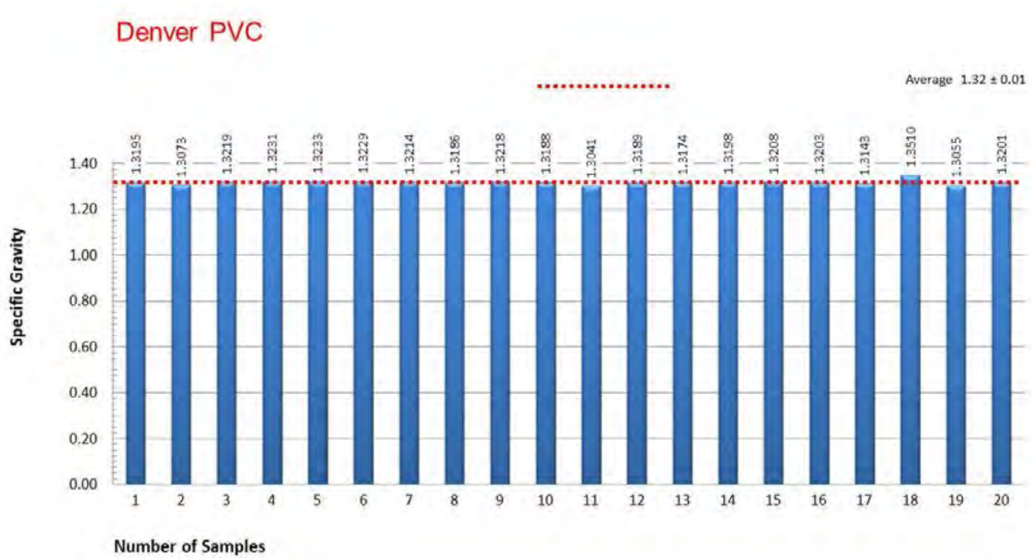

Figure C-4. Denver Ringsby Ct.: Measured Specific Gravity of the Liner

C.1.1.7 Tensile Test (ASTM D638). Specimens, as described in ASTM D638, were cut from the retrieved PVC liner using a router and a band saw. A total of 15 specimens were prepared and tested. The sides of the specimens were smoothed using a grinder. The water jet cutter could not be used as the liner was curved and too small to be mounted inside the cutting board. The tensile test results are presented in Figure C-5 and Table C-4. The average tensile strength was 5,418 ± 547 psi and the average tensile modulus was 288,335 ± 31,968 psi. The elongation at break of Sample 1 was found to be lower than the other samples, but no indication of cracks or deformation was found on the sample prior to the test.

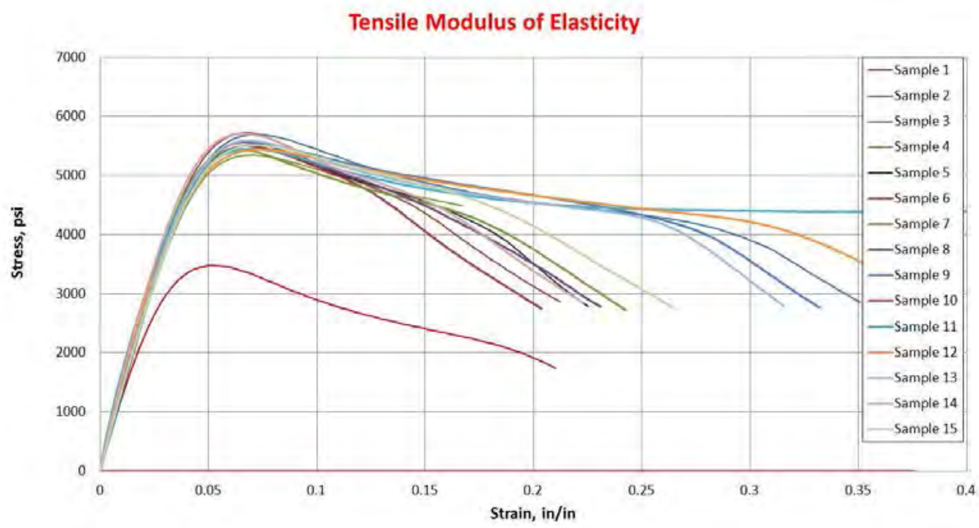

Figure C-5. Denver Ringsby Ct.: Stress – Strain Curves from Tensile Testing

Table C-4. Denver Ringsby Ct.: Tensile Test Results

Sample ID	Area (in.^{2})	Peak Load (lb)	Peak Stress (psi)	Tensile Modulus (psi)
1	0.1056	367.65	3,482	257,766
2	0.0960	549.87	5,728	284,532
3	0.1081	615.53	5,694	259,008
4	0.1013	541.43	5,350	268,382
5	0.0903	503.38	5,575	276,596
6	0.0783	431.06	5,505	273,272
7	0.0937	510.73	5,451	288,645
8	0.0895	498.01	5,564	272,648
9	0.1049	579.37	5,523	279,990
10	0.1090	619.92	5,687	284,205
11	0.0847	461.71	5,451	368,913
12	0.0957	520.93	5,443	334,849
13	0.0781	436.21	5,592	273,541
14	0.0860	490.71	5,706	334,426
15	0.1094	603.67	5,518	268,257
Average		515.35	5,418	288,335
St. Dev		72.66	547	31,968

C.1.1.8 Flexural Test (ASTM D790). Specimens, as described in ASTM D790, were cut from the retrieved liner using a router and a band saw. A total of 15 specimens were prepared and tested. The sides of the specimens were smoothed using a grinder. The water jet cutter could not be used as the liner was curved and too small to be mounted inside the cutting board. The flexure test results are presented graphically in Figure C-6 and are listed in Table C-5. The average flexural modulus was 273,471 ± 8,975 psi and flexure strength was 7,790 ± 197 psi.

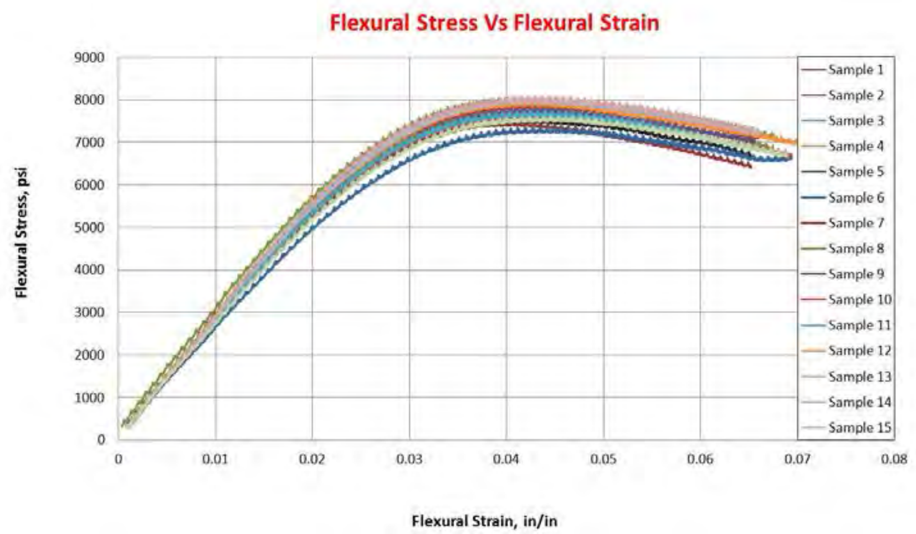

Figure C-6. Denver Ringsby Ct.: Stress – Strain Curves from Flexural Testing

Table C-5. Denver Ringsby Ct.: Flexure Test Results

Sample ID	Area (in.^{2})	Peak Load (lb)	Peak Stress (psi)	Flexural Modulus (psi)
1	0.0029	22.73	7,838	274,955
2	0.0029	21.84	7,531	274,586
3	0.0032	25.42	7,944	277,838
4	0.0031	24.40	7,871	271,132
5	0.0029	22.27	7,679	266,527
6	0.0033	24.26	7,352	251,228
7	0.0030	23.76	7,920	281,238
8	0.0031	24.85	8,016	281,521
9	0.0029	22.93	7,907	275,189
10	0.0033	25.30	7,667	271,606
11	0.0030	22.95	7,650	271,214
12	0.0033	26.17	7,930	275,063
13	0.0030	23.95	7,983	279,494
14	0.0030	23.91	7,970	288,927
15	0.0032	24.34	7,606	261,543
Average		23.94	7,790	273,471
St. Dev		1.23	197	8,975

C.1.1.9 Surface Hardness. A Shore Type D durometer (ASTM D2240) was used to determine the hardness of the liner samples. Samples (1 in. × 1 in.) were cut from the retrieved PVC liner with a band saw. A total of 400 readings were taken on the inner and outer surfaces of the liner specimens. The average recorded hardness values are shown in Figure C-7. The hardness of the surface exposed to the flow (inner surface) was found to be slightly lower than that of the protected (outer) surface.

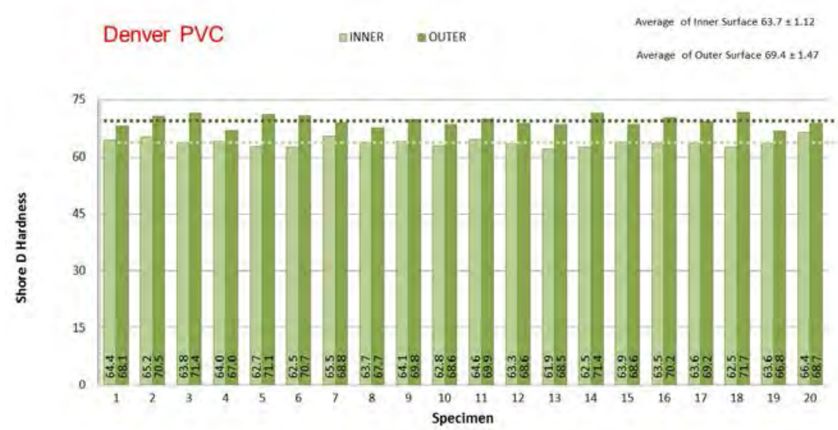

Figure C-7. Denver Ringsby Ct.: Shore D Hardness Readings for the Liner's Inner and Outer Surfaces

C.1.1.10 Pipe Stiffness. Pipe stiffness was measured using the Universal Testing Machine (UTM) equipped with parallel plates according to ASTM D2412. Three 6 in. long specimens were cut from the liner using a table saw and positioned between the plates; the load was applied at 0.50 in./min (see Figure C-8).

Figure C-8. Denver Rigsby Ct.: Parallel Plate Test

According to ASTM D2412, the deformation of the pipe was limited to 5% of the inside diameter and the test results are presented in Table C-6. The average value was found to be 19.75 lbf/in./in.

Table C-6. Denver Rigsby Ct.: Pipe Stiffness Test Results

Sample	Peak Load, lb	Pipe Stiffness at 5% Deformation of Inside Diameter (lbf/in./in.)
1	7.78	20.43
2	7.23	18.99
3	7.55	19.84
Average	7.52	19.75

C.1.2 Nashville Elaine Dr. Sample: A 14-Year Old Fold-and-Form PVC Liner in an 8-in. Clay Pipe. The sample was recovered at 542 Elaine Drive, Nashville, Tennessee on September 22, 2013. The host pipe and liner information are shown in Table C-7. The host pipe was reported to be at depth of 4 to 5 ft below grade.

Table C-7. Nashville Elaine Dr.: Host Pipe and Liner Information

Host pipe	Clay Pipe 8 in. inner diameter
Liner Thickness	Average thickness approximately 5 mm
Liner Type	Fold-and-form PVC
Year of Installation	1999
Liner Vendor/Supplier	Ultraliner

C.1.2.1 Visual Inspection. The PVC sample received along with the host pipe was in good condition. The thickness of the sample was found to be inconsistent with significant variation observed between the maximum and minimum thickness. The retrieved samples in the field and as received at the TTC laboratory are shown in Figure C-9.

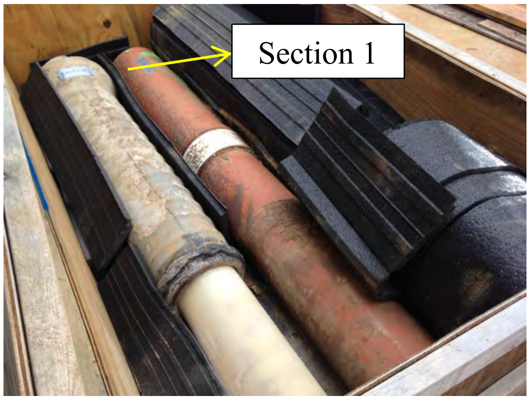

Figure C-9. Nashville Elaine Dr.: Images of the PVC Liner Section after Retrieval (left) and Samples Received at the TTC Lab (right)

C.1.2.2 Annular Gap. The annular gap was measured using a feeler gauge. Eight readings were taken on each section of the liner and are provided in Table C-8.

Table C-8. Nashville Elaine Dr.: Annular Gap Measurements

Position	Gap Measured	
	Section 1 (in.) (mm)	Section 2 (in.) (mm)
12:00	0.19 (4.8)	0.19 (4.8)
1:30	0.01 (0.3)	0.00 (0.0)
3:00	0.00 (0.0)	0.05 (1.3)
5:00	0.19 (4.8)	0.19 (4.8)
6:00	0.11 (2.8)	0.25 (6.4)
7:30	0.08 (2.0)	0.25 (6.4)

9:00	0.00 (0.0)	0.19 (4.8)
11:00	0.03 (0.8)	0.05 (1.3)

C.1.2.3 Environmental Service Conditions. Soil samples surrounding the pipe were not collected. Waste material (2 g) was collected on the inside and outside surfaces of the sample and blended with 200 mL of distilled water. The pH was measured separately using pH-indicator strips. The outside pH was found to be between 6 and 7, while the pH value on the inside was approximately 5.

C.1.2.4 Ovality. The sample's ovality was measured using software as described in Section C.1.1.4 and with the results shown in Figure C-10. Based on the maximum diameter measured, the ovality was 2.96%, while ovality was 1.30% when calculated based on the minimum diameter. The higher ovality value was used as the representative value. The detailed ovality calculation is shown in Table C-9.

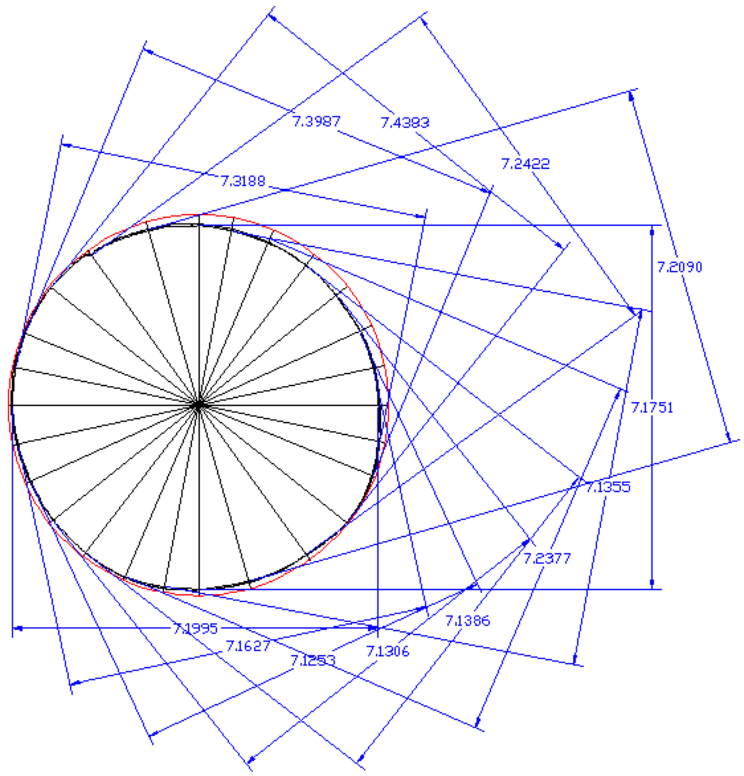

Figure C-10. Nashville Elaine Dr.: Ovality of the Liner

Table C-9. Nashville Elaine Dr.: Ovality Calculation

Measured Diameter (in.)	Diameter (in.)			Ovality (%) Based on	
	Maximum	Minimum	Mean	Max Dia.	Min. Dia.
7.3188	7.4383	7.1305	7.2246	2.9574	1.3027
7.3987					
7.4383					
7.2422					

7.2090					
7.1751					
7.1355					
7.2377					
7.1386					
7.1306					
7.1253					
7.1627					
7.1995					

C.1.2.5 Thickness. A total of 120 readings were taken on 20 1 in. × 1 in. samples cut from different locations of the specimen. The thickness was measured randomly using a micrometer with a resolution of ±0.0025 mm. The average thickness of the liner was found to be 5.22 mm ± 0.89 mm as shown in Figure C-11. The design thickness was unavailable; therefore, no comparison was made.

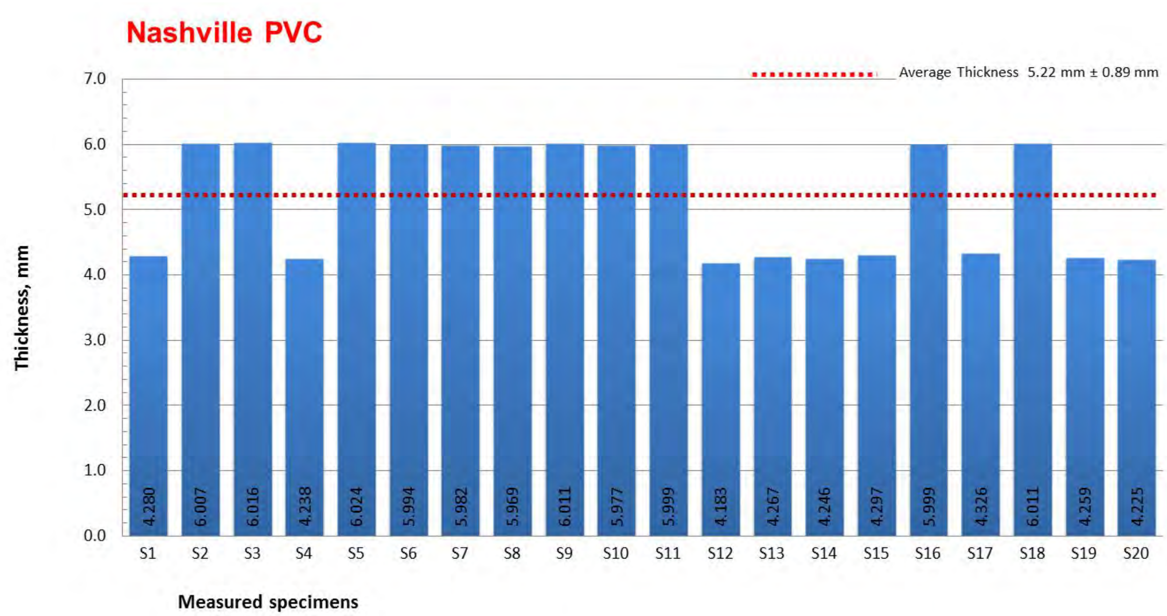

Figure C-11. Nashville Elaine Dr.: Average Thickness of the Liner Sample

C.1.2.6 Specific Gravity. The specific gravity of the liner was measured on 20 1 in. × 1 in. samples in accordance with ASTM D792. The specific gravity values are shown in Figure C-12 and were between 0.99 and 1.34. The average specific gravity was 1.300 ± 0.08.

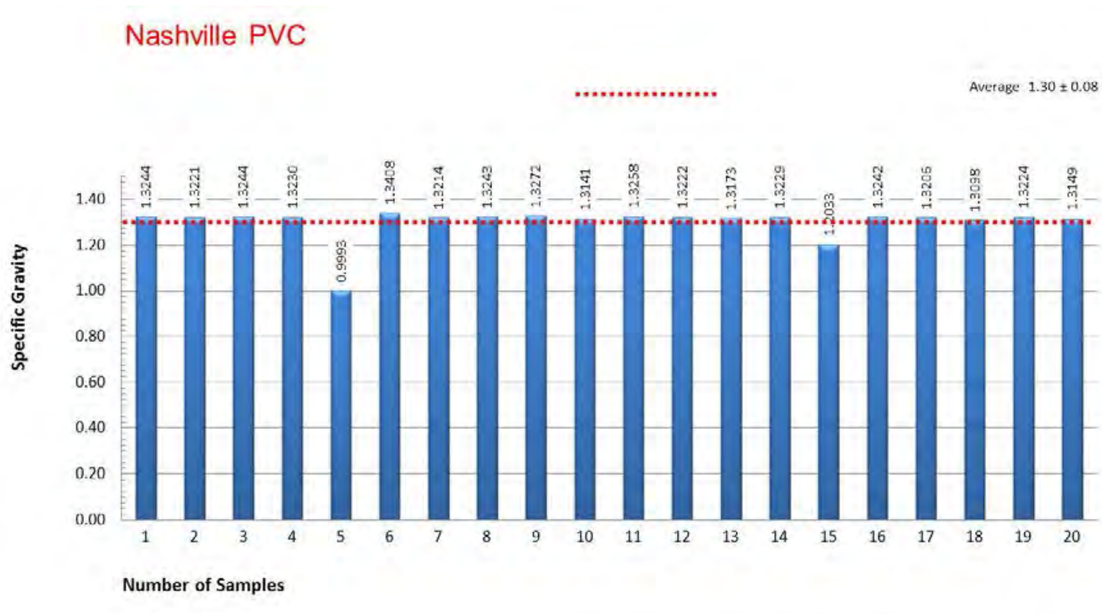

Figure C-12. Nashville Elaine Dr.: Specific Gravity of the Liner

C.1.2.7 Tensile Test (ASTM D638). Specimens, as described in ASTM D638, were cut from the retrieved PVC liner using a router and a band saw. A total of 15 specimens were prepared and tested. The sides of the specimens were smoothed using a grinder. The water jet cutter could not be used as the liner was curved and too small to be mounted inside the cutting board. The tensile test results are presented in Figure C-13 and Table C-10. The average tensile strength was 5,913 ± 163 psi and the average tensile modulus was 314,872 ± 36,523 psi.

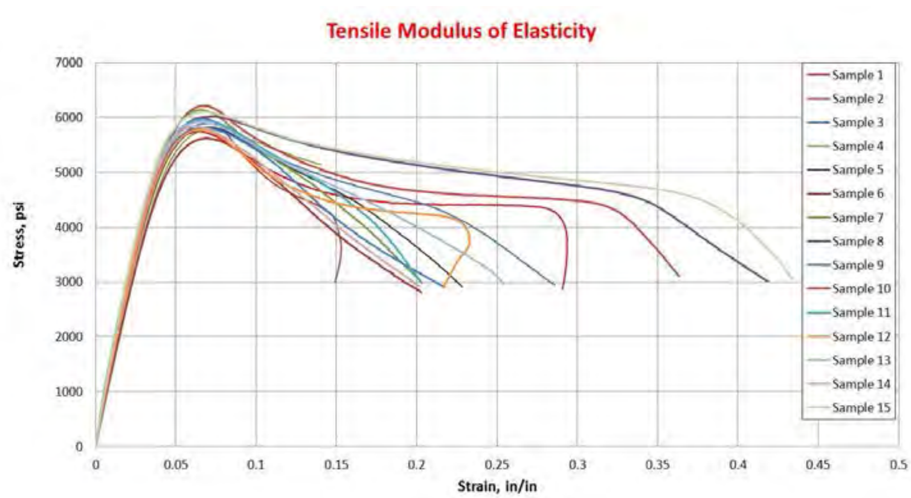

Figure C-13. Nashville Elaine Dr.: Stress – Strain Curves from Tensile Testing

Table C-10. Nashville Elaine Dr.: Tensile Test Results

Sample ID	Area (in.^{2})	Peak Load (lb)	Peak Stress (psi)	Tensile Modulus (psi)
1	0.1264	726.19	5,745	295,908
2	0.1145	687.32	6,003	307,449
3	0.0875	515.71	5,894	314,070
4	0.1149	664.57	5,784	270,931
5	0.1200	699.05	5,825	297,786
6	0.1278	719.00	5,626	268,928
7	0.1067	655.71	6,145	308,754
8	0.1173	706.57	6,024	307,614
9	0.1174	682.44	5,813	342,202
10	0.1161	721.77	6,217	303,730
11	0.0899	536.30	5,966	423,667
12	0.1265	731.97	5,786	297,442
13	0.1119	662.63	5,922	314,982
14	0.1153	674.58	5,851	331,006
15	0.1188	725.43	6,106	338,622
Average		673.95	5,913	314,872
St. Dev		65.22	163	36,523

C.1.2.8 Flexural Test (ASTM D790). Specimens, as described in ASTM D790, were cut from the retrieved liner using a router and a band saw. A total of 15 specimens were prepared and tested. The sides of the specimens were smoothed using a grinder. The water jet cutter could not be used as the liner was curved and too small to be mounted inside the cutting board. The flexure test results are presented graphically in Figure C-14 and are listed in Table C-11. The average flexural modulus was 279,550 ± 8,260 psi and the average flexural strength was 8,581 ± 299 psi.

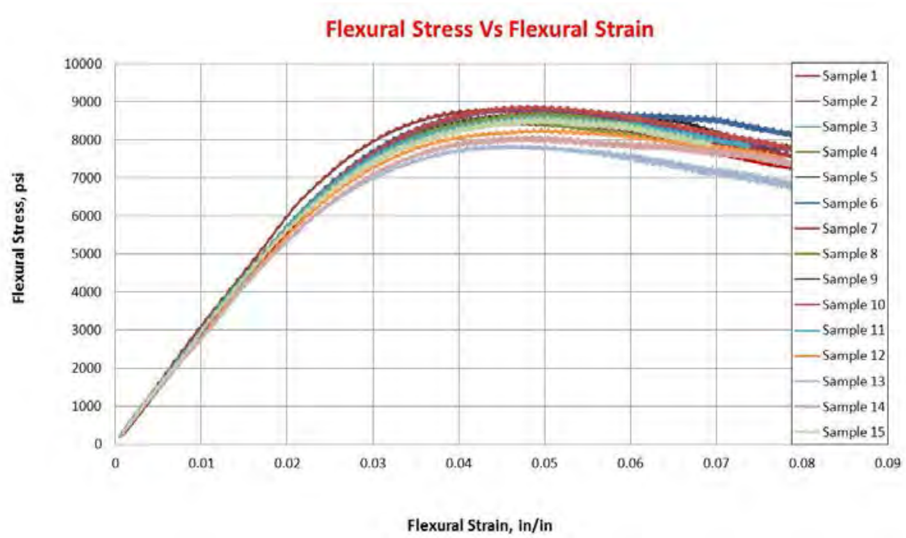

Figure C-14. Nashville Elaine Dr.: Stress – Strain Curves from Flexural Testing

Table C-11. Nashville Elaine Dr.: Flexure Test Results

Sample ID	Area (in.^{2})	Peak Load (lb)	Peak Stress (psi)	Flexural Modulus (psi)
1	0.0043	37.41	8,700	273,235
2	0.0039	32.84	8,421	273,225
3	0.0048	41.92	8,733	276,654
4	0.0049	41.96	8,563	269,910
5	0.0042	36.30	8,643	275,847
6	0.0044	39.26	8,923	282,966
7	0.0048	42.35	8,823	298,603
8	0.0033	28.47	8,627	288,207
9	0.0047	41.96	8,928	283,139
10	0.0048	42.79	8,915	284,201
11	0.0036	30.80	8,556	290,102
12	0.0041	34.01	8,295	273,222
13	0.0048	37.96	7,908	272,615
14	0.0045	36.42	8,093	270,851
15	0.0032	27.49	8,591	280,484
Average		36.80	8,581	279,550
St. Dev		5.14	299	8,260

C.1.2.9 Surface Hardness. A Shore Type D durometer (ASTM D2240) was used to determine the hardness of the liner samples. Samples (1 in. × 1 in.) were cut from the retrieved PVC liner with a band saw. A total of 400 readings were taken on the inner and outer surfaces of the liner specimens. The average recorded hardness values are shown in Figure C-15. The hardness of the surface exposed to the flow (inner surface) was found to be slightly lower than that of the protected (outer) surface.

Figure C-15. Nashville Elaine Dr.: Shore D Hardness Readings for the Liner's Inner and Outer Surfaces

C.1.2.10 Pipe Stiffness. Pipe stiffness was measured using the UTM equipped with parallel plates according to ASTM D2412. Three 6 in. long specimens were cut from the liner using a table saw and positioned in between the plates; the load was applied at 0.50 in./min.

According to ASTM D2412, the deformation of the pipe was limited to 5% of the inside diameter and the test results are presented in Table C-12. The average value was found to be 35.1 lbf/in./in.

Table C-12. Nashville Elaine Dr.: Pipe Stiffness Test Results

Sample	Peak Load, lb	Pipe Stiffness at 5% Deformation of Inside Diameter (lbf/in./in.)
1	11.72	32.55
2	12.23	33.94
3	13.96	38.74
Average	12.63	35.08

C.2 Deform-Reform (HDPE) Samples

C.2.1 Denver Irving St. Sample: A 15-Year Old Deform-Reform HDPE Liner in an 8 in. Vitrified Clay Pipe. The sample was recovered at the west end of the alley running between Irving St. and Grove St. and located between Clyde Pl. and 37th Ave., Denver, Colorado on September 25, 2013. The host pipe and liner information are shown in Table C-13. The invert of the host pipe was at a depth of approximately 11 ft below ground level. There was no evidence of a water table above the top of the pipe at the retrieval time but some water was accumulating in the bottom of the pit during the uncovering of the pipe and preparation of the sample for removal.

Table C-13. Denver Irving St.: Host Pipe and Liner Information

Host pipe	Vitrified clay pipe 8 in. inner diameter (outer diameter not measured due to cracking)
Liner Thickness	Approximately 8 mm
Liner Type	Deform-reform HDPE
Year of Installation	1998
Liner Vendor/Supplier	Hydro Conduit Corporation

C.2.1.1 Visual Inspection. The HDPE sample was retrieved along with the host pipe which was badly cracked. The reasons for the cracking could not be determined. The main possibilities were that the pipe was cracked prior to its relining in 1998 or that the pipe was cracked by the internal pressure used to re-round the HDPE liner during its installation. There was no soil remaining on the samples when received at the TTC laboratory. The retrieved samples are shown in the field and as received at the TTC laboratory in Figure C-16.


Figure C-16. Denver Irving St.: Images of the HDPE Liner Section during Retrieval (left) and in the TTC Laboratory (right)

C.2.1.2 Annular Gap. Annular gaps were not measured due to the cracking of the host pipe.

C.2.1.3 Environmental Service Conditions. No soil or residues were available for pH determination.

C.2.1.4 Ovality. The sample's ovality was measured using software as described in Section C.1.1.4 and illustrated in Figure C-17. Based on the maximum diameter measured, ovality was 3.26%, while the ovality was 5.20% when calculated based on the minimum diameter. The higher ovality value was used as the representative value. The detailed ovality calculation is shown in Table C-14.

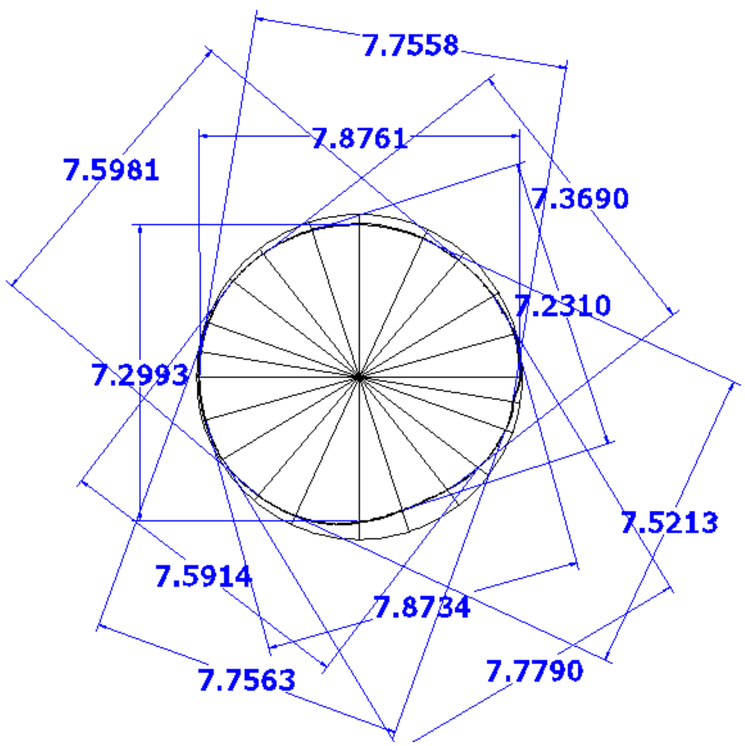

Figure C-17. Denver Irving St.: Ovality of the Liner

Table C-14. Denver Irving St.: Ovality Calculation

Measured Diameter (in.)	Diameter (in.)			Ovality (%) Based on	
	Maximum	Minimum	Mean	Max Dia.	Min. Dia.
7.7558	7.8761	7.2310	7.63	3.263	5.195
7.8761					
7.3690					
7.2310					
7.5213					
7.8734					
7.7790					
7.7563					
7.5914					
7.2993					
7.5981					

7.8761					

C.2.1.5 ***Thickness.*** A total of 120 readings were taken on 20 1 in. × 1 in. samples cut from different locations of the specimen. The thickness was measured randomly using a micrometer with a resolution of ±0.0025 mm. The average thickness of the liner was found to be 7.98 mm ± 0.25 mm as shown in Figure C-18. The design thickness was unavailable; therefore, no comparison was made.

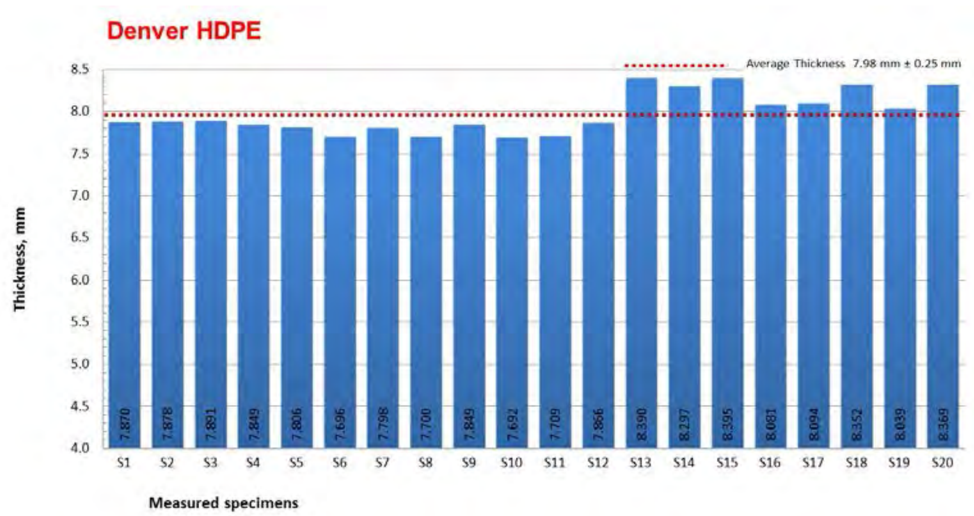

Figure C-18. Denver Irving St.: Average Thickness of the Liner Sample

C.2.1.6 ***Specific Gravity.*** The specific gravity of the liner was measured on 20 1 in. × 1 in. samples in accordance with ASTM D792. The specific gravity values are shown in Figure C-19. The obtained values were between 0.93 and 0.95. The average specific gravity was 0.94 ± 0.01.

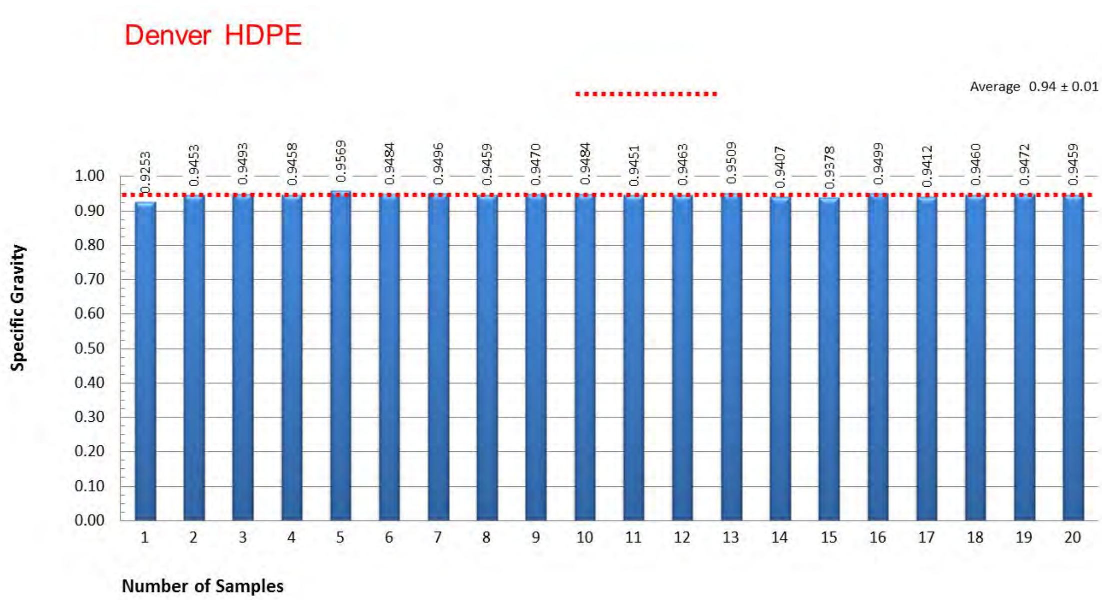

Figure C-19. Denver Irving St.: Specific Gravity of the Liner

C.2.1.7 Tensile Test (ASTM D638). Specimens, as described in ASTM D638, were cut from the retrieved HDPE liner using a router and a band saw. A total of 15 specimens were prepared and tested. The sides of the specimens were smoothed using a grinder. The water jet cutter could not be used as the liner was curved and too small to be mounted inside the cutting board. The tensile test results are presented in Figure C-20 and Table C-15. The average tensile strength was 3,019 ± 403 psi and the average tensile modulus was 145,851 ± 15,144 psi. The elongation at the break of Sample 1 is much smaller than for the others. The reason is unknown as there was no evidence of a crack found on the sample. The test period of Sample 3 was cut short due to a required response to a fire alarm in the laboratory.

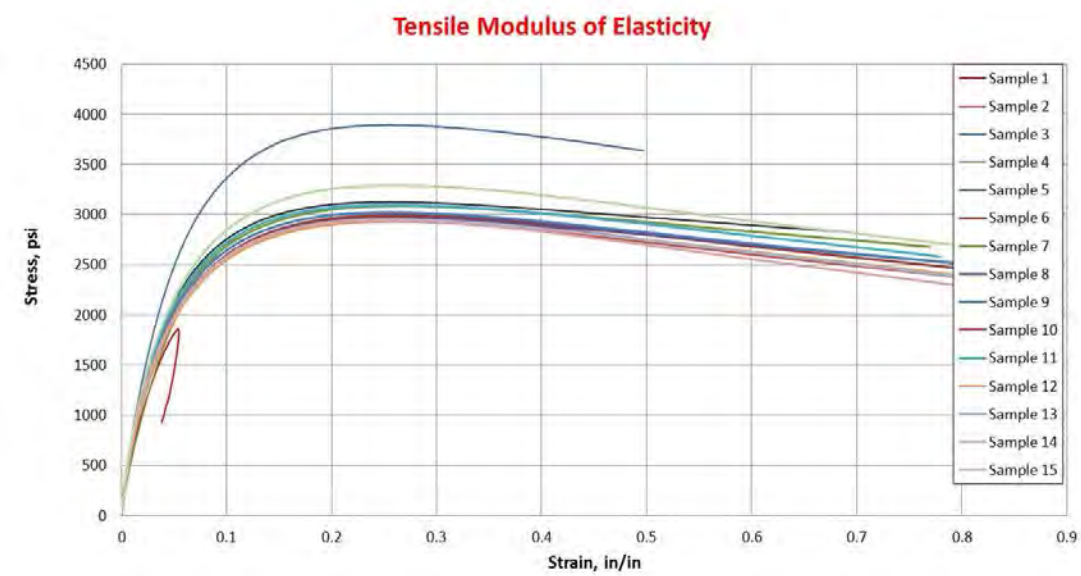

Figure C-20. Denver Irving St.: Stress – Strain Curves from Tensile Testing

Table C-15. Denver Irving St.: Tensile Test Results

Sample ID	Area (in.^{2})	Peak Load (lb)	Peak Stress (psi)	Tensile Modulus (psi)
1	0.1479	274.61	1,857	149,738
2	0.1565	466.91	2,983	144,522
3	0.1292	503.55	3,897	156,627
4	0.1655	524.54	3,169	106,216
5	0.1417	443.21	3,128	128,669
6	0.1661	498.08	2,999	138,613
7	0.1629	503.19	3,089	154,101
8	0.1626	482.87	2,970	167,034
9	0.1635	494.43	3,024	151,868
10	0.1642	482.21	2,937	142,458
11	0.1550	480.45	3,100	160,449
12	0.1561	459.16	2,941	142,756
13	0.1589	469.70	2,956	139,961
14	0.1678	494.23	2,945	141,145

15	0.1473	485.32	3,295	163,611
Average		470.83	3,019	145,851
St. Dev		57.84	403	15,144

C.2.1.8 Flexural Test (ASTM D790). Specimens, as described in ASTM D790, were cut from the retrieved liner using a router and a band saw. A total of 15 specimens were prepared and tested. The sides of the specimens were smoothed using a grinder. The water jet cutter could not be used as the liner was curved and too small to be mounted inside the cutting board. The flexure test results are presented graphically in Figure C-21 and are listed in Table C-16. The average flexural modulus was 108,815± 5,891 psi and the average flexure strength was 3,363 ± 193 psi.

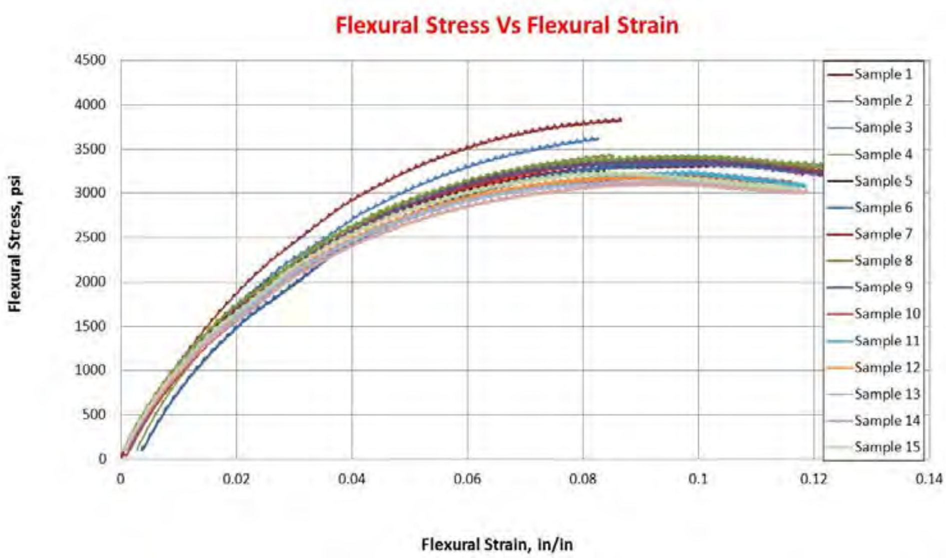

Figure C-21. Denver Irving St.: Stress – Strain Curves from Flexural Testing

Table C-16. Denver Irving St.: Flexure Test Results

Sample ID	Area (in.^{2})	Peak Load (lb)	Peak Stress (psi)	Flexural Modulus (psi)
1	0.0092	31.06	3,376	116,697
2	0.0085	32.92	3,873	119,461
3	0.0093	33.88	3,643	107,377
4	0.0097	33.52	3,456	116,521
5	0.0091	29.81	3,276	113,016
6	0.0092	31.00	3,370	106,391
7	0.0083	28.35	3,416	109,774
8	0.0088	30.31	3,444	111,352
9	0.0099	33.37	3,371	107,793
10	0.0092	29.73	3,232	97,560
11	0.0093	30.10	3,237	102,056
12	0.0096	30.61	3,189	103,655
13	0.0088	27.94	3,175	104,785
14	0.0093	29.34	3,155	107,654
15	0.0091	29.48	3,240	108,143
Average		30.76	3,363	108,815

St. Dev		1.87	193	5,891

C.2.1.9 Surface Hardness. A Shore Type D durometer (ASTM D2240) was used to determine the hardness of the liner samples. Samples (1 in. × 1 in.) were cut from the retrieved HDPE liner with a band saw. A total of 400 readings were taken on the inner and outer surfaces of the liner specimens. The average recorded hardness values are shown in Figure C-22. The hardness of the surface exposed to the flow (inner surface) was found to be slightly lower than that of the protected (outer) surface.

Figure C-22. Denver Irving St.: Shore D Hardness Readings for the Liner's Inner and Outer Surfaces

C.2.1.10 Pipe Stiffness. Pipe stiffness was measured using the UTM equipped with parallel plates according to ASTM D2412. Three 6 in. long specimens were cut from the liner using a table saw and positioned in between the plates; the load was applied at 0.50 in./min. According to ASTM D2412, the deformation of the pipe was limited to 5% of the inside diameter and the test results are presented in Table C-17. The average value was found to be 36.5 lbf/in./in.

Table C-17. Denver Irving St.: Pipe Stiffness Test Results

Sample	Peak Load, lb	Pipe Stiffness at 5% Deformation of Inside Diameter (lbf/in./in.)
1	14.18	36.87
2	14.55	37.84
3	13.41	34.87
Average	14.05	36.53

C.2.1.11 ESCR Testing. Ten specimens each 1.5 in. long, 0.5 in. wide and 0.0775 in. thick were cut from the liner following the condition "C" mentioned in ASTM D1693. This low thickness was achieved by placing the specimen on a belt sander. A notch of 0.015 in. was grooved in the middle of the specimen using a specific pressing tool. Next, all specimens were bent and slid into a holder. The holder with all of the specimens was submerged in reagent (Igepal CO-630) in a test tube and the test tube was kept in an oven at 212°F for 8 days (192 hr) (see Figure C-23) as per the requirement from ASTM D3350.

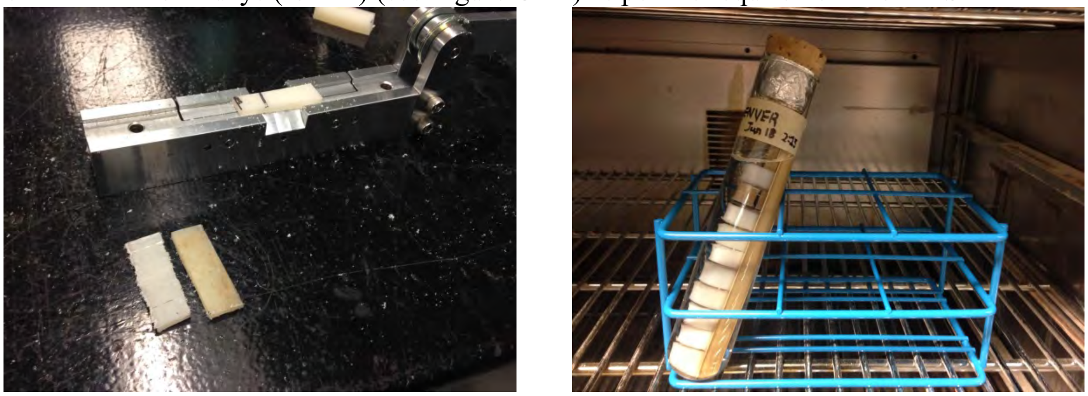

Figure C-23. Preparation of Test Specimen (left) and Specimens Inside the Oven (right)

Later, the specimens were taken out of the test tube and checked for any cracks visible by the naked eye. No cracks were found and the sample passed the limitation of maximum failure percent of 20% as per the standard ASTM D3350 (see Figure C-24).

Figure C-24. Specimens after the Test

C.2.2 Miami 114th St Sample: A 15-Year Old Deform-Reform HDPE Liner in an 8 in. Clay Pipe. The sample was recovered at Basin 698 between MH#93 and MH#94 at SW 114th Court Cross Street and SW 207th Drive, Miami, Florida on May 15, 2013. The host pipe and liner information are provided in Table C-18. The host pipe depth was approximately 4 to 5 ft.

Table C-18. Miami 114th St.: Host Pipe and Liner Information

Host pipe	Clay pipe 8 in.
Liner Thickness	Approximately 8 mm
Liner Type	Deform-reform HDPE
Year of Installation	1998
Liner Vendor/Supplier	Unknown

C.2.2.1 ***Visual Inspection.*** The HDPE sample was found in good condition. No cracks were visible on the pipe. There was no remaining soil accumulation on the samples when received at the TTC laboratory. The retrieved samples are shown in Figure C-25 in the field and prior to testing.

Figure C-25. Miami 114th St.: Images of the HDPE Liner Section in the Field (Left) and Prior to Testing (Right)

C.2.2.2 ***Annular Gap.*** Annular gaps were measured at the site after the sample was exhumed and were recorded as 0.50 in. (12.7 mm) at the 12:00 position and 1 in. (25 mm) at the 1:30 position. However, the cracking and distortion of the host pipe that can be seen in Figure C-25 indicate that the measured values may not be meaningful. The sample was received at TTC without any host pipe attached to it and therefore, no annular readings were recorded.

C.2.2.3 ***Environmental Service Conditions.*** External soil samples were not collected for this sample. Waste material (2 g) from the inside of the sample was collected and blended with 200 mL of distilled water for a pH measurement. The pH value was found to be between 7 and 8. No materials were collected at the outer side of the sample.

C.2.2.4 ***Ovality.*** The sample's ovality was measured using software as described in Section C.1.1.4. The maximum diameter measured ovality was 6.66%, while ovality was 5.82% when calculated based on the minimum diameter. The higher ovality value was used as the representative value. The tracing of the inner circumference of the liner and the resulting diameter measurements are shown in Figure C-26. The detailed ovality calculation is shown in Table C-19.

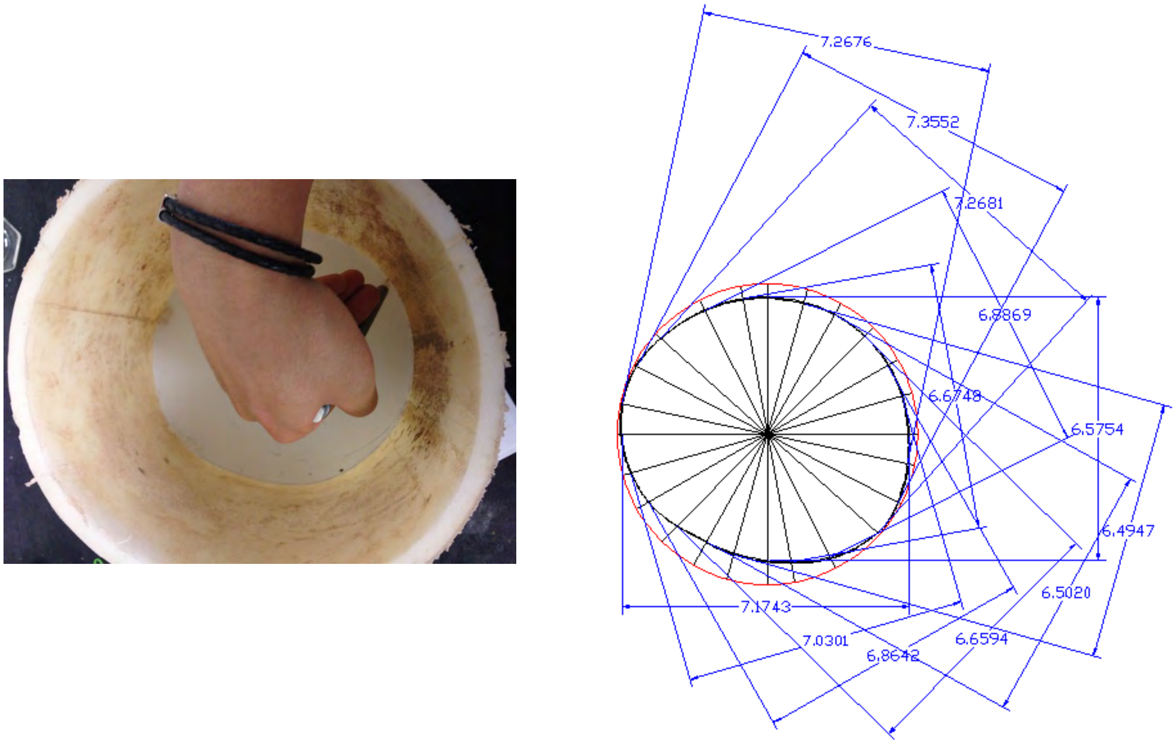

Figure C-26. Miami 114th St.: Tracing the Liner Shape (Left) and Ovality of the Liner (Right)

Table C-19. Miami 114th St.: Ovality Calculation

Measured Diameter (in.)	Diameter (in.)			Ovality (%) Based on	
	Maximum	Minimum	Mean	Max Dia.	Min. Dia.
7.2676	7.3552	6.4947	6.90	6.657	5.82
7.3552					
7.2681					
6.8869					
6.6747					
6.5754					
6.4947					
6.5020					
6.6594					
6.8642					
7.0301					
7.1743					

C.2.2.5 ***Thickness.*** A total of 120 readings were taken on 20 1 in. × 1 in. samples cut from different locations of the specimen. The thickness was measured randomly using a micrometer with a resolution of ±0.0025 mm. The average thickness of the liner was found to be 8.33 mm ± 0.11 mm as shown in Figure C-27. The design thickness was unavailable; therefore, no comparison was made.

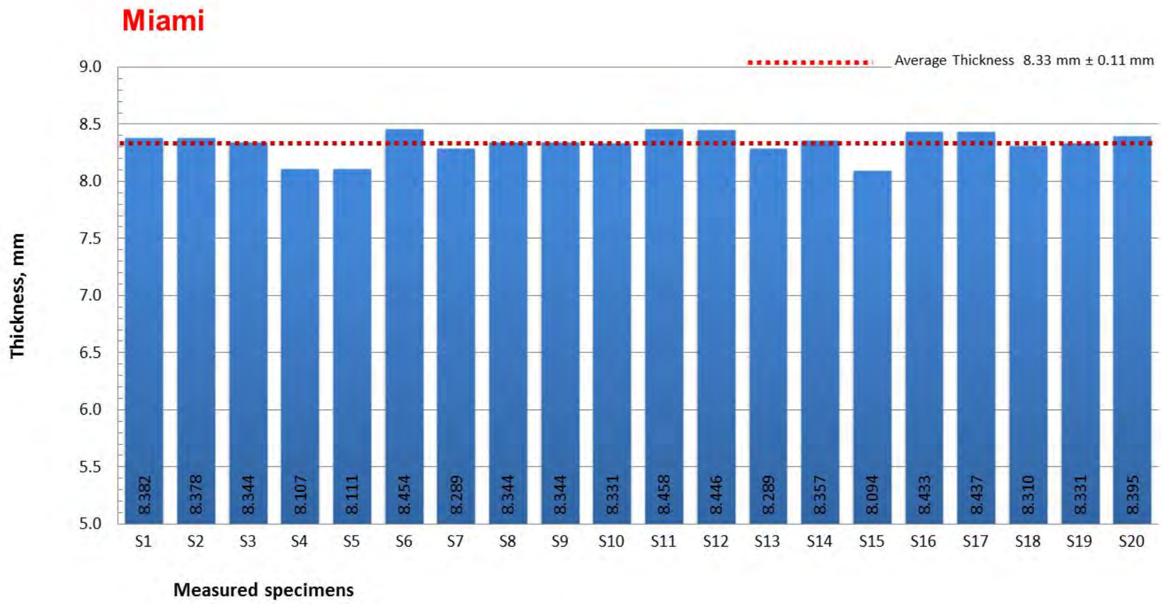

Figure C-27. Miami 114th St.: Average Thickness of the Liner Sample

C.2.2.6 Specific Gravity. The specific gravity of the liner was measured on 20 1 in. × 1 in. samples in accordance with ASTM D792. The specific gravity values are shown in Figure C-28. The obtained values were between 0.91 and 0.95. The average specific gravity was 0.94 ± 0.01.

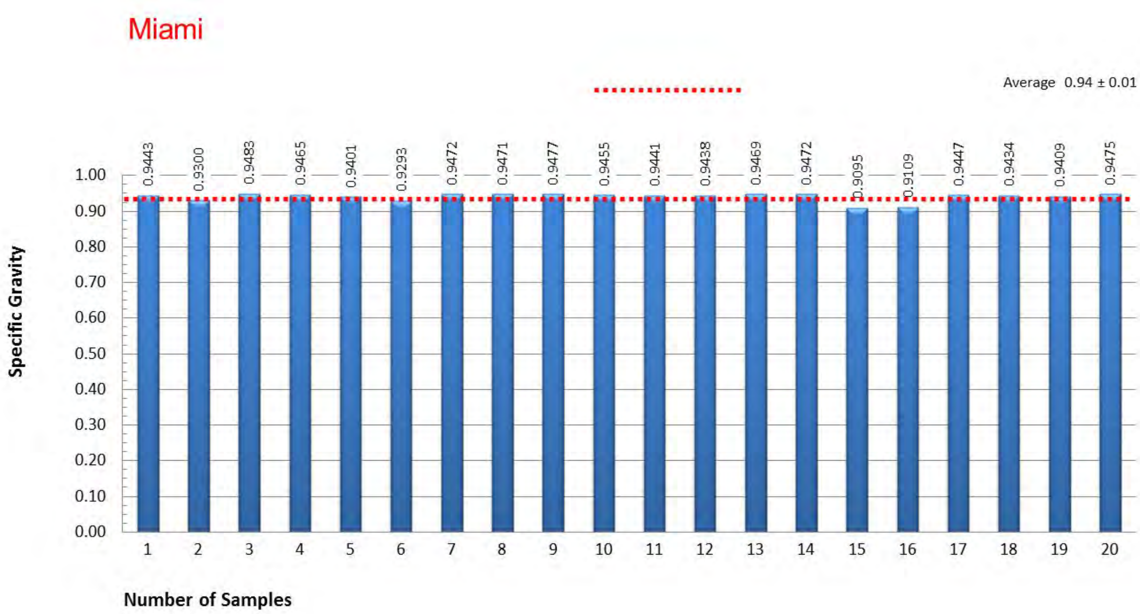

Figure C-28. Miami 114th St.: Specific Gravity of the Liner

C.2.2.7 Tensile Test (ASTM D638). Specimens, as described in ASTM D638, were cut from the retrieved HDPE liner using a router and a band saw. A total of 15 specimens were prepared and tested. The sides of the specimens were smoothed using a grinder. The water jet cutter could not be used as the liner was curved and too small to be mounted inside the cutting board. The tensile test results are presented in Figure C-29 and Table C-20. The average tensile strength was 3,053 ± 92 psi and the average tensile modulus was 142,479 ± 15,583 psi. The elongation at break varied from around 24% to more than 70%.

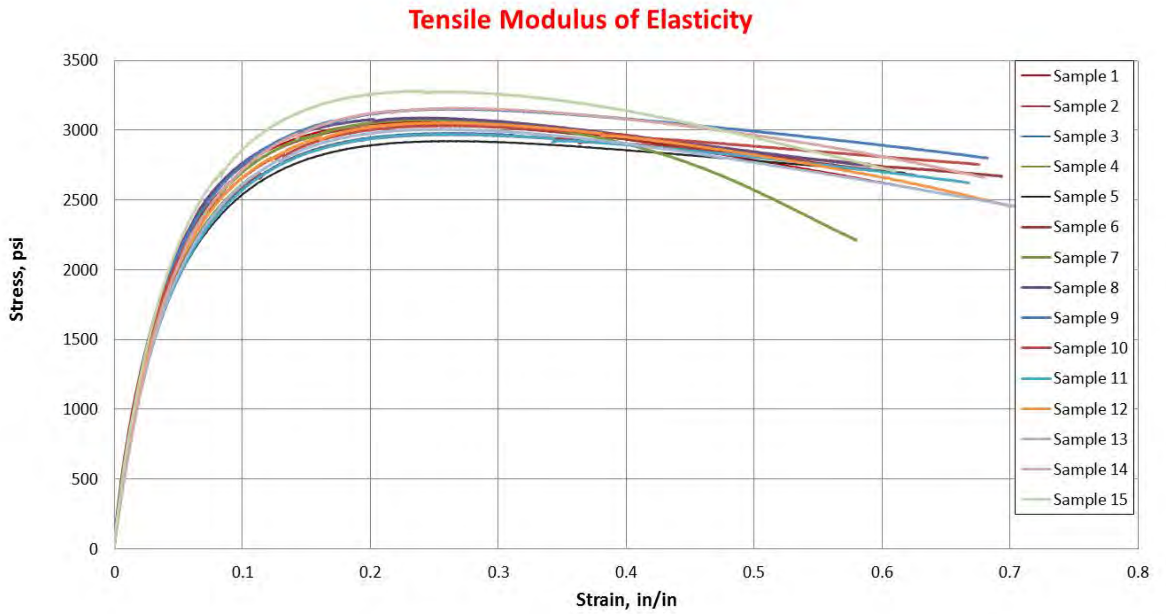

Figure C-29. Miami 114th St.: Stress – Strain Curves from Tensile Testing

Table C-20. Miami 114th St.: Tensile Test Results

Sample ID	Area (in.^{2})	Peak Load (lb)	Peak Stress (psi)	Tensile Modulus (psi)
1	0.1653	505.99	3,061	164,971
2	0.1608	489.33	3,043	156,995
3	0.1725	514.50	2,983	161,175
4	0.1705	506.79	2,972	144,332
5	0.1762	515.34	2,925	154,240
6	0.1645	488.76	2,973	125,518
7	0.1502	462.28	3,078	156,063
8	0.1600	494.37	3,090	154,000
9	0.1557	491.17	3,155	131,150
10	0.1529	463.98	3,035	150,076
11	0.1553	461.87	2,974	129,141
12	0.1574	480.93	3,055	126,534
13	0.1571	472.64	3,009	116,614
14	0.1581	499.50	3,159	125,219
15	0.1512	496.40	3,283	141,166
Average		485.59	3,053	142,479
St. Dev		18.03	92	15,583

C.2.2.8 Flexural Test (ASTM D790). Specimens, as described in ASTM D790, were cut from the retrieved liner using a router and a band saw. A total of 15 specimens were prepared and tested. The sides of the specimens were smoothed using a grinder. The water jet cutter could not be used as the liner was curved and too small to be mounted inside the cutting board. The flexure test results are presented graphically in Figure C-30 and are listed in Table C-21. The area values (Column 2 of Table C-21) were automatically back calculated by the software when the peak load was reached. The average flexural modulus was 103,645 ± 4,015 psi and the average flexure strength was 3,154 ± 113psi.

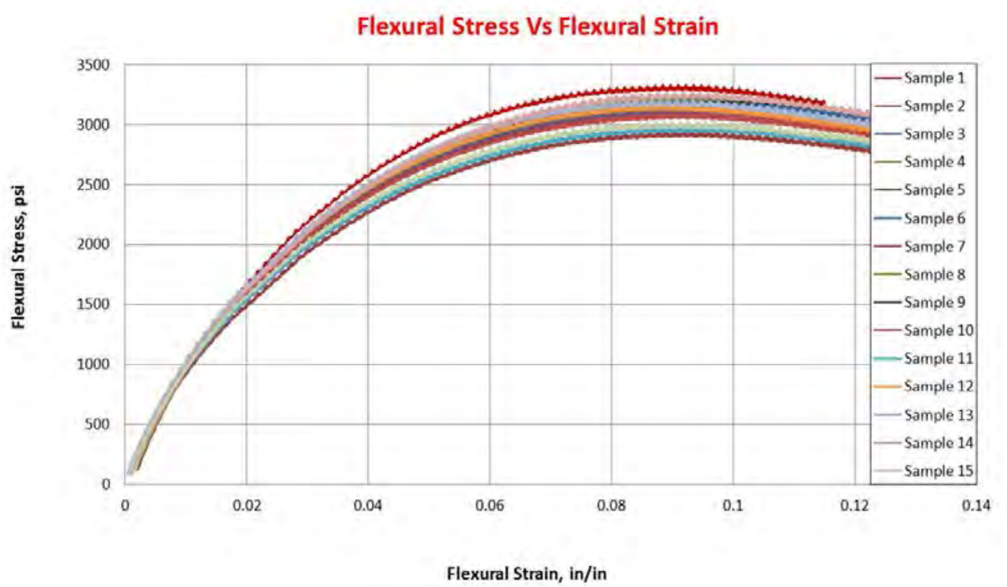

Figure C-30. Miami 114th St.: Stress – Strain Curves from Flexural Testing

Table C-21. Miami 114th St.: Flexure Test Results

Sample ID	Area (in.^{2})	Peak Load (lb)	Peak Stress (psi)	Flexural Modulus (psi)
1	0.0079	26.42	3,344	106,983
2	0.0083	26.10	3,145	95,692
3	0.0088	28.29	3,215	101,799
4	0.0087	28.07	3,226	110,277
5	0.0089	28.75	3,230	103,045
6	0.0100	31.85	3,185	107,648
7	0.0100	29.29	2,929	96,785
8	0.0100	31.43	3,143	105,118
9	0.0096	30.17	3,143	100,583
10	0.0102	31.69	3,107	106,432
11	0.0103	30.68	2,979	100,786
12	0.0102	32.35	3,172	106,738
13	0.0100	32.19	3,219	105,333
14	0.0103	33.72	3,274	104,230
15	0.0098	29.42	3,002	103,234
Average		30.03	3,154	103,645
St. Dev		2.24	113	4,015

C.2.2.9 ***Surface Hardness.*** A Shore Type D durometer (ASTM D2240) was used to determine the hardness of the liner samples. Samples (1 in. × 1 in.) were cut from the retrieved polyethylene liner with a band saw. A total of 400 readings were taken on the inner and outer surfaces of the liner specimens. The average recorded hardness values are shown in Figure C-31. The hardness of the surface exposed to the flow (inner surface) was found to be slightly lower than that of the protected (outer) surface.

Figure C-31. Miami 114th St.: Shore D Hardness Readings for the Liner's Inner and Outer Surfaces

C.2.2.10 ***Pipe Stiffness.*** Pipe stiffness was measured using the UTM equipped with parallel plates according to ASTM D2412. Three 6 in. long specimens were cut from the liner using a table saw; the load was applied at 0.50 in./min. According to ASTM D2412, the deformation of the pipe was limited to 5% of the inside diameter. The test results are shown in Table C-22. The average stiffness was found to be 43.1 lbf/in./in.

Table C-22. Miami 114th Street: Pipe Stiffness Test Results

Sample	Peak Load, lb	Pipe Stiffness at 5% Deformation of Inside Diameter (lbf/in./in.)
1	16.00	44.38
2	15.40	42.70
3	15.17	42.07
Average	15.52	43.05

C.2.2.11 ***ESCR Testing.*** Ten specimens each 1.5 in. long, 0.5 in. wide and 0.0775 in. thick were cut from the liner following the condition "C" mentioned in ASTM D1693. This low thickness was achieved by placing the specimen on a belt sander. A notch of 0.015 in. was grooved in the middle of the specimen using a specific pressing tool. Next, all specimens were bent and slid into a holder. Later, the holder with all of the specimens was submerged in the reagent (Igepal CO-630) in a test tube (see Figure C-32) and the test tube was kept in an oven at 212°F for 8 days (192 hr) as per the requirement from ASTM D3350.

Figure C-32. Specimens inside the Reagent

Following the test period, the specimens were taken out of the test tube and checked for any cracks visible by the naked eye. No cracks were found and the sample passed the limitation of maximum failure percent of 20% as per ASTM D3350 (see Figure C-33).

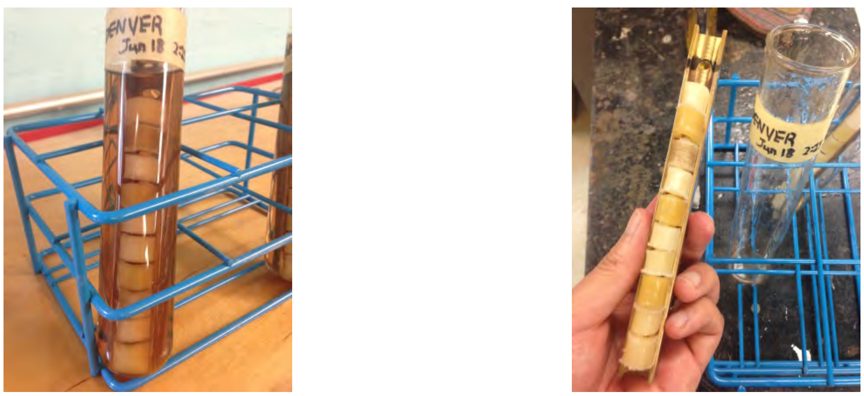

Figure C-33. Specimens after the Test

C.2.3 Nashville Danby Dr. Sample: A 19-Year Old Deform-Reform HDPE Liner in an 8 in. Concrete Pipe. The sample was recovered at 4828 Danby Drive, Nashville, Tennessee on September 22, 2013. The host pipe and liner information are shown in Table C-23. The host pipe was reported to be at depth of 4 to 5 ft below grade.

Table C-23. Nashville Danby Dr.: Host Pipe and Liner Information

Host pipe	Concrete Pipe 8 in. inner diameter
Liner Thickness	Approximately 7 mm
Liner Type	Deform-reform HDPE
Year of Installation	1994
Liner Vendor/ Supplier	Not known

C.2.3.1 Visual Inspection. The HDPE sample with the host pipe was found in good condition. The retrieved sample is shown in Figure C-34.

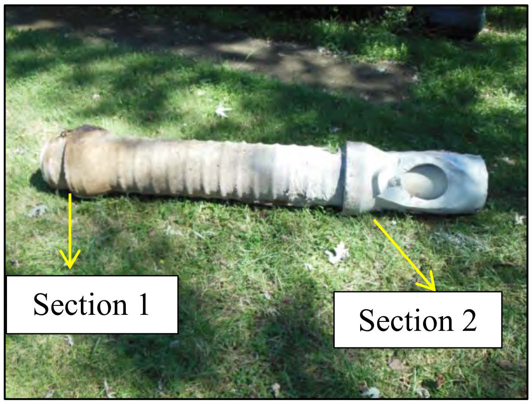

Figure C-34. Nashville Danby Dr.: Images of the HDPE Liner Section after Retrieval (left) and Taken in the TTC Laboratory (right)

C.2.3.2 Annular Gap. The annular gap was measured using a feeler gauge. Eight readings were taken on each section of the liner and are shown in Table C-24. Readings taken at Section 2 may not be representative because that end of the host pipe was broken.

C.2.3.3 Environmental Service Conditions. Soil samples were not collected. Waste material (2 g) was collected on the inside and outside of the sample and blended with 200 mL of distilled water to make the pH measurement. The outside pH was found to be 6 to 7 while the inside pH was slightly lower at 5 to 6.

C.2.3.4 Ovality. The sample's ovality was measured using software as described in Section C.1.1.4. The maximum diameter measured ovality was 6.12%, while ovality was 6.68% when calculated based on the minimum diameter. The higher ovality value was used as the representative value. The diameter measurements are shown in Figure C-35. The detailed ovality calculation is shown in Table C-25.

Table C-24. Nashville Danby Dr. Annular Gap Measurement

Location	Gap Measured on	
	Section 1 (in.) (mm)	Section 2 (in.) (mm)
12:00	0.03 (0.8)	0.13 (3.3)
1:30	0.44 (11.2)	0.06 (1.5)
3:00	0.17 (4.3)	0.06 (1.5)
5:00	0.08 (2.0)	N/A
6:00	0.19 (4.8)	0.44 (11.2)
7:30	0.00 (0.0)	0.50 (12.7)
9:00	0.09 (2.3)	0.50 (12.7)
11:00	0.09 (2.3)	0.50 (12.7)

N/A = Not Available

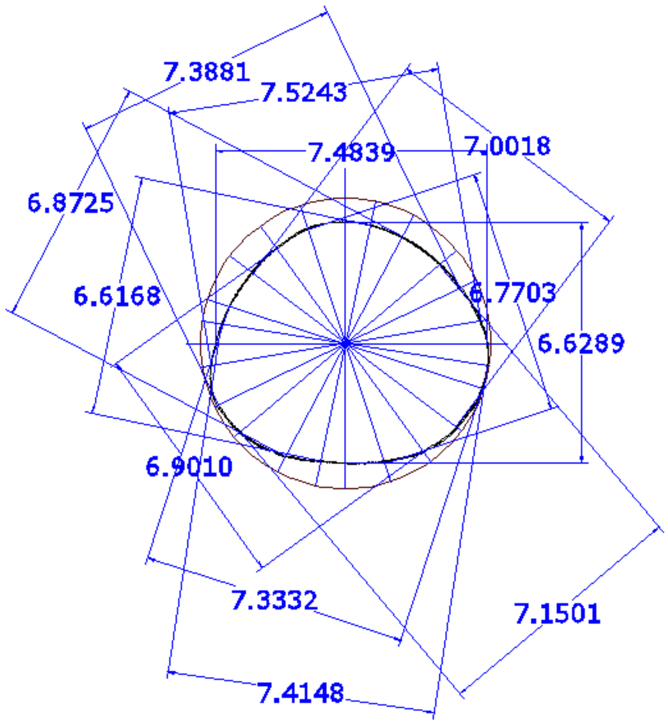

Figure C-35. Nashville Danby Dr.: Ovality of the Liner

C.2.3.4 Thickness. A total of 120 readings were taken on 20 1 in. × 1 in. samples cut from different locations of the specimen. The thickness was measured randomly using a micrometer with a resolution of ±0.0025 mm. The average thickness of the liner was found to be 6.85 mm ± 0.03 mm as shown in Figure C-36. The design thickness was unavailable; therefore, no comparison was made.

Table C-25. Nashville Danby Dr.: Ovality Calculation

Measured Diameter (in.)	Diameter (in.)			Ovality (%) Based on	
	Maximum	Minimum	Mean	Max Dia.	Min. Dia.
7.3881	7.5243	6.6168	7.09	6.118	6.68
7.5243					
7.4839					
7.0018					
6.7703					
6.6289					
7.1501					
7.4148					
7.3332					
6.9010					
6.6168					
6.8725					

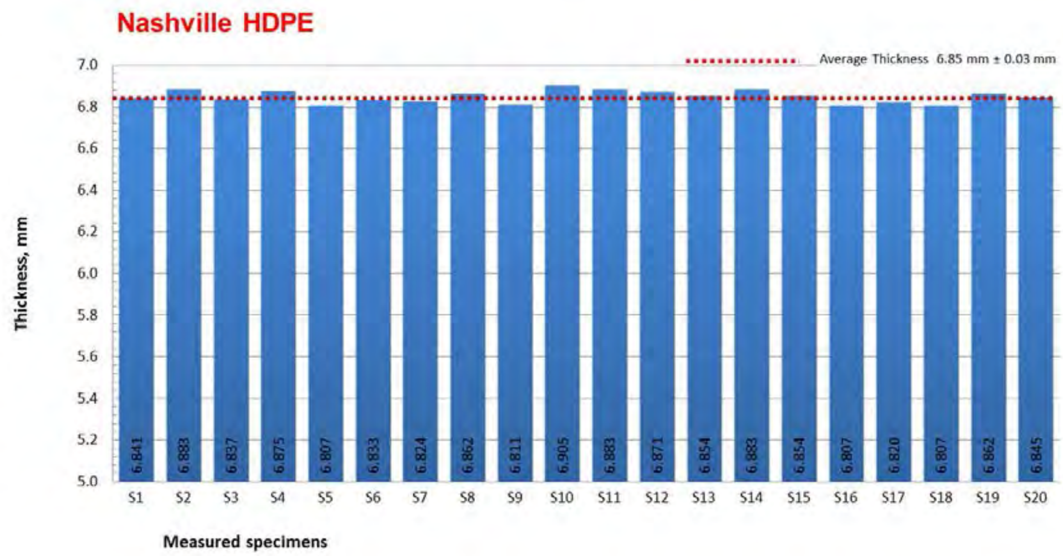

Figure C-36. Nashville Danby Dr.: Average Thickness of the Liner Sample

C.2.3.6 Specific Gravity. The specific gravity of the liner was measured on 20 1 in. × 1 in. samples in accordance with ASTM D792. The specific gravity values are shown in Figure C-37. The obtained values were between 0.93 and 0.96. The average specific gravity was 0.94 ± 0.01.

Figure C-37. Nashville Danby Dr.: Specific Gravity of the Liner

C.2.3.7 Tensile Test (ASTM D638). Specimens, as described in ASTM D638, were cut from the retrieved HDPE liner using a router and a band saw. A total of 15 specimens were prepared and tested. The sides of the specimens were smoothed using a grinder. The water jet cutter could not be used as the liner was curved and too small to be mounted inside the cutting board. The tensile test results are presented in Figure C-38 and Table C-26. The average tensile strength was 2,974 ± 149 psi and the average tensile modulus was 162,567 ± 19,705 psi. The elongation at the break of Samples 5 and 8 was found to be lower in comparison to the other samples, but the reason is unknown since no weak point or area was found on the sample prior to the test.

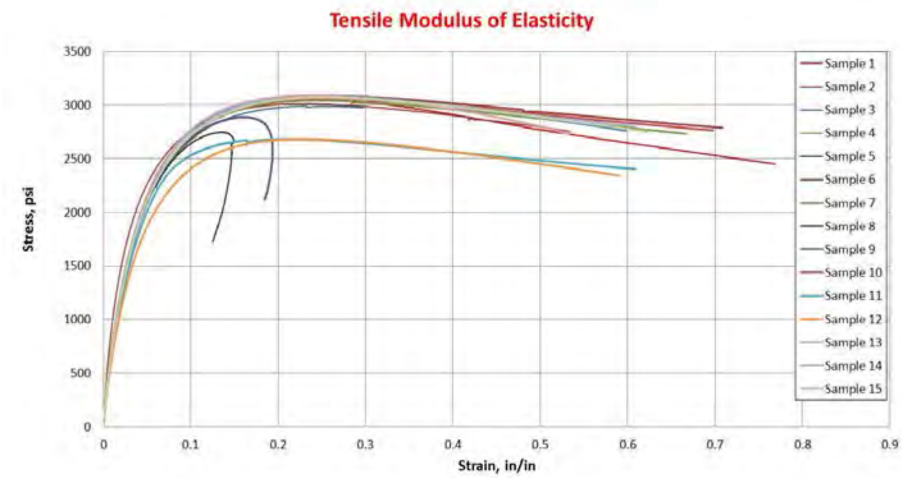

Figure C-38. Nashville Danby Dr.: Stress – Strain Curves from Tensile Testing

Table C-26. Nashville Danby Dr.: Tensile Test Results

Sample ID	Area (in.^{2})	Peak Load (lb)	Peak Stress (psi)	Tensile Modulus (psi)
1	0.1512	462.69	3,060	164,985
2	0.1503	453.32	3,016	228,167
3	0.1526	456.92	2,994	168,306
4	0.1625	484.83	2,984	153,415
5	0.1442	396.53	2,750	150,754
6	0.1473	455.11	3,090	153,601
7	0.1412	430.34	3,048	169,333
8	0.1377	398.05	2,891	149,343
9	0.1397	432.07	3,093	166,247
10	0.1543	473.26	3,067	165,247
11	0.1493	401.17	2,687	162,792
12	0.1385	371.95	2,686	144,757
13	0.1444	445.87	3,088	152,842
14	0.1469	454.29	3,093	155,418
15	0.1438	442.20	3,075	153,300
Average		437.24	2,974	162,567
St. Dev		32.07	149	19,705

C.2.3.8 Flexural Test (ASTM D790). Specimens, as described in ASTM D790, were cut from the retrieved liner using a router and a band saw. A total of 15 specimens were prepared and tested. The sides of the specimens were smoothed using a grinder. A water jet cutter could not be used as the liner was curved and too small to be mounted inside the cutting board. The flexure test results are presented graphically in Figure C-39 and are listed in Table C-27. The area values (Column 2 of Table C-27) were automatically back calculated by the software when the peak load was reached. The average flexural modulus was 108,126 ± 3,386 psi and the average flexural strength was 3,133 ± 75 psi.

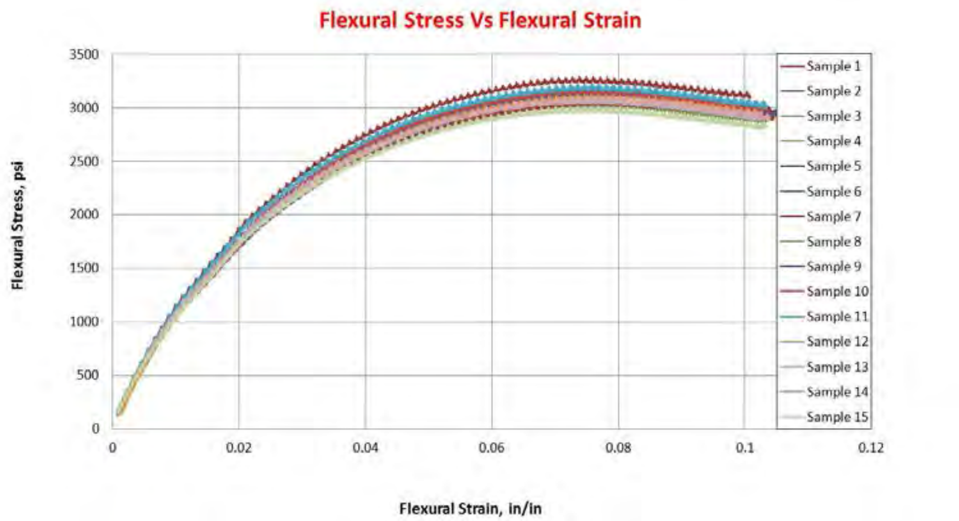

Figure C-39. Nashville Danby Dr.: Stress – Strain Curves from Flexural Testing

Table C-27. Nashville Danby Dr.: Flexure Test Results

Sample ID	Area (in.^{2})	Peak Load (lb)	Peak Stress (psi)	Flexural Modulus (psi)
1	0.0072	22.37	3,107	111,438
2	0.0068	22.50	3,309	115,114
3	0.0068	21.73	3,196	109,535
4	0.0071	21.72	3,059	104,180
5	0.0071	22.07	3,108	106,290
6	0.0072	22.90	3,181	107,101
7	0.0068	20.83	3,063	105,852
8	0.0067	20.75	3,097	106,318
9	0.0073	22.69	3,108	106,001
10	0.0072	22.80	3,167	113,377
11	0.0068	22.00	3,235	110,866
12	0.0070	21.85	3,121	107,794
13	0.0067	20.88	3,116	108,622
14	0.0071	22.12	3,115	106,530
15	0.0067	20.18	3,012	102,867
Average		21.83	3,133	108,126
St. Dev		0.83	75	3,385

C.2.3.9 Surface Hardness. A Shore Type D durometer (ASTM D2240) was used to determine the hardness of the liner samples. Samples (1 in. × 1 in.) were cut from the retrieved HDPE liner with a band saw. A total of 400 readings were taken on the inner and outer surfaces of the liner specimens. The average recorded hardness values are shown in Figure C-40. The hardness of the surface exposed to the flow (inner surface) was found to be slightly lower than that of the protected (outer) surface.

Figure C-40. Nashville Danby Dr.: Shore D Hardness Readings for the Liner's Inner and Outer Surfaces

C.2.3.10 Pipe Stiffness. Pipe stiffness was measured using the UTM equipped with parallel plates according to ASTM D2412. Three 6 in. long specimens were cut from the liner using a table saw; the load was applied at 0.50 in./min. According to ASTM D2412, the deformation of the pipe was limited to 5% of the inside diameter. The test results are shown in Table C-28. The average value was found to be 31.3 lbf/in./in.

Table C-28. Nashville Danby Dr.: Pipe Stiffness Test Results

Sample	Peak Load, lb	Pipe Stiffness at 5% Deformation of Inside Diameter (lbf/in./in.)
1	12.84	34.68
2	10.83	29.25
3	11.08	29.92
Average	11.58	31.28

C.2.3.11 ESCR Testing. Ten specimens each 1.5 in. long, 0.5 in. wide and 0.0775 in. thick were cut from the liner following the condition "C" mentioned in ASTM D1693. This low thickness was achieved by placing the specimen on a belt sander. A notch of 0.015 in. was grooved in the middle of the specimen using a specific pressing tool. All specimens were bent and slid into a holder. Later, the holder with all the specimens was submerged in reagent (Igepal CO-630) in a test tube and the test tube was kept in an oven at 212°F for 8 days (192 hr) (Figure C-41) as per the requirement from ASTM D3350.

Figure C-41. Igepal CO-630 Reagent (left) and Specimens inside the Oven (right)

Later, the specimens were taken out of the test tube and checked for any cracks visible by the naked eye. No cracks were found and the sample passed the limitation of maximum failure percent of 20% as per ASTM D3350 (Figure C-42).

Figure C-42. Specimens after the Test

C.3 Sliplining (Polyethylene Pipe) Samples

C.3.1 Houston Greiner Dr. Sample: An 18-year Old Green Polyethylene Sliplined in an 8 in. Non-reinforced Concrete Pipe. The sample was recovered between manholes 63 and 64 on Greiner Drive, Houston, Texas on March 14, 2013. The host pipe and liner information are shown in Table C-29. Field information was not available for this liner.

Table C-29. Houston Greiner Dr.: Host Pipe and Liner Information

Host pipe	Non-reinforced concrete pipe 8 in.
Liner Thickness	0.30 inch
Liner Type	Slipliner using green colored polyethylene pipe
Year of Installation	1995
Liner Vendor/Supplier	Unknown

C.3.1.1 Visual Inspection. The polyethylene sample came in good condition and the thickness was constant along the length and circumference of the sample. The sample as received at the TTC laboratory is shown in Figure C-43.

Figure C-43. Houston Greiner Dr.: Image of the PE Liner Section at the TTC Laboratory

C.3.1.2 Annular Gap. The sample was received without the host pipe and no annular measurement was recorded and received from the site.

C.3.1.3 Environmental Service Conditions. Soil samples were not collected. Waste material (2 g) was collected at the inside of the sample and blended with 200 mL of distilled water for the pH measurement. The pH was found to be approximately 8 to 8.5. No measurement was possible for the outside of the sample.

C.3.1.4 Ovality. The sample's ovality was measured using software as described in Section C.1.1.4. The resulting diameter measurements are shown in Figure C-44. The detailed ovality calculation is shown in Table C-30. Based on the maximum diameter measured, the ovality was 1.72%, while the ovality was 1.76% when calculated based on the minimum diameter. The higher ovality value was used as the representative value.

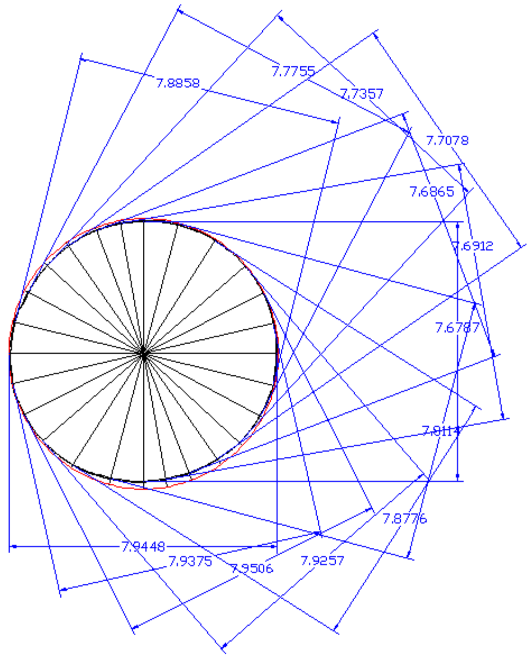

Figure C-44. Houston Greiner Dr.: Ovality of the Liner

Table C-30. Houston Greiner Dr.: Ovality Calculation

Measured Diameter (in.)	Diameter (in.)			Ovality (%) Based on	
	Maximum	Minimum	Mean	Max Dia.	Min. Dia.
7.8858	7.9506	7.6787	7.8161	1.721	1.757
7.7755					
7.7357					
7.7078					
7.6865					
7.6912					
7.6787					
7.8114					
7.8776					
7.9257					
7.9506					
7.9375					
7.9448					

C.3.1.5 Thickness. A total of 120 readings were taken on 20 1 in. × 1 in. samples cut from different locations of the specimen. The thickness was measured randomly using a micrometer with a resolution of ±0.0025 mm. The average thickness of the liner was found to be 7.57 mm ± 0.09 mm as shown in Figure C-45. The design thickness was not available; therefore, no comparison was made.

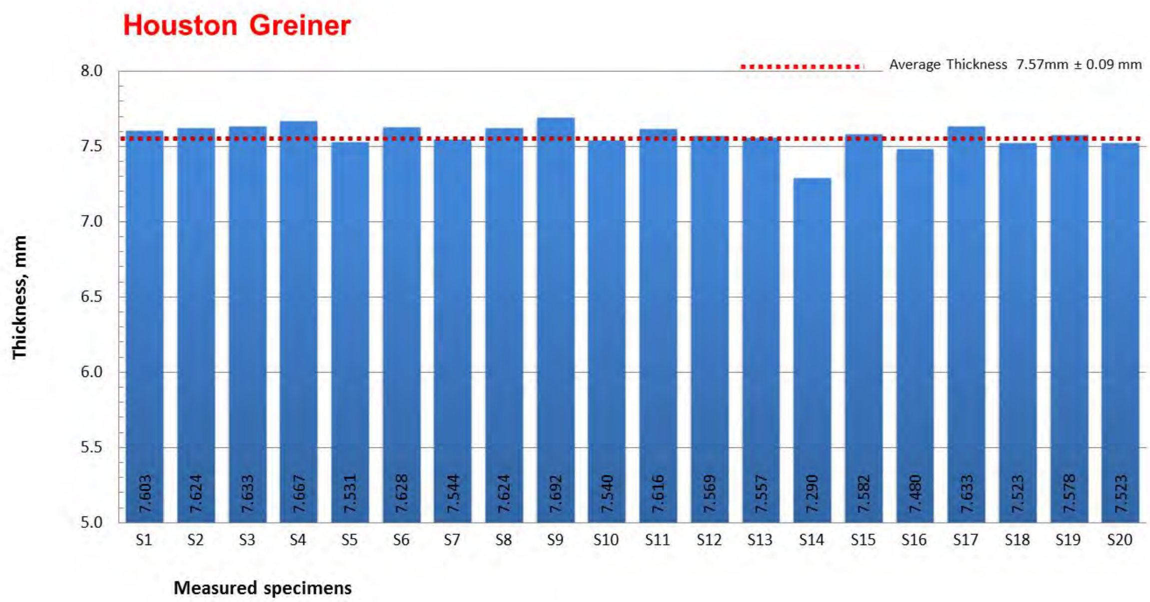

Figure C-45. Houston Greiner Dr.: Average Thickness of the Liner Sample

C.3.1.6 Specific Gravity. The specific gravity of the liner was measured on 20 1 in. × 1 in. samples in accordance with ASTM D792. The specific gravity values are shown in Figure C-46. The obtained values were between 0.924 and 0.949. The average specific gravity was 0.94 ± 0.01.

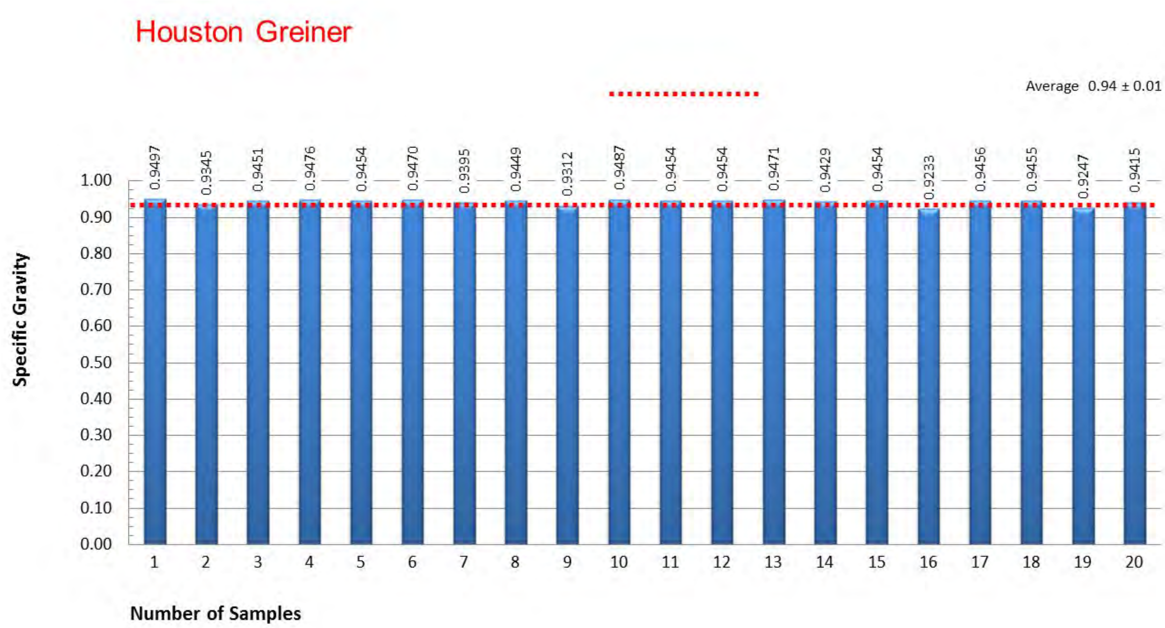

Figure C-46. Houston Greiner Dr.: Specific Gravity of the Liner

C.3.1.7 Tensile Test (ASTM D638). Specimens, as described in ASTM D638, were cut from the retrieved polyethylene liner using a router and a band saw. A total of 14 specimens were prepared and tested. The sides of the specimens were smoothed using a grinder. The water jet cutter could not be used as the liner was curved and too small to be mounted inside the cutting board. The tensile test results are presented in Figure C-47 and Table C-31. The average tensile strength was 2,979 ± 239 psi and the average tensile modulus was 137,875 ± 81,053 psi.

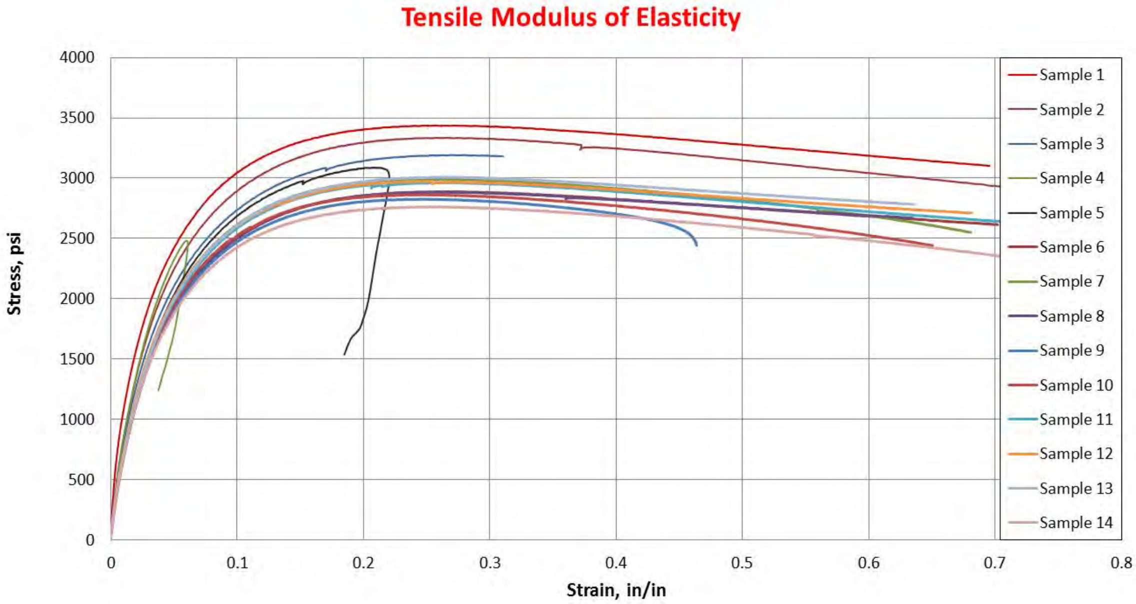

Figure C-47. Houston Greiner Dr.: Stress – Strain Curves from Tensile Testing

Table C-31. Houston Greiner Dr.: Tensile Test Results

Sample ID	Area (in.^{2})	Peak Load (lb)	Peak Stress (psi)	Tensile Modulus (psi)
1	0.1489	511.87	3,438	447,587
2	0.1444	481.65	3,336	195,890
3	0.1529	488.13	3,192	183,295
4	0.1697	421.26	2,482	199,023
5	0.1788	552.08	3,088	143,327
6	0.1601	462.55	2,889	154,311
7	0.1595	477.53	2,994	136,706
8	0.1496	431.69	2,886	151,878
9	0.1588	449.04	2,828	142,051
10	0.1650	472.44	2,863	151,199
11	0.1576	467.26	2,965	125,190
12	0.1485	441.78	2,975	131,959
13	0.1588	477.95	3,010	151,763
14	0.1739	480.66	2,764	191,900
Average		472.56	2,979	137,875
St. Dev		33.10	239	81,053

C.3.1.8 Flexural Test (ASTM D790). Specimens, as described in ASTM D790, were cut from the retrieved liner using a router and a band saw. A total of 15 specimens were prepared and tested. The sides of the specimens were smoothed using a grinder. The water jet cutter could not be used as the liner was curved and too small to be mounted inside the cutting board. The flexure test results are presented graphically in Figure C-48 and are listed in Table C-32. The average flexural modulus was 100,636 ± 4,728 psi and the average flexural strength was 3,152 ± 116 psi. The bending modulus reaches the classification limits of Class 4 from the ASTM D3350, but no material information was available on this liner.

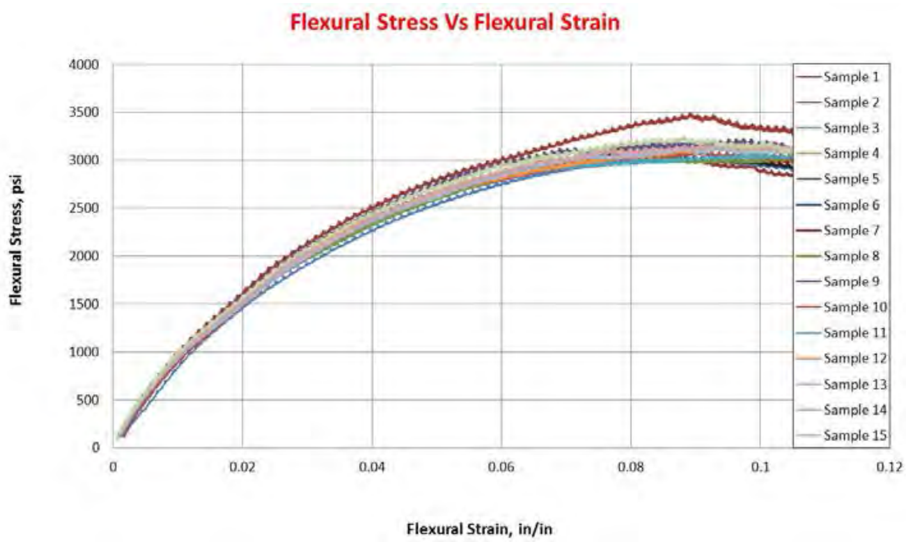

Figure C-48. Houston Greiner Dr.: Stress – Strain Curves from Flexural Testing

Table C-32. Houston Greiner Dr.: Flexure Test Results

Sample ID	Area (in.^{2})	Peak Load (lb)	Peak Stress (psi)	Flexural Modulus (psi)
1	0.0076	23.36	3,074	109,133
2	0.0073	22.35	3,062	101,058
3	0.0076	23.10	3,039	94,260
4	0.0074	23.54	3,181	103,207
5	0.0075	22.93	3,057	106,024
6	0.0085	27.12	3,191	101,023
7	0.0080	27.96	3,495	106,383
8	0.0084	25.54	3,040	96,367
9	0.0080	25.66	3,208	104,519
10	0.0080	24.96	3,120	92,962
11	0.0083	25.44	3,065	100,327
12	0.0083	26.27	3,165	96,736
13	0.0086	27.26	3,170	97,300
14	0.0081	25.87	3,194	97,680
15	0.0083	26.81	3,230	102,570
Average		25.21	3,152	100,636
St. Dev		1.77	116	4,728

C.3.1.9 Surface Hardness. A Shore Type D durometer (ASTM D2240) was used to determine the hardness of the liner samples. Samples (1 in. × 1 in.) were cut from the retrieved polyethylene liner with a band saw. A total of 400 readings were taken on the inner and outer surfaces of the liner specimens. The average recorded hardness values are shown in Figure C-49. The hardness of the surface exposed to the flow (inner surface) was found to be slightly lower than that of the protected (outer) surface.

Figure C-49. Houston Greiner Dr.: Shore D Hardness Readings for the Liner's Inner and Outer Surfaces

C.3.1.10 Pipe Stiffness. Pipe stiffness was measured using the UTM equipped with parallel plates according to ASTM D2412. Three 6 in. long specimens were cut from the liner using a table saw; the load was applied at 0.50 in./min. According to ASTM D2412, the deformation of the pipe was limited to 5% of the inside diameter. The test results are shown in Table C-33. The average value was found to be 41.2 lbf/in./in.

Table C-33. Houston Greiner Dr.: Pipe Stiffness Test Results

Sample	Peak Load, lb	Pipe Stiffness at 5% Deformation of Inside Diameter (lbf/in./in.)
1	15.11	44.89
2	13.54	40.22
3	12.94	38.46
Average	13.86	41.19

C.3.2 Houston Norton: A Black Polyethylene Slipline Sample in an 8 in. Concrete Host Pipe. The sample was recovered between manholes 088 and 091 on Friendship/Norton Drive, Houston, Texas on March 14, 2013. The host pipe and liner information are provided in Table C-34.

Table C-34. Houston Norton: Host Pipe and Liner Information

Host pipe	Non-reinforced concrete pipe 8 in. installed between 1953-1956
Liner Thickness	Approximately 8 mm
Liner Type	Black polyethylene pipe
Year of Installation	Unknown but probably at least 15 years old
Liner Vendor/Supplier	Unknown

C.3.2.1 Visual Inspection. The black polyethylene slipline sample was found in good condition. No cracks were visible on the pipe. There was no evidence of soil accumulation on the samples when received at the TTC laboratory. The retrieved sample is shown in Figure C-50.


Figure C-50. Houston – Norton Dr.: Images of the Black Polyethylene Slipliner Section Prior to Testing

C.3.2.2 Annular Gap. Annular gaps were not measured at the site on this sample and the sample was received at the TTC without any host pipe attached to it; therefore, no annular gap readings were obtained.

C.3.2.3 Environmental Service Conditions. No soil samples were collected. Waste material (2 g) was collected from the inside of the sample and stirred in 200 mL of distilled water to allow pH testing. The inside pH value was 7 to 8. No test could be conducted for the outside value.

C.3.2.4 Ovality. The sample's ovality was measured using software as described in Section C.1.1.4. The pipe ready for tracing and the resulting diameter measurements are shown in Figure C-51. The detailed ovality calculation is shown in Table C-35. Based on the maximum diameter measured, the ovality was 2.83%, while the ovality was 3.33% when calculated based on the minimum diameter. The higher ovality value was used as the representative value.

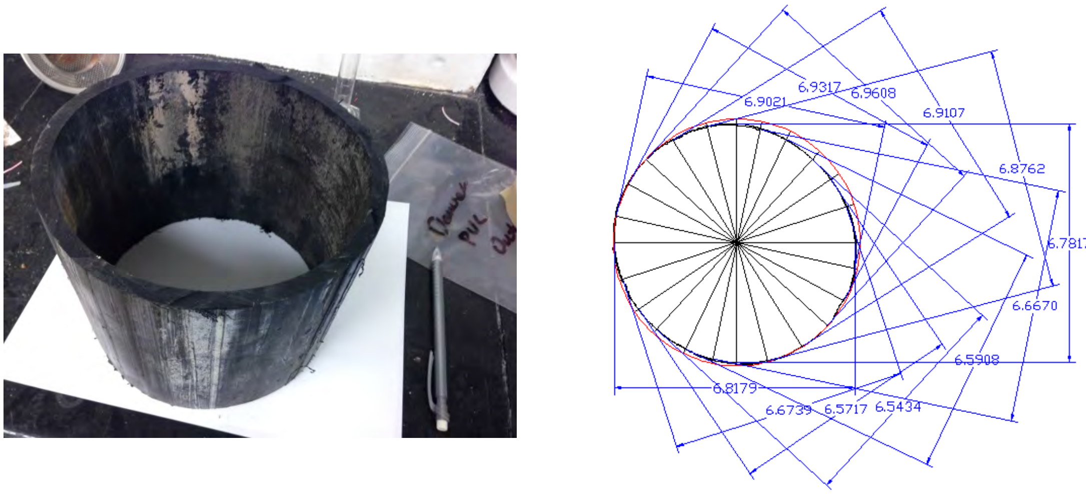

Figure C-51. Houston – Norton Dr.: Ovality of the Liner

Table C-35. Houston Norton Dr.: Ovality Calculation

Measured Diameter (in.)	Diameter (in.)			Ovality (%) Based on	
	Maximum	Minimum	Mean	Max Dia.	Min. Dia.
6.9021	6.9608	6.5434	6.77	2.834	3.332
6.9318					
6.9608					
6.9108					
6.8762					
6.7817					
6.6670					
6.5909					
6.5434					
6.5717					
6.6739					
6.8179					

C.3.2.5 ***Thickness.*** A total of 120 readings were taken on 20 1 in. × 1 in. samples cut from different locations of the specimen. The thickness was measured randomly using a micrometer with a resolution of ±0.0025 mm. The average thickness of the liner was found to be 8.447 mm ± 0.05 mm as shown in Figure C-52. The design thickness was unavailable; therefore, no comparison was made.

Figure C-52. Houston-Norton Dr.: Average Thickness of the Liner Sample

C.3.2.6 ***Specific Gravity.*** The specific gravity of the liner was measured on 20 1 in. × 1 in. samples in accordance with ASTM D792. The specific gravity values are shown in Figure C-53. The obtained values were between 0.93 and 0.98. The average specific gravity was 0.97 ± 0.01.

Figure C-53. Houston Norton Dr.: Specific Gravity of the Liner

C.3.2.7 ***Tensile Test (ASTM D638).*** Specimens, as described in ASTM D638, were cut from the retrieved polyethylene slipliner using a router and a band saw. A total of 15 specimens were prepared and tested. The sides of the specimens were smoothed using a grinder. A water jet cutter could not be used as the liner was curved and too small to be mounted inside the cutting board. The tensile test results are presented in Figure C-54 and Table C-36. The average tensile strength was 3,098 ± 542 psi and the average tensile modulus was 147,875 ± 32,900 psi. The elongation at break varied from around 24% to more than 70%. Sample 13 produced a lower peak stress value than the others possibly due to a localized crack created while preparing the sample. The modulus value for the sample was found to be reasonable and, therefore, the test data obtained for this sample were kept.

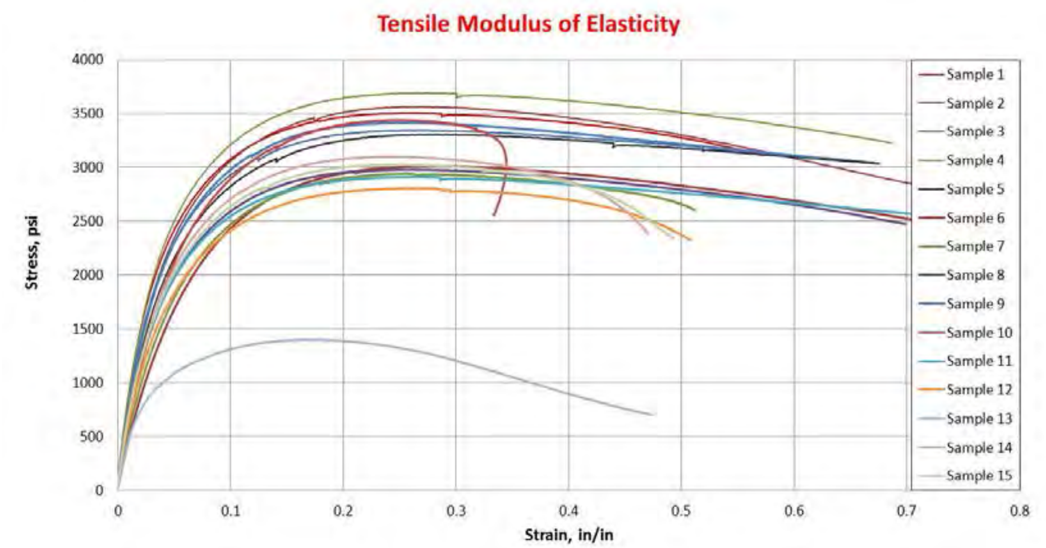

Figure C-54. Houston Norton Dr.: Stress – Strain Curves from Tensile Testing

Table C-36. Houston Norton Dr.: Tensile Test Results

Sample ID	Area (in.^{2})	Peak Load (lb)	Peak Stress (psi)	Tensile Modulus (psi)
1	0.1767	619.77	3,507	225,012
2	0.1695	604.62	3,567	155,477
3	0.1730	579.18	3,348	162,352
4	0.1731	639.41	3,694	183,404
5	0.1708	565.05	3,308	137,874
6	0.1796	541.28	3,014	91,292
7	0.1720	506.41	2,944	108,415
8	0.1760	524.78	2,982	143,188
9	0.1667	569.58	3,417	170,930
10	0.1628	560.14	3,441	128,383
11	0.1766	514.38	2,913	167,460
12	0.1835	515.15	2,807	130,589
13	0.1581	221.27	1,400	113,518
14	0.1737	538.74	3,102	148,039
15	0.1695	513.27	3,028	152,192
Average		534.20	3,098	147,875
St. Dev		95.73	542	32,900

C.3.2.8 Flexural Test (ASTM D790). Specimens, as described in ASTM D790, were cut from the retrieved polyethylene slipliner using a router and a band saw. A total of 15 specimens were prepared and tested. The sides of the specimens were smoothed using a grinder. A water jet cutter could not be used as the liner was curved and too small to be mounted inside the cutting board. The flexure test results are presented graphically in Figure C-55 and are listed in Table C-37. The average flexural modulus was 101,881 ± 10,373 psi and the average flexural strength was 3,174 ± 255 psi.

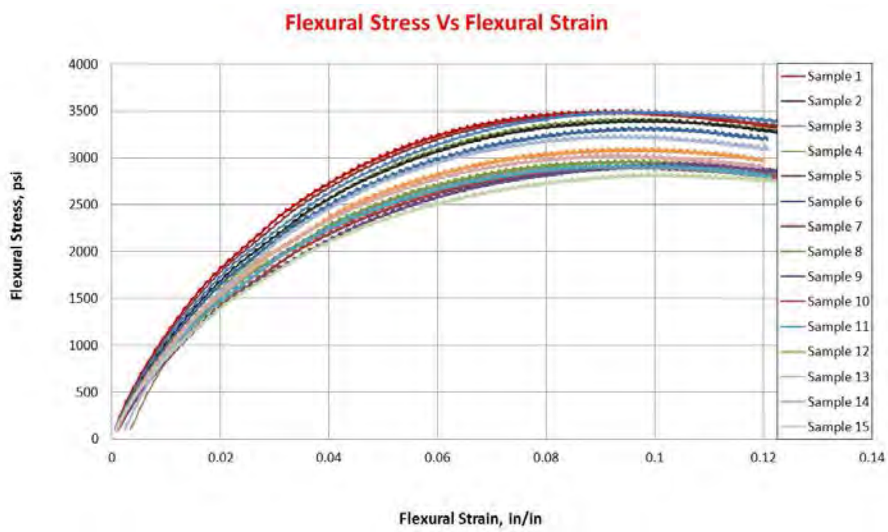

Figure C-55. Houston Norton Dr.: Stress – Strain Curves from Flexural Testing

Table C-37. Houston Norton Dr.: Flexure Test Results

Sample ID	Area (in.^{2})	Peak Load (lb)	Peak Stress (psi)	Flexural Modulus (psi)
1	0.0088	30.96	3,518	115,606
2	0.0089	31.23	3,509	117,596
3	0.0095	33.24	3,499	114,931
4	0.0090	30.94	3,438	112,626
5	0.0097	33.28	3,431	105,718
6	0.0096	31.89	3,322	104,838
7	0.0107	31.24	2,920	88,202
8	0.0104	30.90	2,971	96,315
9	0.0111	32.70	2,946	84,951
10	0.0108	31.62	2,928	90,610
11	0.0103	30.07	2,919	97,871
12	0.0100	30.97	3,097	99,754
13	0.0094	30.41	3,235	106,552
14	0.0100	30.38	3,038	99,936
15	0.0113	32.15	2,845	92,721
Average		31.47	3,174	101,881
St. Dev		1.00	255	10,373

C.3.2.9 Surface Hardness. A Shore Type D durometer (ASTM D2240) was used to determine the hardness of the liner samples. Samples (1 in. × 1 in.) were cut from the retrieved polyethylene slipliner with a band saw. A total of 400 readings were taken on the inner and outer surfaces of the liner specimens. The average recorded hardness values are shown in Figure C-56. The hardness of the surface exposed to the flow (inner surface) was found to be slightly lower than that of the protected (outer) surface.

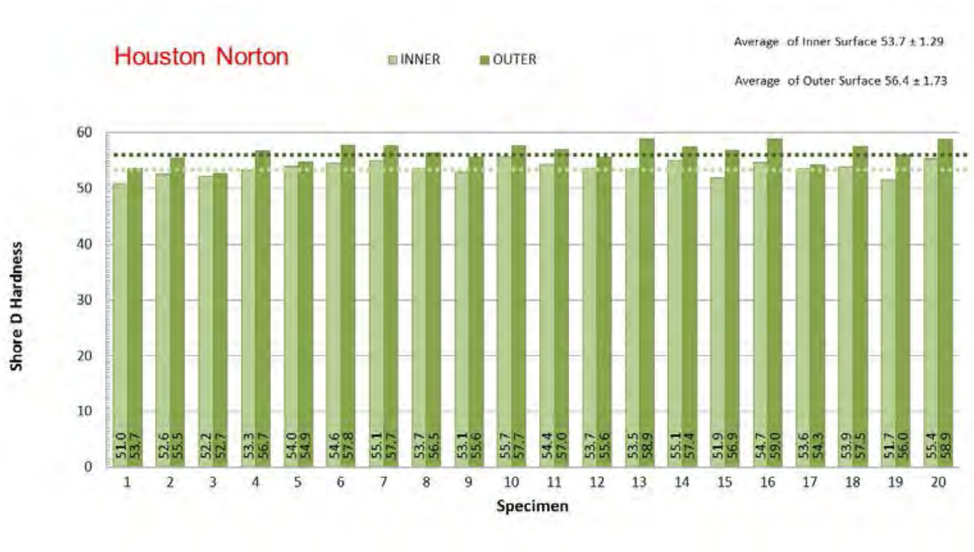

Figure C-56. Houston Norton Dr.: Shore D Hardness Readings for the Liner's Inner and Outer Surfaces

C.3.2.10 Pipe Stiffness. Pipe stiffness was measured using the UTM equipped with parallel plates according to ASTM D2412. Three 6 in. long specimens were cut from the liner using a table saw; the load was applied at 0.50 in./min. According to ASTM D2412, the deformation of the pipe was limited to 5% of the inside diameter. The test results are shown in Table C-38. The average value was found to be 61.6 lbf/in./in.

Table C-38. Houston Norton Dr.: Pipe Stiffness Test Results

Sample	Peak Load, lb	Pipe Stiffness at 5% Deformation of Inside Diameter (lbf/in./in.)
1	20.37	60.51
2	20.74	61.63
3	21.10	62.70
Average	20.74	61.61

APPENDIX D

QUALITATIVE OBSERVATIONS CONCERNING WASTEWATER REHABILITATION PERFORMANCE

To supplement the physical data, municipalities contacted about participating in the physical sample retrieval were also asked to provide information about their overall experiences with various rehabilitation technologies. This section describes additional qualitative performance evaluation information for the rehabilitation technologies selected in the current retrospective study including cured-in-place pipe (CIPP), polyvinyl chloride (PVC) fold-and-form, deform/reform high density polyethylene (HDPE), and sliplining. This appendix summarizes the qualitative assessments made by municipalities about the performance of each technology related to installation and long-term performance issues.

D.1 CIPP (Thermal and UV Cure)

CIPP is by far the dominant rehabilitation method in use for gravity sewers in the U.S. It involves the insertion of a liquid-resin-impregnated fabric into the host pipe where it is held tightly against the inside wall of the host pipe while it is cured thermally or by ultraviolet (UV) light. A fuller description of CIPP is provided in Section 3.1 of this report and also with significantly more detail in EPA (2010). For this study, seven municipalities in the U.S. were selected to participate by providing CIPP samples (Columbus, Denver, Houston, Indianapolis, Nashville, Northbrook, and New York). In addition, the City of Omaha that was contacted about providing samples also provided qualitative information. Not all of the participating municipalities provided qualitative information and, hence, five responses on the performance of CIPP liners are included as summarized in Table D-1.

Table D-1. Types and Amounts of CIPP for Participating Municipalities

Municipality	System Length (mi)	CIPP	
		Thermal Cure (ft)	UV Cure (ft)
Houston, TX	6,950	1,177,440	None
Indianapolis, IN	NP	100,000	100
Nashville, TN	3,096	1,500,000	None
New York, NY	6,400	NP	None
Omaha, NE	2,412	39,400	None

NP = Not provided

The lengths installed by individual municipalities ranged from 39,400 ft to approximately 1.5 million ft. All had used thermal cure CIPP and one municipality also reported using UV cure CIPP (Indianapolis) starting in 2013. The first installations among these municipalities for thermal cure CIPP were in the 1970s in New York. All of the responses presented in this section are for thermal cured CIPP (unless noted separately as related to UV cure).

As shown in Table D-2, the participating utilities indicated the severity of the installation issues for CIPP to be “almost none” to “minor” and primarily occurring at an estimated frequency below 4% (four out of five participating utilities). Four out of five participating utilities considered the severity of long-term performance issues for CIPP to be “almost none” to “minor” with one listing this as “moderate.” The occurrence of such long-term performance issues was assessed at an estimated frequency below 4% (five out of five participating utilities). The overall assessment of long-term cost-benefit value for thermal cure CIPP was deemed to be “high” for all of the participating municipalities. For UV cure CIPP, the City of Indianapolis (which used UV cure CIPP for the first time in 2013) gave a “reasonable” assessment.

Table D-2. Qualitative CIPP Considerations

Municipality	First year used	Frequency of CIPP installation issues						Severity of CIPP installation issues				Frequency of CIPP long-term performance issues						Severity of CIPP long-term performance issues				Overall assessment of CIPP long-term cost-benefit value		
		None	0-1%	1-4%	5-9%	10-20%	>20%	Almost none	Minor	Moderate	Severe	None	0-1%	1-4%	5-9%	10-20%	>20%	Almost none	Minor	Moderate	Severe	Poor	Reasonable	High
Houston	1986		X					X					X					X						X
Indianapolis	1980s				X			X						X						X				X
Nashville	1989		X					X					X					X						X
New York	1970s		X						X			X						X						X
Omaha	1986			X						X			X						X					X

As summarized below, general input on CIPP installation issues was received at the Trenchless Technology Center's (TTC) Colorado Municipal Users' Forum on September 26, 2013 and the Minnesota Municipal Users' Forum on May 15, 2013.

The types of installation issues identified included the following:

- Wrinkles/folds in liner; poorly sized liner
- Missed taps or over/under cutting
- Failure of resin to cure /inadequate curing resources
- Collapse of liner
- Rough cuts on taps
- Inconsistent resin impregnation
- Care and experienced installers a requirement for success
- Premature resin curing
- Resin slugs in laterals
- Inability to span voids
- Inadequately prepared/televised pipe
- Styrene odor complaints for larger diameter installations.

The key long-term performance issues identified were as follows:

- Delamination of sealing layer
- Excessive wrinkles causing constriction in main
- Wrinkles impact cleaning and closed-circuit television (CCTV)
- Infiltration at lateral openings
- Roots still enter main from non-rehabilitated laterals

- Large piece of CIPP liner found on wastewater treatment plant screen (source location unknown at present).

Other key issued related to CIPP rehabilitation were as follows:

- Maintenance practices need to be modified/controlled to avoid damage
- Used in larger diameters where loss of cross-section is less important
- Pipe bursting preferred when diameter less than 15 in. and depth less than 15 ft; CIPP preferred for diameters between 24 in. and 108 in.
- Tried and true method; Continuing to use CIPP; product holds up well
- Great product, but still have some water entering the system through annular space
- Good results for both thermal and UV cure CIPP; no long-term failures.

D.2 Fold-and-Form (PVC)

The vast majority of PVC fold-and-form rehabilitation in the U.S. used the "Ultraliner" technology, but it is not certain that all of the municipal responses under this category do refer specifically to the Ultraliner system. The technology was introduced into the U.S. market in the 1990s and had an important impact of providing competition to the CIPP process.

Three municipalities provided fold-and-form samples for the retrospective study (Denver, Miami, and Nashville). Of these three participating utilities, only Nashville provided qualitative information on fold-and-form performance. Nashville had by far the greatest use of the technology with approximately 225,000 ft (42.6 miles) installed. This was supplemented with technology assessment information from Littleton, Colorado and Westminster, Colorado. These two additional responding municipalities could serve as potential future sampling locations if additional PVC fold-and-form samples are sought. As shown in Table D-3, these three municipalities had installation lengths ranging from 5,000 to 225,000 ft. Since each of the municipalities reported first installations in the 1990s, there have been 14 or more years of experience with the fold-and-form technology.

Table D-3. Types and Amounts of PVC Fold-and-Form by Municipalities

Municipality	System Length (mi)	Fold-and-Form PVC (ft)
Littleton, CO	130	10,000
Nashville, TN	3,096	225,000
Westminster, CO	410	5,000

As shown in Table D-4, the utilities reported the severity of the installation issues for PVC fold-and-form to be "almost none" to "minor" and primarily occurring at an estimated frequency below 10% (three out of three participating utilities). The responding utilities reported the severity of long-term performance issues for PVC fold-and-form to be "almost none" to "moderate" and primarily occurring at an estimated frequency below 10% (three out of three participating utilities). As shown in Table D-4, the overall assessment of long-term cost-benefit value by all three responding municipalities was "reasonable." It is worth noting that Nashville, with the most experience with fold-and-form, estimated the lowest frequency of both installation and long-term performance issues and the lowest associated severity of impact.

Table D-4. Qualitative PVC Fold-and-Form Considerations

Municipality	First year used	Frequency of FnF installation issues						Severity of FnF installation issues				Frequency of FnF long-term performance issues						Severity of FnF long-term performance issues				Overall assessment of FnF long-term cost-benefit value		
		None	0-1%	1-4%	5-9%	10-20%	>20%	Almost none	Minor	Moderate	Severe	None	0-1%	1-4%	5-9%	10-20%	>20%	Almost none	Minor	Moderate	Severe	Poor	Reasonable	High
Littleton	1998			X					X						X					X			X	
Nashville	1990s		X					X					X					X					X	
Westminster	1997				X				X				X							X			X	

FnF = fold-and-form

The key issues identified for PVC fold-and-form are:

- Creep and/or thermal longitudinal movement in the liner after installation (i.e., the liner is not locked in place longitudinally within the host pipe). When this occurs after the liner cuts have been made for service reconnection, then service connections may become blocked.
- Inaccurate measurement of host pipe ID or variations in this ID can cause a mismatch with the liner being installed, resulting in folds in the liner after installation.

The types of installation issues identified for PVC fold-and-form included the following:

- Under heating caused pipe to get stuck requiring liner to be pulled, reheated, and reinstalled
- Folds due to improper match to host pipe ID
- Creep of the liner; liner movement covering service connections.

The type of long-term performance issues for PVC fold-and-form included the following:

- Liner moved over time causing misalignment of lateral service connections
- Ovality issues
- Service connection failures.

Other considerations for PVC fold-and-form performance included the following:

- Requires careful inspection and observance over time
- No longer used due to movement within the pipe
- Dependent on installation crews for quality control
- Variations in host pipe ID can promote defects
- More difficult to make service line reconnections.

D.3 Deform-Reform (HDPE)

Deform-reform rehabilitation using a folded HDPE pipe has a number of technology variants that have been used in both gravity flow sewers and pressure pipes.

Two municipalities provided deform-reform HDPE samples for the retrospective study (Denver and Nashville). However, neither provided qualitative information to assess the performance of deform-reform HDPE. This was supplemented with technology assessment information from Shreveport, Louisiana, which could serve as a potential future sampling location if additional samples are pursued. This municipality estimated the frequency of both installation and performance issues at 0 to 1% with minor severity of impacts in both cases. Their overall assessment of long-term cost-benefit and value was assessed as “reasonable.” Some problems were noted with reforming during installation and significant issues relating to the longitudinal movement of the liner within the host pipe after the cutting of service reconnections.

D.4 Sliplining (Large Diameter)

Large diameter sliplining typically involves the segmental slip lining of large diameter host pipes by sliding sections of new pipe within the old pipe, often without bypassing the existing flow. After sliplining, the annular space between the lining and the host pipe is typically grouted. A common type of pipe used for sliplining is a fiberglass pipe and the pipe joints for sectional installations are typically configured to provide a push-fit sealing as the sections are joined together.

As shown in Table D-5, five municipalities (Houston, Littleton, Nashville, Shreveport, and Westminster) provided qualitative performance information for both large and small diameter sliplining. The City of Houston had the largest length of large diameter sliplining reported at 15,840 ft, although it was only able to provide small diameter sliplining samples for the study due to the cost and difficulty in retrieving samples and repairing the slipliner in large diameter installations. The additional four municipalities could serve as potential future sampling locations if supplemental sliplining samples are sought. The first uses of sliplining in these responses were reported by Nashville from the 1960s.

Table D-5. Types and Amounts of Large and Small Diameter Sliplining by Municipalities

<table>
<tr><th>Municipality</th><th>System Length (mi)</th><th>Large Diameter Sliplining (ft)</th><th>Small Diameter Sliplining (ft)</th></tr>
<tr><td>Houston, TX</td><td>6,950</td><td>15,840</td><td>NE</td></tr>
<tr><td>Littleton, CO</td><td>130</td><td>1,050</td><td>NE</td></tr>
<tr><td>Nashville, TN</td><td>3,096</td><td colspan="2">10,000</td></tr>
<tr><td>Shreveport, LA</td><td>1,079</td><td colspan="2">36,960</td></tr>
<tr><td>Westminster, CO</td><td>410</td><td>0</td><td>800</td></tr>
</table>

Note: NE = No estimate

As shown in Table D-6, the overall assessment of long-term cost-benefit value by three responding municipalities (Houston, Littleton, and Nashville) with large diameter sliplining was “reasonable” to “high.” It is worth noting that Houston, with the most experience identified specifically as large diameter sliplining, did identify some installation issues (1 to 4%) and some long-term performance issues (0 to 1%), but gave an overall assessment of long-term cost-benefit value of “high.”

Table D-6. Qualitative Large Diameter Sliplining Considerations

Municipality	First year used	Frequency of large diameter sliplining installation issues						Severity of large diameter sliplining installation issues				Frequency of large diameter long-term performance issues						Severity of large diameter long-term performance issues				Overall assessment of large diameter long-term cost-benefit value		
		None	0-1%	1-4%	5-9%	10-20%	>20%	Almost none	Minor	Moderate	Severe	None	0-1%	1-4%	5-9%	10-20%	>20%	Almost none	Minor	Moderate	Severe	Poor	Reasonable	High
Houston	1999			X				X					X					X						X
Littleton	2011		X					X				X						X						X
Nashville	1960s	X						X				X						X					X	

The key issues identified for large diameter sliplining are:

- The benefits of maintaining flow during installation; limited bypass requirements
- Significant decrease in internal diameter after slip lining but improved roughness coefficients
- Poor joint alignment/sealing issues during installation leading to infiltration at joints
- Pipe stress may be introduced by friction during installation and by annular space grouting.

The types of installation issues indicated for large diameter sliplining included the following:

- Limited bypass needed
- Friction induced lining pipe stress
- Poor joint alignment
- Back-grouting-induced lining pipe stress
- Some adjustment required with bends.

The type of long-term performance issues for large diameter sliplining included the following:

- Does decrease internal diameter
- Infiltration at joints.

Other issues related to large diameter sliplining included the following:

- Used for large diameter for better structural integrity and less flow friction
- Looks good after rehabilitation
- Good results
- Both segmental and fused pipe methods used
- Creep issues for fused pipe
- Segmental method allows flow through during installation.

D.5 Sliplining (Small Diameter)

Small diameter sliplining may use either segmental or fused lengths of pipe for insertion. All of the specifically identified small diameter sliplining was reported as being started in the 1990s. Houston provided two 8 in. sliplining samples for the retrospective study. As shown in Table D-7, the overall assessment of long-term cost-benefit value was “poor” to “reasonable” with the lower rating associated with a comment of removal of the slipline due to grease buildup.

Table D-7. Qualitative Small Diameter Sliplining Considerations

Municipality	First year used	Frequency of small diameter sliplining installation issues						Severity of small diameter sliplining installation issues				Frequency of small diameter sliplining long-term performance issues						Severity of small diameter sliplining long-term performance issues				Overall assessment of small diameter long-term cost-benefit value		
		None	0-1%	1-4%	5-9%	10-20%	>20%	Almost none	Minor	Moderate	Severe	None	0-1%	1-4%	5-9%	10-20%	>20%	Almost none	Minor	Moderate	Severe	Poor	Reasonable	High
Shreveport	1990s			X					X				X						X				X	
Westminster	1990		X						X					X						X		X		

The key issues identified for small diameter sliplining are:

- Service reconnection issues; every service connection must be excavated
- Floating of liner during grouting of the annular space
- Grease build up in the lined pipe
- Pull pits needed adjacent to manholes.

The types of installation issues identified for small diameter sliplining included the following:

- Floated the liner pipe during grouting of the annular space
- Service connection issues
- Needed pull pits by manholes
- Every tap must be excavated.

The type of long-term performance issues for small diameter sliplining included the following:

- Grease started building up causing backups.

Other issues related to small diameter sliplining included the following:

- Mixed results
- Started collecting grease; slipline was removed.

D.6 Overall Summary of the Experience of the Municipalities Participating in the Study

The responses from the municipalities described above indicate a significant degree of satisfaction with almost all of the rehabilitation methods with which they had experience. Most municipalities reported that the technologies and/or their installation were not completely trouble free. However, the percentages of problems or issues in terms of installation or long-term performance were generally low and considered acceptable. The overall value of the rehabilitation technologies issues was generally perceived to be high.

CIPP technology has become the dominant rehabilitation technology for sewer collection systems with some of the other technologies that were introduced in past decades disappearing from the marketplace – either due to some of the performance issues identified above or commercial issues in technology delivery or cost competitiveness. Nevertheless, there are many circumstances in which other technologies do compete with CIPP or offer solutions where CIPP would not be applicable.

While the municipalities responding indicate overall satisfaction with their rehabilitation technologies and long-term performance appears to be good, there is still plenty of room for improvement in the quality control of rehabilitation efforts.

APPENDIX E

RELEVANT ASTM STANDARDS

The following table lists ASTM standards that are referenced in this report.

Standard	Description
ASTM C128	Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate
ASTM C136	Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates
ASTM D543	Standard Practices for Evaluating the Resistance of Plastics to Chemical Reagents
ASTM D621 – 64 (1988)	Test Methods for Deformation of Plastics Under Load (Withdrawn 1994)
ASTM D638	Standard Test Method for Tensile Properties of Plastics
ASTM D648	Standard Test Method for Deflection Temperature of Plastics Under Flexural Load in the Edgewise Position
ASTM D671	Standard Test Method for Flexural Fatigue of Plastics by Constant Amplitude of Force (Withdrawn 2002)
ASTM D695	Standard Test Method for Compressive Properties of Rigid Plastics
ASTM D696	Standard Test Method for Coefficient of Linear Thermal Expansion of Plastics Between −30°C and 30°C with a Vitreous Silica Dilatometer
ASTM D732	Standard Test Method for Shear Strength of Plastics by Punch Tool
ASTM D790	Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials
ASTM D792	Standard Test Methods for Density and Specific Gravity (Relative Density) of Plastics by Displacement
ASTM D953	Standard Test Method for Bearing Strength of Plastics
ASTM D1693	Standard Test Method for Environmental Stress-Cracking of Ethylene Plastics
ASTM D 1784	Standard Specification for Rigid Poly(Vinyl Chloride) (PVC) Compounds and Chlorinated Poly(Vinyl Chloride) (CPVC) Compounds
ASTM D2122	Standard Test Method for Determining Dimensions of Thermoplastic Pipe and Fittings
ASTM D2216	Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass
ASTM D2412	Standard Test Method for Determination of External Loading Characteristics of Plastic Pipe by Parallel-Plate Loading
ASTM D2583	Standard Test Method for Indentation Hardness of Rigid Plastics by Means of a Barcol Impressor
ASTM D3350	Standard Specification for Polyethylene Plastics Pipe and Fittings Materials
ASTM D5813	Standard Specification for Cured-In-Place Thermosetting Resin Sewer Piping Systems
ASTM E1356	Standard Test Method for Assignment of the Glass Transition Temperatures by Differential Scanning Calorimetry
ASTM F585	Standard Guide for Insertion of Flexible Polyethylene Pipe Into Existing Sewers
ASTM F1216	Standard Practice for Rehabilitation of Existing Pipelines and Conduits by the Inversion and Curing of a Resin-Impregnated Tube

Standard	Description
ASTM F1504	Standard Specification for Folded Poly(Vinyl Chloride) (PVC) Pipe for Existing Sewer and Conduit Rehabilitation
ASTM F1533	Standard Specification for Deformed Polyethylene (PE) Liner
ASTM F1743	Standard Practice for Rehabilitation of Existing Pipelines and Conduits by Pulled-in-Place Installation of Cured-in-Place Thermosetting Resin Pipe (CIPP)
ASTM F1867	Standard Practice for Installation of Folded/Formed Poly (Vinyl Chloride) (PVC) Pipe Type A for Existing Sewer and Conduit Rehabilitation
ASTM F1871	Standard Specification for Folded/Formed Poly (Vinyl Chloride) Pipe Type A for Existing Sewer and Conduit Rehabilitation (Withdrawn 2011)
ASTM F2019	Standard Practice for Rehabilitation of Existing Pipelines and Conduits by the Pulled in Place Installation of Glass Reinforced Plastic (GRP) Cured-in-Place Thermosetting Resin Pipe (CIPP)
ASTM F2599	Standard Practice for The Sectional Repair of Damaged Pipe By Means of An Inverted Cured-In-Place Liner