Short-Term and Long-Term Mechanical Properties of CIPP Liners

by

Amir Mahdi Riahi

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Amir Mahdi Riahi

Abstract

Cured In-Place Pipe (CIPP) is a well-established method used for rehabilitation of underground pipelines. Within North America, CIPP liners used for rehabilitation of gravity pipelines are typically designed according to the design methodology provided in the non-mandatory Appendix (X1) of ASTM F1216. In the design equations provided in the standard, there are two parameters, liner long-term time-corrected modulus of elasticity and long-term time-corrected flexural strength, which are related to the CIPP long-term creep behavior. However, ASTM F1216 does not specify any methodology for characterizing the material long-term physical properties. Common industry practice has been to adopt a creep retention factor of 0.5 for all CIPP materials. With all the new CIPP product varieties that have entered the gravity pipeline renovation market since Insituform's patent expiry, a creep retention factor of 0.5 may not apply. This thesis provides a comparison between the ASTM D2990 methodology used for the prediction of 50-year physical properties for four CIPP resins used within the City of Toronto sewers and reported in the CATT Report (2005) and the hydrostatic buckling test methodology used for long-term behavior characterization of various lining systems reported in TTC Report 302 (1994). Based on the comparison of reported results, ASTM D2990 test procedures is recommended and used for characterizing the long-term mechanical properties of nine different reinforced CIPP products used for pressure pipe. Short-term tensile and flexural properties of the nine CIPP liners are also studied. CIPP liners are typically tested for a period of 10,000 hours to evaluate the liner long-term behavior. In this thesis, long-term test analyses conducted for CIPP products used within the City of Toronto sewers based on 10,000 hours (about 1.2 years) and 96,000 hours (about 11 years) of test data are also compared. The results of this research provide a better understanding of CIPP liners short-term and long-term mechanical properties. This work also demonstrates the importance of proper and consistent interpretation of long-term test results.

Keywords: CIPP liner, ASTM F1216, ASTM D2990, short-term behavior, long-term behavior

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Dedication

I would like to dedicate this thesis to my dear family who has always supported me in every stage of my life.

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1 Introduction to the Test Program

1.1 Introduction

Underground pipelines are arteries of cities and towns. As the water and wastewater distribution networks age, they deteriorate and require rehabilitation. The traditional approach to renew/repair the deteriorated pipe involves extensive excavation along the pipe section. An alternative to open-cut construction is application of a trenchless technology such as Cured In-Place Pipe (CIPP) lining. Through the CIPP renovation process, a resin-impregnated lining tube is inserted into the existing deteriorated pipe which is then cured to form a tight fit against the pipe wall (*WRc Sewerage Rehabilitation Manual*, 1993). The resin used for tube impregnation is a thermosetting polymer. Thermosetting and thermoplastic materials have a creep relationship when under stress over time (*Schrock*, 1999). Thus, CIPP liners demonstrate a viscoelastic behavior under stress. This means that their behavior is time and stress dependent and CIPP liners creep under load. Within North America, CIPP liners used for rehabilitation of gravity pipelines are typically designed according to the design methodology provided in the non-mandatory Appendix (X1) of ASTM F1216 (*Olivier*, 2004). This standard requires the designer to apply parameters that are related to the long-term creep behavior of the liner. ASTM F1216 does not specify how to characterize the material long-term behavior. In this thesis, different methods used for evaluation of CIPP liners long-term behavior are reviewed. Then, based on the recommended methodology, the long-term behaviors of nine different reinforced CIPP products used for pressure applications are analyzed. Short-term tensile and flexural properties of the liners are also studied. The results of both the short-term and long-term tests are presented in the corresponding chapters. Findings are outlined to provide a better understanding of CIPP material mechanical properties.

1.2 Motivation

CIPP is a well-established trenchless technology used for rehabilitation of water and wastewater pipelines and is becoming more popular within the municipalities (*Oxner and Allsup*, 1999). Lining systems should be tested before use in order to check if the material properties meet the design requirements or not (*Straughan et al.*, 1995). There are usually third-party testing companies that evaluate the short-term and long-term mechanical properties of this kind of liner. However, based on review of some of the reports published on CIPP long-term mechanical properties, there is an inconsistency found in the method of evaluating the long-term test results. Therefore, there is a need for the industry to adopt a standard practice for testing CIPPs and interpretation of test results. In this thesis, different methods used for CIPP material long-term behavior characterization are reviewed and compared. Then, based on the comparison results, one of the methodologies is recommended and used for analysis of long-term mechanical properties of nine reinforced CIPP liners.

For characterization of long-term (typically 50-years) physical properties, CIPPs are usually tested for a period of 10,000 hours. In this research, long-term behavior of four different CIPP products, commonly used within North America are analyzed based on 96,000 hours (9.6 times the standard practice) of long-term test data and compared with the 10,000 hours analysis. Afterwards, short-term and long-term mechanical properties of nine different CIPP products provided by the Interplastic Corporation, one of the major suppliers of CIPP resins within North America, are studied.

1.3 Research Objectives

Physical properties of CIPP liners including short-term and long-term properties need to be analyzed before installation to ensure that the design requirements are met. Within North America, circular CIPP liners are typically designed in accordance with ASTM F1216 design methodology. However, ASTM F1216 does not provide a methodology for obtaining long-term properties required for CIPP design. It has often become industry practice to adopt a creep retention factor of 0.5 for CIPP materials (*TTC Report 302*, 1994). Since Insituform's patent expiry in late 1990's, many new CIPP products have entered the market. With all the new CIPP product varieties, the TTC creep retention factor of 0.5 may not apply to all products. The objectives of this research include:

- **To compare different methods used for evaluation of CIPP liners long-term behavior.** Then, the methodology which is more cost and time effective is recommended.

- **To compare long-term test results based on 10,000 hours versus 96,000 hours of test data.** It is desirable to compare the 50-year predicted behavior of CIPP liners to the real behavior. However, due to the significant costs associated with long-term tests, the liners are not usually tested longer than 10,000 hours (*Straughan et al.,* 1995). Thus, the results of the analysis based on 96,000 hours (about 11 years) of creep test data will provide valuable information on long-term behavior of CIPP liners.

- **To investigate the short-term and long-term mechanical properties of nine different CIPP products.** To select an appropriate rehabilitation liner, physical properties of the liner should be well-understood. This study will provide an analysis of short-term and long-term behaviors of various CIPP products used for pressure applications.

1.4 Thesis Organization

The thesis is subdivided into eight chapters. Chapter 2 provides background information on the problems associated with underground pipelines and the methods usually used to rehabilitate water and wastewater distribution networks. This chapter presents the review of previous research and current practice regarding the characterization of CIPP liners long-term behavior. It also presents 10,000 hours versus 96,000 hours of creep test data of four other CIPP products commonly used within North America. In Chapter 3, the test program for investigation of short-term and long-term mechanical properties of nine different CIPP products is described. Chapter 4 describes the short-term tensile test procedure, specimens, equipment, and tensile mechanical properties. Chapter 5 focuses on the short-term flexural test procedure, specimens, equipment, results and discussion of CIPP liners short-term flexural mechanical properties. Chapter 6 describes long-term flexural creep test procedure, specimens, test loads, prediction of materials deflection levels based on the selected test loads, and test equipment. The creep test results are presented and discussed in this chapter. In Chapter 7, predicted CIPP liners long-term behavior based on the collected long-term creep test data are analyzed. Finally in Chapter 8, conclusions and recommendations are drawn.

2 Background and Review of Previous Research and Current Practice

2.1 Background

Buried infrastructure, such as undergroung pipelines, are usually less emphesized comparing to other infrastructures due to the fact that they are hidden under the ground (*Rehan et al.*, 2011). However, they play an important role in everyday life of all people whether living in big cities or small towns. They provide potable water to residents and businesses, collect and transport wastewater from residences and businesses to treatment plants, and also collect and transport storm water. However, these arteries deteriorate over time and may fail to provide the expected service. According to RBC Canadian water attitudes study (2012), the replacement cost of water and wastewater linear assets (i.e., pipes) is about \$50 billion and \$55 billion, respectively. As the water and wastewater distribution systems age, they deteriorate, crack, leak, and finally break (*FCM*, 2003).

Water distribution networks are typically high pressure systems. Signs of an aging water distribution system include pipe material degradation and increasing break frequency (*FCM*, 2003). Figure 2.1 shows a water pipe deteriorated as a result of material degradation. Figure 2.2 demonstrates the increasing trend of watermain break frequency in the City of Waterloo, Ontario.

Figure 2.1 - Material degradation (pipe corrosion)
(Adapted from *Knight*, 2013)

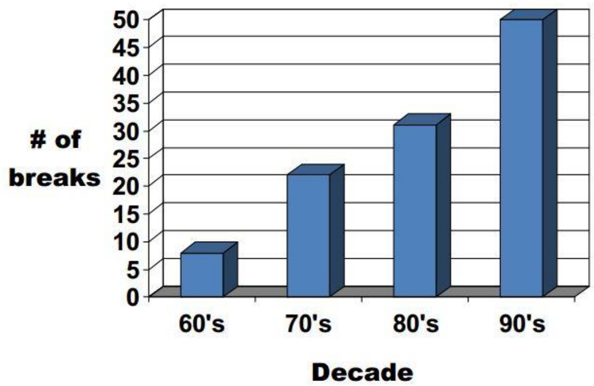


Figure 2.2 - Watermain break frequency in the City of Waterloo
(Adapted from *Knight*, 2013)

Water distribution systems may also corrode internally resulting in reduction of flow capacity, reduction of chlorine residuals, and poor drinking water quality (*FCM*, 2003). Figure 2.3 illustrates a water pipe that is heavily corroded internally.

Figure 2.3 - Internal pipe corrosion
(Adapted from *Knight*, 2013)

Problems associated with aging wastewater distribution systems include structural distress, pipe material degradation, inflow and infiltration, and poor hydraulic performance (*Knight*, 2013). Figure 2.4 shows a sinkhole created as a result of wastewater pipe collapse.

Figure 2.4 - Sinkhole created from collapse of wastewater pipe in the City of Winnipeg (Adapted from *Knight*, 2013)

Problems associated with deteriorated water and wastewater pipelines cost municipalities a great deal of money each year (*Boyce and Bried*, 1998). To increase the level of service (i.e., to improve the performance, reliability, and safety) of underground infrastructures, there are typically two options (*Boyce and Bried*, 1998):

1- To replace the deteriorated pipe using open-cut construction (i.e., excavating the entire pipe section), or
2- To repair/renovate the pipe using a trenchless technology.

Replacing an underground pipe using open-cut construction involves excavation along the entire pipe section, taking the old pipe out, installing a new pipe and backfilling the trench. The entire process is usually costly and the construction phase negatively impacts the traffic and businesses especially in congested metropolitan areas (*Boyce and Bried*, 1998). An alternative to open-cut construction is application of a trenchless technology, such as Cured In-Place Pipe (CIPP), for repair/renovation of the deteriorated pipe. Through the CIPP renovation process a resin-impregnated lining tube is inserted into the existing deteriorated pipe which is then cured to form a tight fit against the pipe wall (*WRc Sewerage Rehabilitation Manual*, 1993).

This trenchless technique utilizes the existing alignment and easements and the deteriorated pipe acts as a casing for the installation process which may or may not contribute to structural performance of the CIPP liner (*Oxner and Allsup*, 1999). CIPP was first implemented in early 1970's in Britain, and in the late 1970's the technology was brought to North America (*Oxner and Allsup*, 1999). Figure 2.5 illustrates the CIPP installation process.

Figure 2.5 - CIPP installation process (*Unitracc*, 2013)

Unlike the traditional methods used for underground pipelines repair/renewal which require extensive trenching to replace the deteriorated pipe, the CIPP process requires little or no excavation (*Oxner and Allsup*, 1999). CIPP liners can be used for structural reconstruction or it can serve as a corrosion barrier to shield existing pipe walls from the flow stream which may be contributing to the degradation of wall thickness (*Oxner and Allsup*, 1999). The rehabilitation liner reduces inflow and infiltration of unwanted surface or ground water, and usually improves the flow characteristics of the system (*Straughan et al.*, 1995). Social and environmental costs can also be greatly minimized using the CIPP pipeline rehabilitation method, compared to the open-cut construction (*Boyce and Bried*, 1998). When the direct cost of rehabilitating a pipeline using trenchless methods is equal to the cost of open-cut methods, benefit to Society is a major factor that needs to be considered for selection of a rehabilitation technique (*Boyce and Bried*, 1998).

Figure 2.6 - CIPP liner cured inside a deteriorated pipe
(Adapted from *Knight*, 2013)

Figure 2.6 shows a CIPP liner cured inside a deteriorated water pipe. The resin used for CIPP tube impregnation is a thermosetting polymer. Thermoset polymers change irreversibly to an insoluble solid when cured with application of heat and/or radiation (*Nawab et al.*, 2013). Thus, CIPP resins cannot be melted or reshaped once cured. Depending on the application and strength requirements, the lining tubes are designed with or without reinforcement (*Oxner and Allsup*, 1999). Reinforced tubes tend to produce higher strength liners with less wall thickness. Polyester, vinyl ester, and epoxy are the three types of thermosetting resins typically used in CIPP applications based on the economics, waste stream chemistry, strength requirements, and potable versus non-potable applications (*Kleweno*, 1994). Characteristics and properties of these resins are described below (*Knight*, 2013):

Polyester Resin

- Most common resin for rehabilitation of municipal sewage pipelines
- Contains Styrene (an organic compound) which helps the polymerization process when heated

Vinyl Ester Resin

- Most common resin for rehabilitation of industrial pipelines, effluents
- Better corrosion and chemical resistance than polyesters
- Higher temperature range application than polyesters
- Higher ductility, better choice for pressure applications

- Fast wet-out and easy to handle compared to epoxy
- Good curing characteristics in presence of water, and
- Typically more expensive than polyester resin

Epoxy Resin

- Commonly used for rehabilitation of pressure pipelines
- Suitable for potable water applications
- High chemical resistance
- Typically more expensive than polyester and vinyl ester

In the design of CIPP liners, resin selection is an extremely important aspect of the decision making process for the specifying design engineer (*Knasel*, 1998). As mentioned in Chapter 1, thermosetting materials like CIPP resins, creep under stress. The rate of creep is influenced by resin type, applied load, degree of cure, and the environmental conditions (*Richard*, 1993). Creep rate is one of the major influential factors in the design of CIPP liners (*Knasel*, 1994).

There are several methods used for design of CIPP liners around the world. For example, ASTM F1216 is commonly used in North America, ATV-M 127-2 in Germany and AGHTM RRR in France (*Olivier*, 2004). ASTM F1216, "Standard Practice for Rehabilitation of Existing Pipelines and Conduits by the Inversion and Curing of a Resin-Impregnated Tube", describes the procedures for the reconstruction of pipelines and conduits by the installation of a resin-impregnated flexible tube which is inverted into the existing conduit by use of a hydrostatic head or air pressure. This standard also contains a non-mandatory Appendix (X1) outlining CIPP design considerations that have become an industry standard in North America for the circular gravity pipelines (*Olivier*, 2004).

According to Appendix "X1" of ASTM F1216-09, the condition of existing pipe can be classified into two categories; partially deteriorated or fully deteriorated. ASTM F1216-09 states that in a partially deteriorated condition, it is assumed that the original pipe will support the soil and surcharge loads throughout the design life of the rehabilitated pipe, and in the case of a fully deteriorated condition, it is assumed that the original pipe is not structurally sound and will not support soil and live loads or is expected to reach this condition over the design life of the rehabilitated pipe. Various possible external loads considered in CIPP design are illustrated in Figure 2.7.

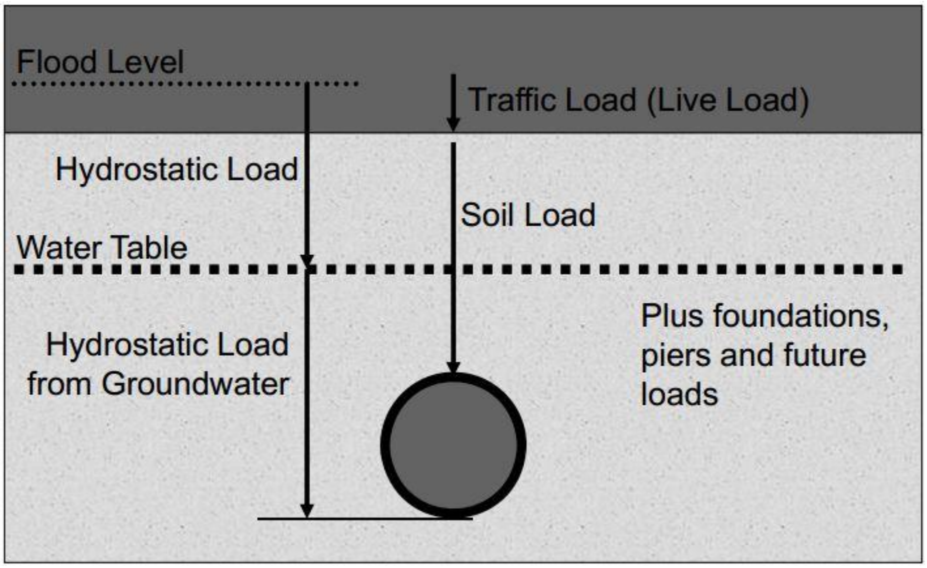


Figure 2.7 - External load possibilities
(Adapted from *Knight*, 2013)

The condition of the pipe is usually determined through judgment call, CCTV or scan inspection information and interpretation, severity of diameter distortion, past history of pipeline, ground conditions and the type of pipe material (*FCM*, 2003). It is important to consider the future deterioration of the pipe, as well as, the present condition (*FCM*, 2003). To determine the minimum required CIPP liner thickness, ASTM F1216-09 Appendix "X1" provides two design equations (X1.1, and X1.2) to be checked for partially deteriorated condition and four equations (X1.1, X1.2, X1.3, and X1.4) including the two for partially deteriorated case, for the fully deteriorated condition. It should be noted that the ASTM F1216 design methodology only applies to circular pipes. The four CIPP design equations used for gravity pipelines and the parameters related to CIPP mechanical properties are outlined below:

Equation X1.1:

In the design of gravity sewer pipes, the prevention of buckling of the pipe under external hydrostatic pressure is one of the primary criteria to be addressed (*Straughan et al.,* 1995). This equation checks for the liner buckling resistance against ground water pressure.

$$P = \frac{2KE_L}{(1-v^2)} \frac{1}{(DR-1)^3} \frac{C}{N} \quad \textbf{(2.1)}$$

where,

P = groundwater load, psi (MPa),

K = enhancement factor of the soil and existing pipe adjacent to the new pipe (a minimum value of 7.0 is recommended where there is full support of the existing pipe),

E_L = long-term (time-corrected) modulus of elasticity of CIPP liner, psi (MPa),

v = Poisson's ratio (0.3 average),

DR = dimension ratio of CIPP liner = D/t (mean liner diameter over average liner thickness),

C = ovality reduction factor,

N = factor of safety.

Equation X1.2:

Minimum liner thickness required for rehabilitation of a circular pipe that has gone out of round is determined through Equation (X1.2).

$$1.5 \frac{\Delta}{100}\left(1 + \frac{\Delta}{100}\right) DR^2 - 0.5\left(1 + \frac{\Delta}{100}\right) DR = \frac{\sigma_L}{PN} \quad \textbf{(2.2)}$$

where,

Δ = percent ovality of existing pipe,

DR = dimension ratio of liner,

σ_L = long-term (time-corrected) flexural strength for CIPP, psi (MPa),

P = ground water pressure, psi (MPa),

N = factor of safety.

In the case of a partially deteriorated condition, the required liner thickness is the largest thickness obtained through Equations "X1.1" and "X1.2". For the fully deteriorated condition, two extra equations (X1.3 and X1.4) should also be checked and the largest thickness determined by all the four equations (X1.1, X1.2, X1.3, and X1.4) is taken as the required liner thickness.

Equation X1.3:

This equation is used to determine the required CIPP thickness withstanding all the external loads such as soil, live and water loads applied on the pipe without collapsing (*ASTM F1216-09*).

$$q_t = \frac{1}{N}\left[32 R_w B' E'_s \, . \, C \, (E_L I / D^3)\right]^{1/2} \quad \textbf{(2.3)}$$

where,

q_t = total external pressure on pipe, psi (MPa),

= $0.433H_w$ + $wHR_w/144$ + W_s, (English Units),

= $0.00981H_w$ + $wHR_w/1000$ + W_s, (Metric Units)

R_w = water buoyancy factor (0.67 min) = 1 – 0.33 (H_w/H),

w = soil density, $lb.ft^3$ (kN/m^3),

W_s = live load, psi (MPa),

H_w = height of water above top of pipe, ft (m),

H = height of soil above top of pipe, ft (m),

B' = coefficient of elastic support = $1/(1 + 4e^{-0.065H})$ inch-pound units,

$1/(1 + 4e^{-0.213H})$ SI units.

I = moment of inertia of CIPP liner, $in.^4/in$, (mm^4/mm),

C = ovality reduction factor,

N = factor of safety,

E'_s = modulus of soil reaction, psi (MPa),

E_L = long-term modulus of elasticity for CIPP Liner, psi (MPa), and

D = mean inside diameter of host pipe, in. (mm).

Equation X1.4:

As an additional check, CIPP designed using equation (X1.3) should have the minimum thickness specified by equation (X1.4).

$$\frac{EI}{D^3} = \frac{E}{12(DR)^3} \geq 0.093 \quad (\textit{inch – pound units}) \qquad \textbf{(2.4)}$$

or

$$\frac{EI}{D^3} = \frac{E}{12(DR)^3} \geq 0.00064 \quad (\textit{SI units}) \qquad \textbf{(2.5)}$$

where,

E = initial (short-term) modulus of CIPP, psi (MPa),

I = moment of inertia of CIPP liner, $\text{in.}^4/\text{in}$, (mm^4/mm),

D = mean inside diameter of original pipe, in. (mm),

DR = dimension ratio.

Equation (X1.4) provides for a maximum liner dimension ratio dependent only on the liner short-term modulus (*ASTM F1216-09*). The long-term time-corrected modulus of elasticity and the long-term time-corrected flexural strength are the two long-term parameters outlined in the CIPP design equations required by ASTM F1216. There is no methodology specified in ASTM F1216 to estimate the two long-term properties. The following sections review procedures for the determination of CIPP long-term mechanical properties.

2.2 Review of Previous Research and Current Practice

As mentioned earlier, CIPP liners creep under stress and the rate of creep is influenced by resin type, applied load, degree of cure, and the environmental conditions (*Richard*, 1993). Therefore, the modulus and strength values used in engineering design should be obtained under conditions (time, stress, and temperature, etc.) that simulate the environment in which a particular CIPP liner is expected to confront over its design life (*ASTM D2990-09*). The two parameters E_L and σ_L outlined in the CIPP design equations, represent the material long-term modulus of elasticity and long-term flexural strength, respectively. It is has become a common industry practice to define E_L as long-term flexural modulus of elasticity rather than tensile or compressive modulus due to the stress conditions CIPP liners may experience during the service life (*TTC Report 302*, 1994). As discussed in Section 2.1, ASTM F1216-09 requires the designer to input these two parameters (i.e., E_L and σ_L) in CIPP design equations, but it does not specify how to obtain the long-term values. It does state that E_L depends on the estimated duration of the application of the load on the liner, either continuously applied or the sum of intermittent periods of loading in relation to the design life of the structure. A 50-year design life example is used in the standard stating that the appropriately conservative choice for the value of E_L will be that given for 50 years of continuous loading at the maximum ground or fluid temperature expected to be reached over the design life of the liner. The same concept applies for determination of the liner long-term time-corrected flexural strength (σ_L) (*ASTM F1216-09*).

Structural behavior of sewer lining systems is governed by their capacity to resist creep buckling within the confines of the host pipe (*Boot and Welch*, 1996). Creep is the progressive deformation of a material under a constant stress (*Knight and Sarrami*, 2007). ASTM Standard D2990, "Test Method for Tensile, Compressive, and Flexural Creep and Creep Rupture of Plastics," has been widely used within North America for characterization of CIPP liners creep behavior (*Hazen*, 2015). ASTM Standard D2990 provides a procedure for long-term testing of simply supported beam samples of plastics through which creep modulus is measured as a function of specimen deformation under a constant load and temperature over the test period. The creep modulus of a specimen is defined as a ratio of the constant stress to the accumulated strain over the loading period (*ASTM D2990-09*). Based on ASTM D2990, creep moduli values calculated at specified time steps are extrapolated to predict the specimen long-term (50-year) creep modulus as an indication of material long-term behavior. However, it is stated in TTC Report 302 (1994) that ASTM Standard D2990 is not directly applicable to plastic pipe buckling design and is not an indicator of the long-term behavior of plastic pipes.

In the following sections, two different techniques used for the evaluation of CIPP liners long-term mechanical properties provided by two independent research centers; Trenchless Technology Center (TTC) at Louisiana Tech University (1994), and Center for Advancement of Trenchless Technologies (CATT) at University of Waterloo (2005), are reviewed and compared, and one of the test methods is recommended for CIPP long-term behavior characterization.

2.2.1 TTC Report

The Trenchless Technology Center at Louisiana Tech University, joined by the US Army Corps of Engineers (1994) published a technical report (#302) "Long-Term Structural Behavior of Pipeline Rehabilitation Systems" with a primary objective of evaluating the long-term structural behavior of different thermosetting plastic and thermoplastic pipe lining systems under a uniform external hydrostatic pressure loading similar to what would be experienced in a partially deteriorated sewer. The experiments and analytical studies in this report are limited to straight pipes which are essentially round, snug-fitting, without major defects or anomalies, and where bonding does not exist between the liner and the host pipe. Long-term tests are conducted on liners installed in steel casing pipes and subjected to uniform external pressures so that the liners would fail during a 10,000 hour test period. Specimens from each liner are tested under constant pressure for the duration of the test and the results are plotted and extrapolated beyond the test period to predict the material long-term behavior. The following ASTM Standards which are test procedures for evaluating the long-term performance of plastic pipes subject to constant internal pressure are used as a basis for developing the test procedure for analysis of the effect of long-term external hydrostatic pressure on liners:

- ASTM D1598, "Test Method for Time-to-Failure of Plastic Pipe Under Constant Internal Pressure"
- ASTM D2992, "Obtaining Hydrostatic or Pressure Design Basis for "Fiberglass" (Glass-Fiber-Reinforced Thermosetting-Resin Pipe and Fittings)", and
- ASTM D2837, "Obtaining Hydrostatic or Pressure Design Basis for Thermoplastic Pipe Materials.

It is stated that the tests conducted for external loadings on plastic liners use a similar approach to that of ASTM D2837 internal pressure testing procedure.

2.2.1.1 TTC Test Material

The experimental and analytical studies presented in the TTC Report 302 focus on the buckling behavior of both CIPP and Fold-and-Formed Pipe (FFP) lining systems. Six different CIPP products and one FFP product from five manufacturers are studied in this research. It is reported that for the long-term tests at least 25 specimens of each product are tested and two products have 40 samples each to produce statistically significant data due to the variability associated with viscoelasticity, the buckling phenomenon and possible product non-uniformity. Two of the CIPP products from Insituform Technologies Inc. called Standard and Enhanced are analyzed here for comparison purposes since the other long-term test technique (presented in the CATT Report) which will be reviewed later focuses on properties of CIPP liners which are similar to these two particular product types. The components of the two CIPP products are presented in Table 2.1.

Table 2.1 - CIPP products considered for analysis (Adapted from *TTC Report 302*, 1994)

Company/Product	**Type of Tube**	**Type of Resin/Base Material**	**No. of Tests**
Insituform Standard	Non-woven polyester fabric with interior elastomeric (polyurethane) coating	Polyester	40
Insituform Enhanced	Non-woven polyester fabric with interior elastomeric (polyurethane) coating	Polyester (with a compound added)	40

2.2.1.2 TTC Test Method

Tensile and flexural tests are conducted for material characterization in accordance with ASTM D638-89, "Standard Test Method for Tensile Properties of Plastics", and ASTM D790-86, "Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials", respectively. Specimens for material characterization tests are cut from the flat sections of pipe so that the long direction of the specimens is in the transverse direction of the liner. For long-term behavior prediction, CIPP products are tested under external hydrostatic pressure for a period of 10,000 hours. Specimens are installed to fit snugly inside a pipe having a length of at least six times the pipe diameter to minimize the possible effects of edge restraint at the ends. External hydrostatic pressure is applied between the host pipe and liner product from a pressurized water distribution system and the air is removed from the annular space between the product and the host pipe through a pressure relief port (refer to the TTC Report 302 (1994) for details of the test procedure). Once the specimens are prepared for the long-term tests, short-term buckling tests are conducted on at least three specimens to establish an upper limit for the pressures used in the long-term tests. The theoretical buckling pressures of the materials are also computed using Equation 2.6:

$$P_{cr} = \frac{2\,K\,E}{1-v^2} * \frac{1}{(DR-1)^3} \tag{2.6}$$

where, K = enhancement factor (taken as 7 for consistency), E = modulus of elasticity (taken as average ASTM D790 short-term flexural modulus), v = Poisson's ratio (estimated value of 0.35 is used), and DR = dimension ratio. It should be noted that this equation is the same as Equation 2.1 with no safety factor (N) and ovality reduction factor (C).

For the long-term tests, specimens are pressurized at a rate of 10 psi/min (6.9 kPa/min) to the desired test pressure which is held constant for the duration of the test. Once a specimen failed under external hydrostatic pressure, the time of failure is recorded and the test data are plotted on a graph of external pressure at failure versus time to failure on a log-log scale. For prediction of the liner long-term behavior, a curve is then fitted to the test data and extrapolated to 50 years. Test results will be presented in Section 2.2.1.3.

2.2.1.3 TTC Test Results

- ***Material Characterization Tests***

Flexural and tensile modulus of elasticity and strength values are presented in Table 2.2. It is reported that at least six specimens per product are used for the flexural and tensile tests and the results tabulated in Table 2.2 are average values. It should be noted that the flexural and tensile properties are calculated based upon the full wall thickness including any film coating. Modulus of elasticity is calculated using Equation 2.7:

$$E = L^3 M / 4bd^3 \tag{2.7}$$

where E = modulus of elasticity, L = support span, M = slope of the tangent to the initial straight-line portion of the load-deflection curve, b = width of specimen, d = thickness of specimen. Exclusion of the coating thickness from the measured specimen depth increases the value of modulus of elasticity.

Table 2.2 - Material characterization test results (Adapted from *TTC Report 302*, 1994)

Product	**Flexural Test**				**Tensile Test**			
	Modulus of Elasticity, E		Strength		Modulus of Elasticity, E		Strength	
	(MPa)	(psi)	(MPa)	(psi)	(MPa)	(psi)	(MPa)	(psi)
Insituform Standard	3,093	448,630	64.2	9,310	3,934	570,590	27.3	3,960
Insituform Enhanced	3,714	538,620	57.9	8,400	4,498	652,400	27.0	3,910

➢ ***Long-Term Tests***

For the long-term test data analysis, time of failure of the specimens at specified pressures are recorded and plotted on a log-log scale with the pressure on the ordinate and time on the abscissa. It is stated that the specimens which did not fail over the test period are considered as failed at 10,000 hours. For prediction of the long-term behavior of the liners, best-fitting regression is applied using the basic equation of the straight line:

$$Y = a - bX \tag{2.8}$$

where,

$$Y = \log(P) \tag{2.9}$$

and

$$X = \log(t) \tag{2.10}$$

where the values of intercept *a* and slope *b* are determined through linear regression analysis. The test pressure versus time to failure plots generated based on the hydrostatic buckling test results are presented in Figures 2.8 and 2.9.

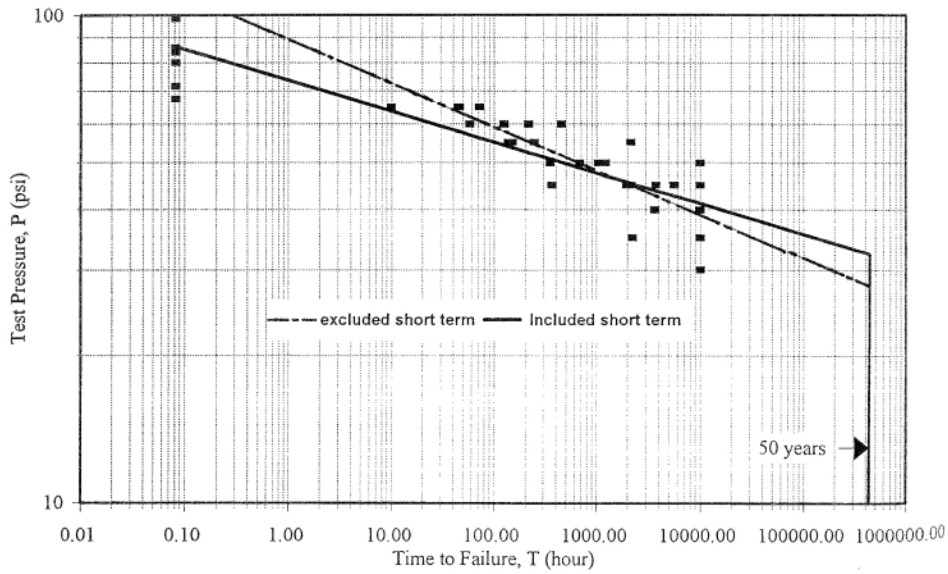


Figure 2.8 - Long-term test and regression results for Insituform Standard product (Adapted from *TTC Report 302*, 1994)

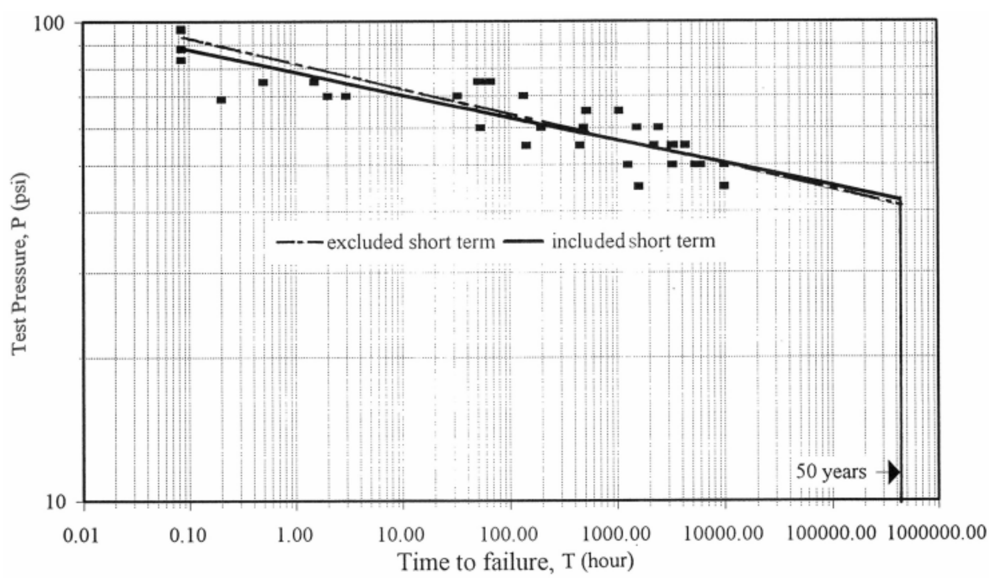


Figure 2.9 - Long-term test and regression results for Insituform Enhanced product (Adapted from *TTC Report 302*, 1994)

The long-term test data are analyzed both by including and excluding the short-term buckling test data. It is reported that there is a better correlation between analytical and experimental results when the short-term data are included in the analysis. From the regression curve, the 50-year extrapolated value of the test buckling pressure ($P_{test50Y}$), which represents the average pressure at which buckling would occur for a liner which has been under that pressure for 50-years, is estimated. The creep factor (C_L) is then defined as the ratio of $E_{test50Y}$ to E_{exp} where $E_{test50Y}$ is the experimentally-derived creep modulus back-calculated from Equation 2.6 by letting $P_{cr} = P_{test50Y}$, and E_{exp} is the experimental (ASTM D790) flexural modulus. The estimated creep factors for the two products are presented in Table 2.3.

Table 2.3 - Estimated creep factors for Insituform Standard and Enhanced CIPP samples (Adapted from *TTC Report 302*, 1994)

Product	$\boldsymbol{E_{exp}}$		$\boldsymbol{E_{test50Y}}$		$\boldsymbol{C_L}$
	(MPa)	(psi)	(MPa)	(psi)	
Insituform Standard	3,093	448,630	1,793	259,990	0.580
Insituform Enhanced	3,714	538,620	2,716	393,965	0.731

The creep factor is applied to the ASTM D790 flexural modulus such that Equation 2.6 predicts the same long-term buckling pressure as determined from the extrapolated regression analysis (*TTC Report 302*, 1994). In the following, a review of the technique used by CATT for prediction of CIPP liners long-term behavior is presented.

2.2.2 CATT Report

The Center for Advancement of Trenchless Technologies (2005) published a report "Testing of AOC and Interplastic Corp. CIPP Resins used within the City of Toronto Sewers" with the objective of providing a better understanding of CIPP resins including short-term and long-term design strength properties and creep factors. Tensile, flexural and flexural creep tests are completed on four different CIPP resins used for rehabilitation of the City of Toronto wastewater network.

To evaluate the long-term behavior of the CIPP resins, rectangular specimens are tested as a beam in flexural creep under a constant load for a period of 10,000 hours in accordance with ASTM D2990-01 specifications. Creep moduli values of a particular specimen calculated based on the amount of deflection at specified time steps are plotted versus time on a semi-logarithmic scale. These data are then extrapolated beyond the 10,000 hour test period to estimate the material 50-year creep modulus. The materials analyzed in this report are similar to the materials discussed in the TTC Report 302 in the previous section. Test results are compared to that of TTC Report and a summary of the comparison between the two techniques is provided in Section 2.2.3.

2.2.2.1 CATT Test Material

Test materials supplied by AOC and Interplastic Corp. are CIPP resin products called Standard and Enhanced. The Enhanced resins contained a filler to increase the flexural properties. The CIPP resin samples are provided in the form of flat plates. The product designation for each of the four CIPP resins is presented in Table 2.4.

Table 2.4 - CIPP products provided by the manufacturers (Adapted from *CATT Report*, 2005)

Supplier	Resin Type	Product
AOC	Standard	102NA
AOC	Enhanced	102TA
Interplastic Corp.	Standard	COR72-AA-455HV
Interplastic Corp.	Enhanced	COR72-AT-470

It is reported that the Interplastic Corp. Standard resin COR72-AA-455HV is a high viscosity version of resin COR72-AA-455 while the Enhanced resin COR72-AT-470 is a thixotropic, strength enhanced, polyester, perkadox catalyzed system. Specimens for both the short-term and long-term tests are cut out of the plates using computer controlled abrasive water jet cutting technology which produces test specimens with no heat distortion, mechanical stresses and that are residual stress free (*CATT Report*, 2005).

2.2.2.2 CATT Test Method

Short-term flexural and tensile tests are conducted for material characterization in accordance with ASTM D790-03 and ASTM D638-03, respectively. The long-term creep tests are conducted in accordance with ASTM D2990-01 which outlines the test procedure for determining the long-term flexural creep modulus. For the creep tests, simply supported rectangular specimens are loaded at mid-span for a period of 10,000 hours in a controlled temperature and humidity laboratory. It is reported that the specimens are prepared to have a span to depth ratio of 16+/-1 to avoid shear stress effects. ASTM D2990 does not specify the load required for long-term tests. However, it is stated in the CATT Report (2005) that based on the review of North American and European practices, a load that creates a flexural stress equivalent to 25 percent of the material ASTM D790 yield stress is selected for the long-term creep test. After application of the load, deflection measurements are taken for each test specimen at approximately 1, 6, 12, 30 minutes and then at 1, 2, 5, 10, 30, 60, 100, 300, 500, 1000, 2000, 3000, 4000, 5000, 6000, 7000, 8000, 9000, and 10,000 hours. Specimen deflection is monitored using dial gages, with a reading resolution of ± 0.0005 in. (0.01 mm). A typical flexural creep test setup is shown in Figure 2.10.

Figure 2.10 - End view of specimens under creep load
(Adapted from *CATT Report*, 2005)

A minimum of five specimens are tested from each test plate. Creep modulus is calculated at each test reading to generate a plot of creep modulus versus time on a semi-log scale to predict the CIPP resin long-term behavior. Results for both the short-term and long-term tests are presented in Section 2.2.2.3.

2.2.2.3 CATT Test Results

- ***Short-Term Tests***

For the tensile tests, the specimens which failed outside of the limits of extensometer gage are not considered for analysis. Short-term flexural and tensile modulus of elasticity and strength values are presented in Table 2.5. It is reported that at least five specimens from each resin type are tested for both tensile and flexural tests, and the results presented in Table 2.5 are average values. The flexural and tensile properties are calculated based upon the average thickness of the specimens.

Table 2.5 - Short-term flexural and tensile test results (Adapted from *CATT Report*, 2005)

Product	**Flexural Test**				**Tensile Test**			
	Modulus of Elasticity, E		Strength		Modulus of Elasticity, E		Strength	
	(MPa)	(psi)	(MPa)	(psi)	(MPa)	(psi)	(MPa)	(psi)
AOC Standard	3,931	570,127	56.6	8,215	3,744	543,000	33.0	4,786
AOC Enhanced	5,022	728,449	55.3	8,022	Failure occurred outside of gage length			
Interplastic Corp. Standard	4,526	656,427	58.9	8,541	3,359	487,254	31.4	4,557
Interplastic Corp. Enhanced	6,073	880,816	55.5	8,051	4,367	633,380	28.0	4,061

➢ *Long-Term Tests*

For prediction of the liner long-term behavior, a plot is generated with creep modulus on the ordinate and time on the abscissa for each of the test specimens. The data are extrapolated using a linear regression analysis to predict the 50-year (about 438,000 hours) creep modulus using the following relationship:

$$\text{Creep modulus} = a * \log(\text{time}) + b \qquad \textbf{(2.9)}$$

where *a* and *b* are regression constants.

The creep factor (C_L) is then defined as the ratio of E_L to E where E_L is the long-term time-corrected flexural modulus (taken as the 50-year predicted creep modulus) and E is the resin short-term ASTM D790 flexural modulus. The 50-year creep modulus is estimated using two regression analyses; (1) using all 10,000 hour test data, and (2) using 1000 hour interval test data only. An example plot showing the two regression analyses is illustrated in Figure 2.11.

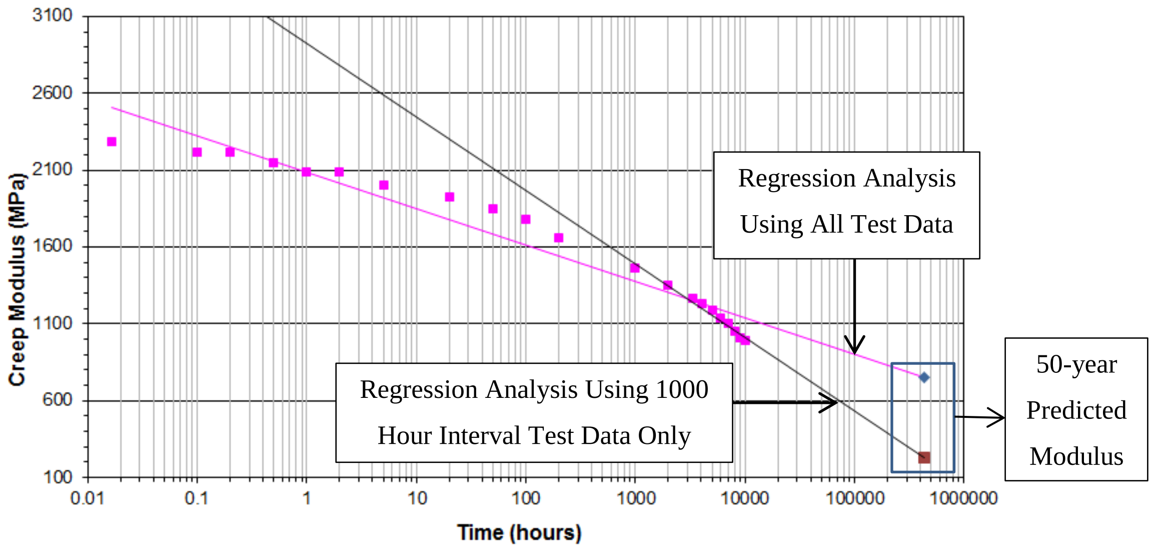


Figure 2.11 - Example plot showing the two regression analyses

This Figure shows that the two regression analyses methods can result in very different 50-year modulus, approximately 800 MPa when all test data is used and approximately 200 MPa when only 1000 hour interval data is used. This is a factor of four difference. It is agreed that the regression of 1000 hour interval data results in a better prediction of the 50-year modulus and the regression of all test data is not appropriate or realistic for the materials that do not have a linear response on a creep modulus versus log time graph (*CATT Report*, 2005). Creep modulus versus time plots showing the 50-year predicted creep modulus estimated using 1000 hour interval data for AOC and Interplastic Corp. resins are presented in Figures 2.12 to 2.15.

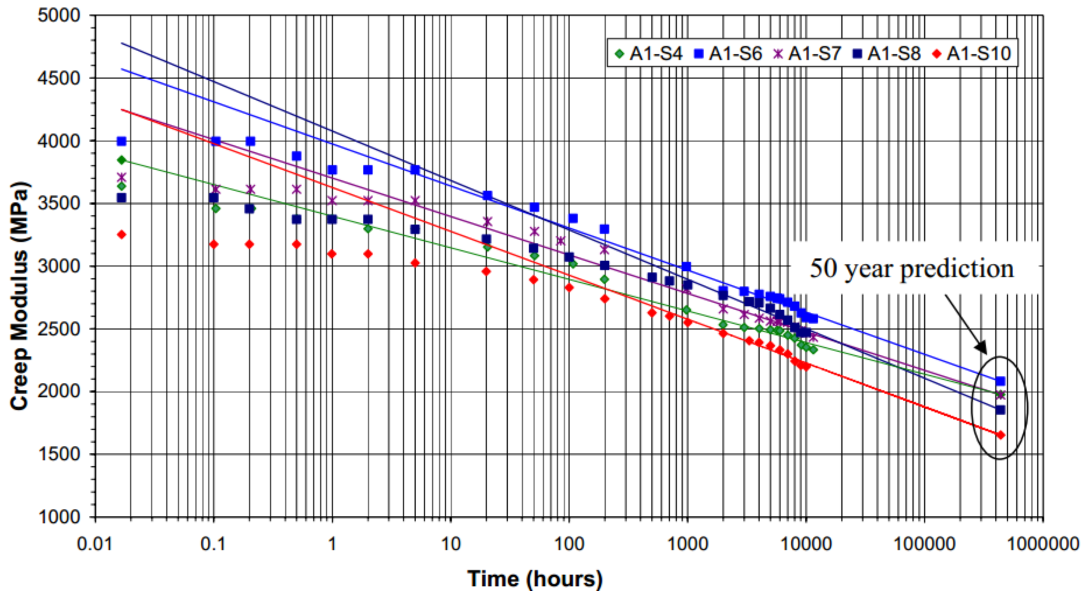


Figure 2.12 - AOC Standard resin long-term test analysis
(Adapted from *CATT Report*, 2005)

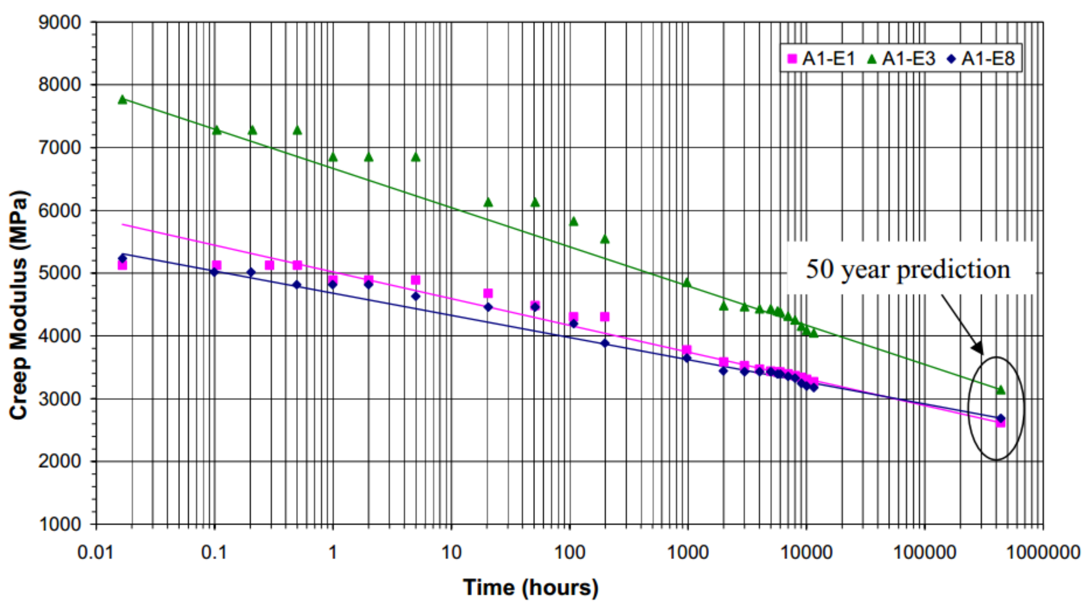


Figure 2.13 - AOC Enhanced resin long-term test analysis
(Adapted from *CATT Report*, 2005)

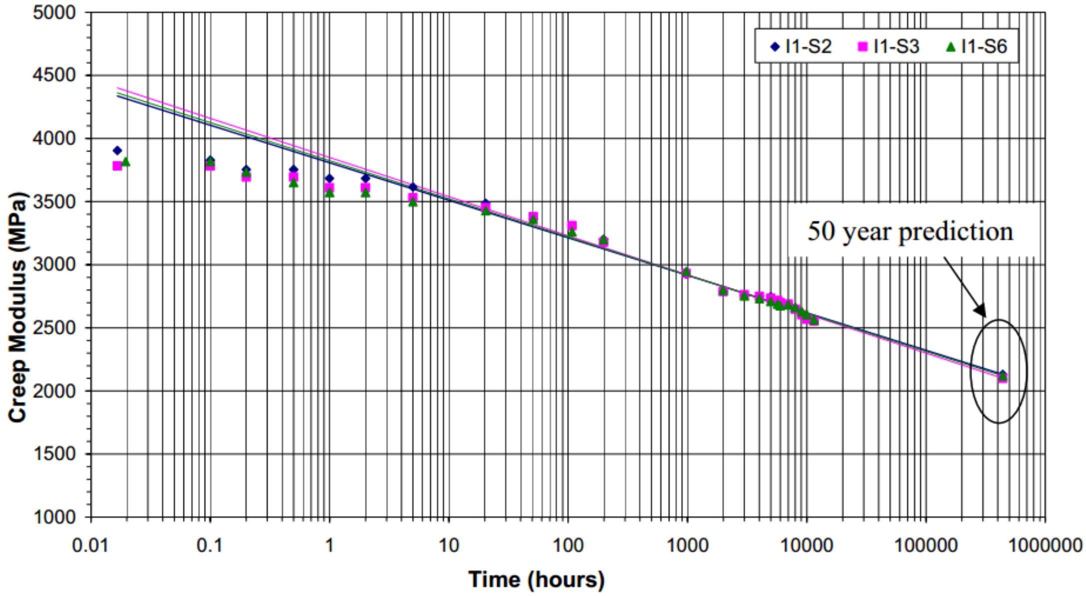


Figure 2.14 - Interplastic Corp. Standard resin long-term test analysis
(Adapted from *CATT Report*, 2005)

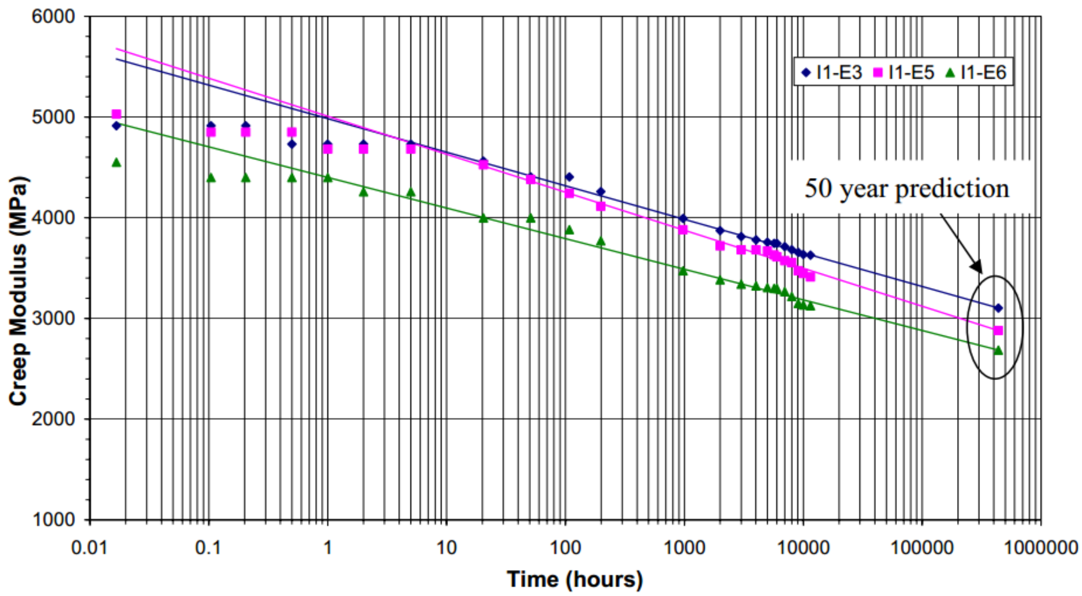


Figure 2.15 - Interplastic Corp. Enhanced resin long-term test analysis
(Adapted from *CATT Report*, 2005)

The creep factors estimated using both regression analyses are presented in Table 2.6. Based on the data presented in Table 2.6, the estimated creep retention factors using 1000 hour interval test data are lower than the ones estimated by using all test data.

Table 2.6 - Estimated creep factors for the four CIPP resin samples (Adapted from *CATT Report*, 2005)

Product	**Average Short-term ASTM D790 Initial Tangent Modulus**		**Average Long-term Extrapolated 50-year Creep Modulus**				**Average Creep Factor (C_L)**	
			Using all test data		Using 1000 hour interval test data		Using all test data	Using 1000 hour interval test data
	(MPa)	(psi)	(MPa)	(psi)	(MPa)	(psi)		
AOC Standard	3,931	570,127	2,150	311,869	1,908	276,672	0.55	0.49
AOC Enhanced	5,022	728,449	2,873	416,701	2,817	408,593	0.57	0.56
Interplastic Corp. Standard	4,526	656,427	2,286	331,539	2,116	306,955	0.51	0.47
Interplastic Corp. Enhanced	6,073	880,816	3,071	445,481	2,889	419,036	0.51	0.48

2.2.3 Summary of the TTC and CATT Creep Testing

Based on the test results reported in Tables 2.2 and 2.5, the Insituform Standard product has a higher tensile modulus of elasticity (E_{D638}) than the AOC and Interplastic Corp. Standard resins. However, the tensile strength (σ_{D638}) of the Insituform Standard product is lower compared to the AOC and Interplastic Corp. Standard resins. The Insituform Enhanced product has similar tensile properties to that of Interplastic Corp. Enhanced resin. The reported flexural modulus of elasticity (E_{D790}) for the Insituform Standard resin is less than the AOC and Interplastic Corp. Standard resins by about 838 MPa and 1433 MPa, respectively. The reported E_{D790} value for the Insituform Enhanced resin is less than the AOC and Interplastic Corp. Enhanced resins by about 1308 MPa and 2359 MPa, respectively. However, the Insituform products have higher flexural strength (σ_{D790}) values compared to the AOC and Interplastic Corp. resins.

The creep factors reported using both methodologies are estimated based on the assumption that the long-term time-corrected modulus of elasticity, E_L can be defined by multiplying the short-term ASTM D790 flexural modulus by some factor to account for material creep behavior. The creep factors obtained using the hydrostatic buckling test and the ASTM D2990 flexural creep test are compared in Figure 2.16.

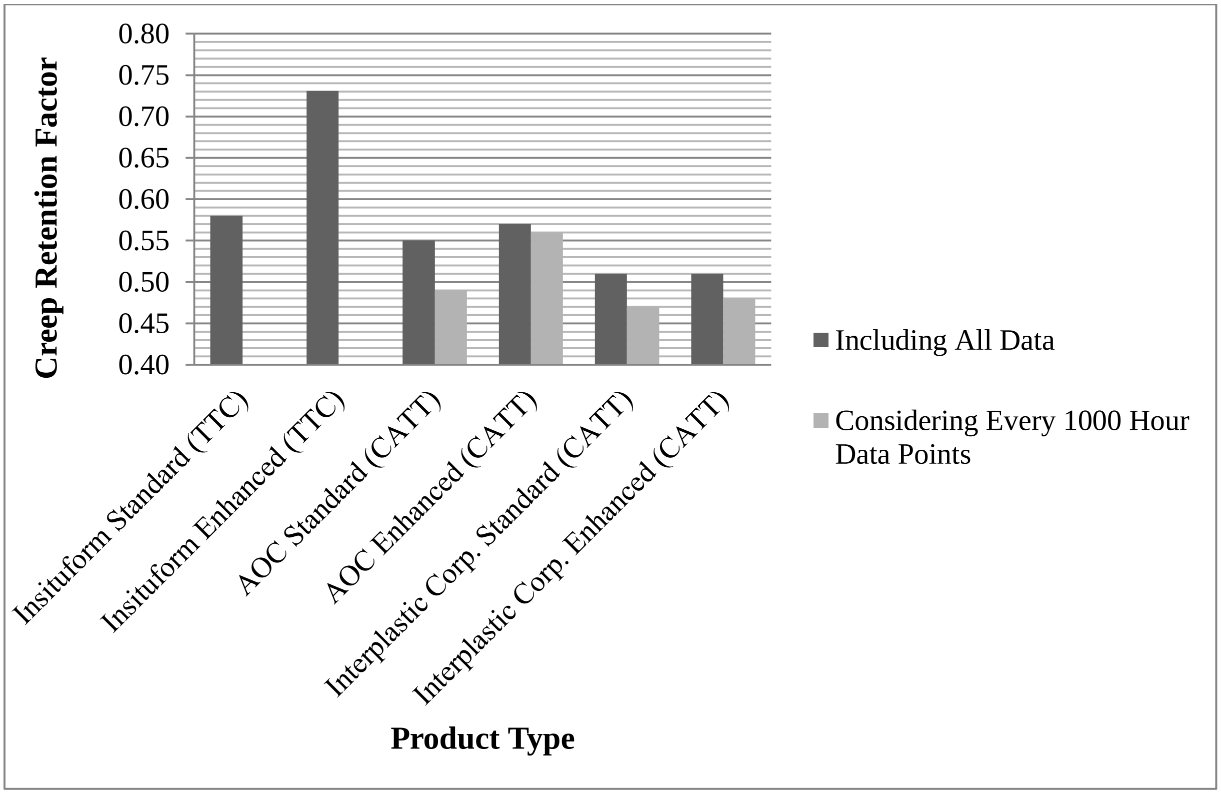


Figure 2.16 - Comparison of creep factors reported in TTC and CATT reports

As shown in Figure 2.16, the estimated creep factors reported by TTC are higher than the factors reported by CATT. It should be noted that direct comparison between the different products may be misleading. However, the difference in creep factors can be attributed to the different test methods, each measuring different long-term properties. Also, inclusion of specimens which did not fail over the test period considered as failed at 10,000 hours, may add to the conservativeness of the creep retention factors obtained using the hydrostatic buckling test.

It has become industry standard practice to set E_L at 50% of the initial value of the modulus of elasticity of a CIPP liner for an expected service life of 50 years (*TTC Report 302*, 1994). The estimated creep factors of 0.580 and 0.731 for the Insituform Standard and Enhanced products respectively, suggest that 50% reduction of initial flexural modulus of elasticity would be conservative (*TTC Report 302*, 1994). The creep factors presented in the TTC Report are estimated based on the linear regression analysis of buckling time versus applied pressure data. It should be noted that the long-term buckling experiments of liners demonstrated a large amount of scatter when the buckling time is plotted against the applied pressure (*Zhao et al.*, 2005).

The creep factors estimated by considering all of the data (i.e. initial 1-minute to final) and reported by CATT range from 0.51 to 0.57 and the creep factors estimated by considering the data points at every 1000 hours, range from 0.47 to 0.56. A standard creep retention factor of 0.5 seems to be reasonable for CIPP resins manufactured by AOC and Interplastic Corp. and no significant difference is observed between the creep response of the Standard and Enhanced resins (*CATT Report*, 2005).

Based on the data presented in Figure 2.16, the results of both long-term test methods presented in TTC and CATT Reports are similar and both suggest that the choice of 0.5 as a creep retention factor applied to the short-term flexural modulus is reasonable and conservative for the products tested. Therefore, application of ASTM D2990 Standard for prediction of plastic material long-term behavior does provide comparable results to the long-term tests using sustained external hydrostatic pressure.

Kleweno (1998) also compared long-term test results obtained from various resin types and testing conditions utilizing ASTM D2990 test method to the long-term data reported in TTC Report 302 (1994) and concluded that the two test methods can be correlated closely. Kleweno (1998) also stated that the correlation indicates both methodologies produce similar long-term performance predictions of pipe lining systems. Long-term hydrostatic buckling test involves a number of sample production steps, specialized test equipment, and a large facility to maintain the specimens (*Kleweno*, 1998). Comparing to the method described in TTC Report 302, the ASTM D2990 provides a relatively simple test procedure for obtaining an estimate of the long-term performance of CIPP lining systems.

2.3 Analysis of 96,000 Hours of Flexural Creep Test Data

For the selection of rehabilitation liner systems, it is highly desirable to test the material properties as long as the design life of the liner (*TTC Report 302*, 1994). However, because of the costs associated with long-term testing, it has become industry standard to perform long-term tests on rehabilitation liners for a period of 10,000 hours to predict the material long-term behavior (*TTC Report 302*, 1994). After CATT's (2005) completion of 10,000 hours (about 1.14 years) of creep test, sample deflection readings were continued annually until 11 years of creep data was obtained. The test started in 2003 with a minimum of five specimens from each resin type. Some of the specimens failed over time and some are still undergoing the test at the time this thesis was written. It is not clear exactly why some of the specimens have failed. However, it should be noted that there is sometimes variations in specimens cut from the laboratory manufactured CIPP panels provided by the supplier.

In 2010, after about seven years of creep test, one specimen from each resin type was removed to be tested in flexure to analyze the effect of continuously applied stress on the flexural properties of the resin. The flexural test results are provided in Section 2.4. For all surviving specimens, 50-year creep moduli values are estimated based on 96,000 hours (about 11 years) of creep test data. This test period is 9.6 times the standard test period of 10,000 hours. The AOC and Interplastic Corp. creep modulus versus time plots with the extrapolated 50-year creep moduli values are illustrated in Figures 2.17 to 2.20.

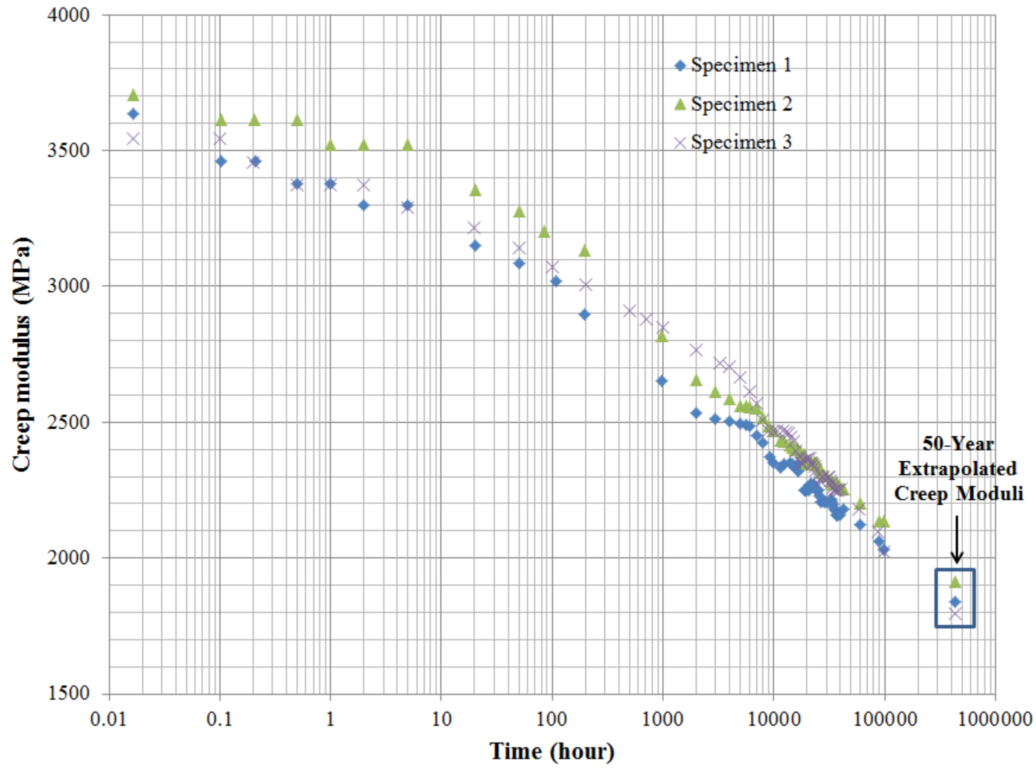


Figure 2.17 - AOC Standard – 96,000 Hours Analysis

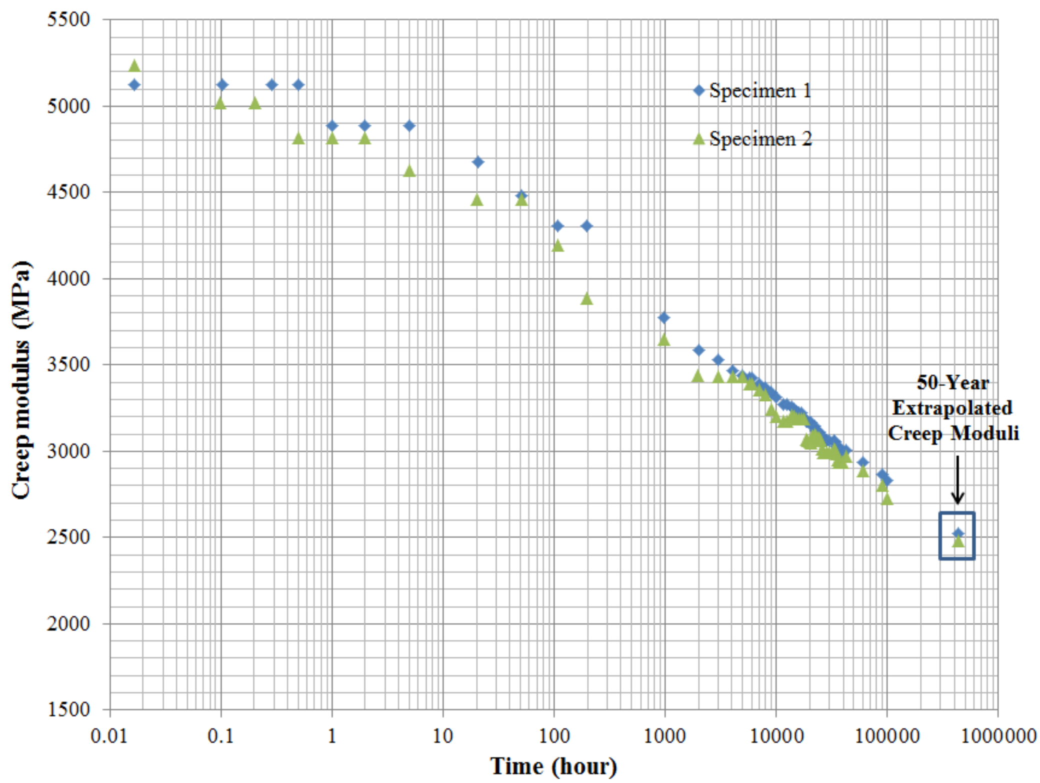


Figure 2.18 - AOC Enhanced – 96,000 Hours Analysis

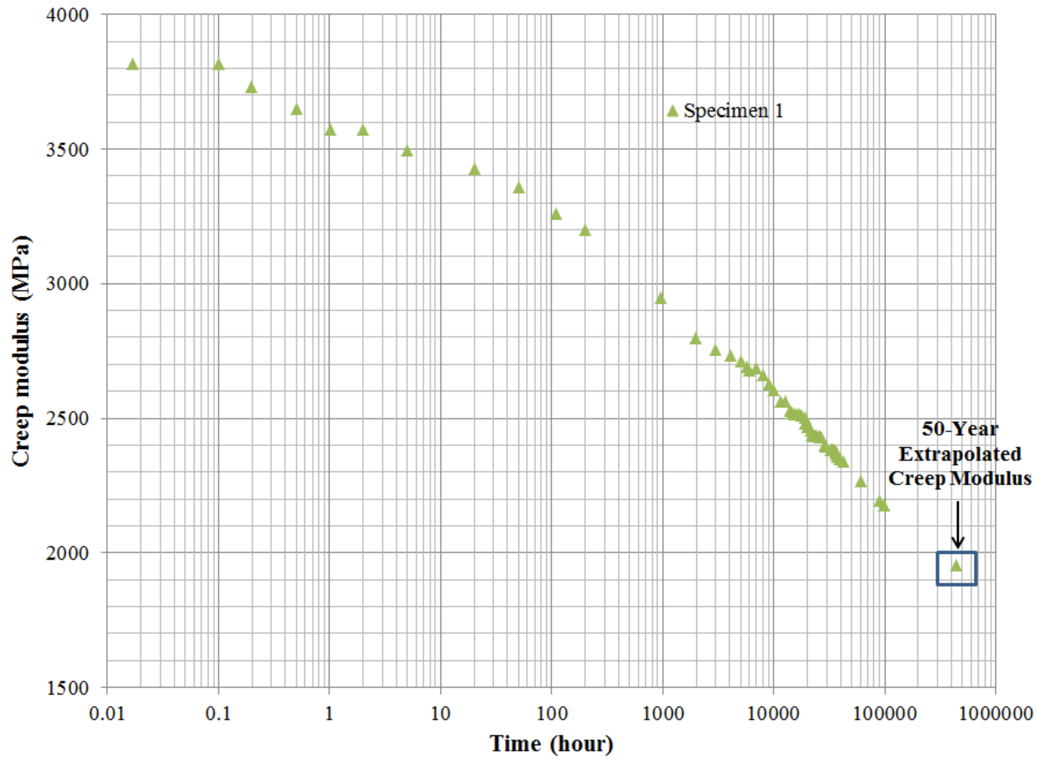


Figure 2.19 - Interplastic Corp. Standard – 96,000 Hours Analysis

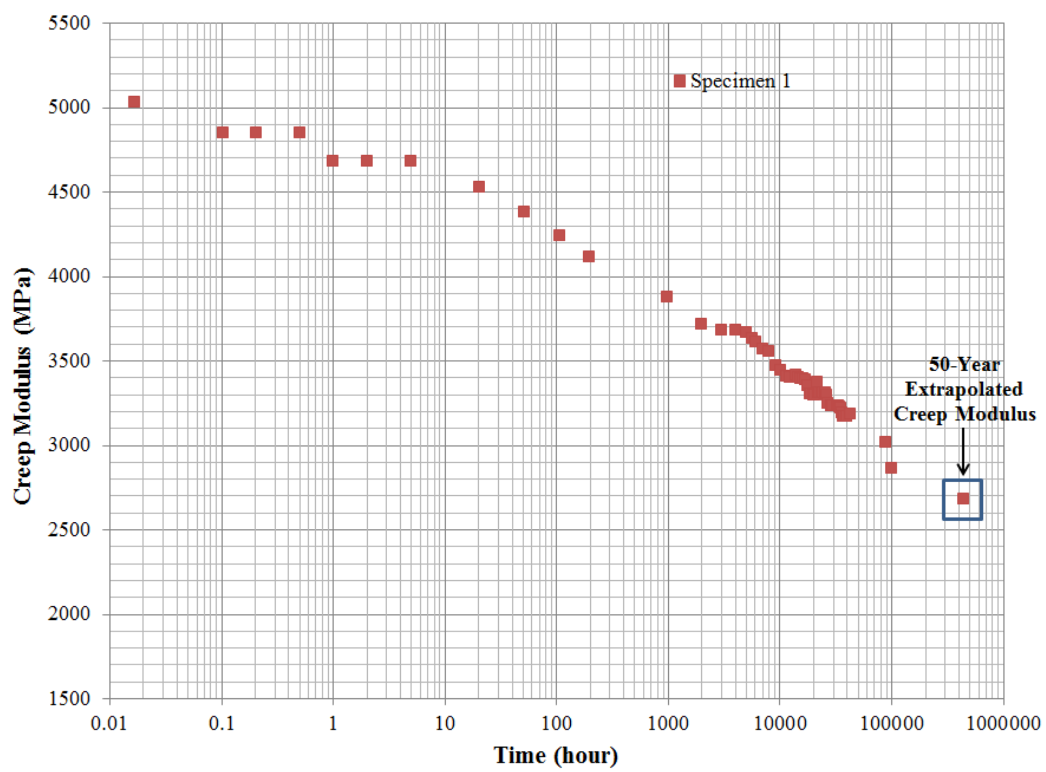


Figure 2.20 - Interplastic Corp. Enhanced – 96,000 Hours Analysis

The 50-year creep moduli values estimated using 96,000 hours of creep test data based on the two regression analyses (i.e., using all test data versus using only after the 1000 hour data points) are presented in Table 2.7. The creep retention factors estimated using 10,000 hours and 96,000 hours of creep test data are compared in Table 2.8.

Table 2.7 - Extrapolated 50-year creep moduli values using 96,000 hours of creep test data

Product	**No. of Specimens**	**Average Short-term ASTM D790 Initial Tangent Modulus**		**Extrapolated 50-Year Creep Modulus**							
				Using all data				Using only after the 1000 hour data points			
				Mean		Standard Deviation		Mean		Standard Deviation	
		(MPa)	(psi)	(MPa)	(psi)	(MPa)	(psi)	(MPa)	(psi)	(MPa)	(psi)
AOC Standard	3	3,931	570,127	2,008	291,236	59	8,557	1,850	268,320	60	8,702
AOC Enhanced	2	5,022	728,449	2,604	377,678	36	5,221	2,502	362,884	32	4,641
Interplastic Corp. Standard	1	4,526	656,427	2,125	308,205	N/A	N/A	1,955	283,549	N/A	N/A
Interplastic Corp. Enhanced	1	6,073	880,816	2,902	420,899	N/A	N/A	2,683	389,136	N/A	N/A

Table 2.8 - Comparison of creep factors estimated based on 10,000 hours and 96,000 hours of test data

Product	**Average C_L Based on 10,000 Hours Analysis**		**Average C_L Based on 96,000 Hours Analysis**		***Difference in C_L**	
	Using all test data	Using only after the 1000 hour data points	Using all test data	Using only after the 1000 hour data points	Using all test data	Using only after the 1000 hour data points
AOC Standard	0.55	0.49	0.51	0.47	-0.04	-0.02
AOC Enhanced	0.57	0.56	0.52	0.50	-0.05	-0.06
Interplastic Corp. Standard	0.51	0.47	0.47	0.43	-0.04	-0.04
Interplastic Corp. Enhanced	0.51	0.48	0.48	0.44	-0.03	-0.04

* (-) means decrease in creep factor

As shown in Table 2.8, the estimated creep factors for all of the four CIPP products have decreased when comparing the values based on 10,000 hours and 96,000 hours of testing regardless of the method of analysis. Based on 11 years of test data, the estimated creep factors considering only after the 1000 hours data points, are all below 0.5 except the AOC Enhanced resin which is 0.5. This demonstrates that the creep rate is slightly increasing after the 10,000 hours test period. However, the data presented in Table 2.8 suggest that the industry standard creep retention factor of 0.5 may not be conservative as oppose to the factors obtained based on 10,000 hours of long-term testing. Thus, creep retention factor of 0.5 may not be applicable for all resin types and designers may want to consider using lower creep retention factors.

As mentioned above, some specimens failed (one from each of the Interplastic Corp. resin products) after the 10,000 hours and one specimen was removed from each of the four products for flexural analysis. Thus, the number of specimens, and in particular the Interplastic Corp. resins, that survived the 96,000 hours of constant loading is not sufficient for statistical analysis. However, the analysis presented does provide valuable insight on how the creep behavior of different CIPP resins has changed beyond the standard test period of 10,000 hours.

2.4 Impact of 61,000 Hours of Creep Test on Flexural Properties

In 2010, after about seven years (approximately 61,000 hours) of creep test, one specimen from each resin type was removed to be tested in flexure in accordance with ASTM D790 specifications to analyze the effect of continuously applied constant stress on flexural properties of the CIPP products. The flexural stress-strain responses of four specimens from AOC and Interplastic Corp. resins tested initially in flexure and a specimen tested in flexure after seven years of undergoing creep test are compared in Figures 2.21 to 2.24.

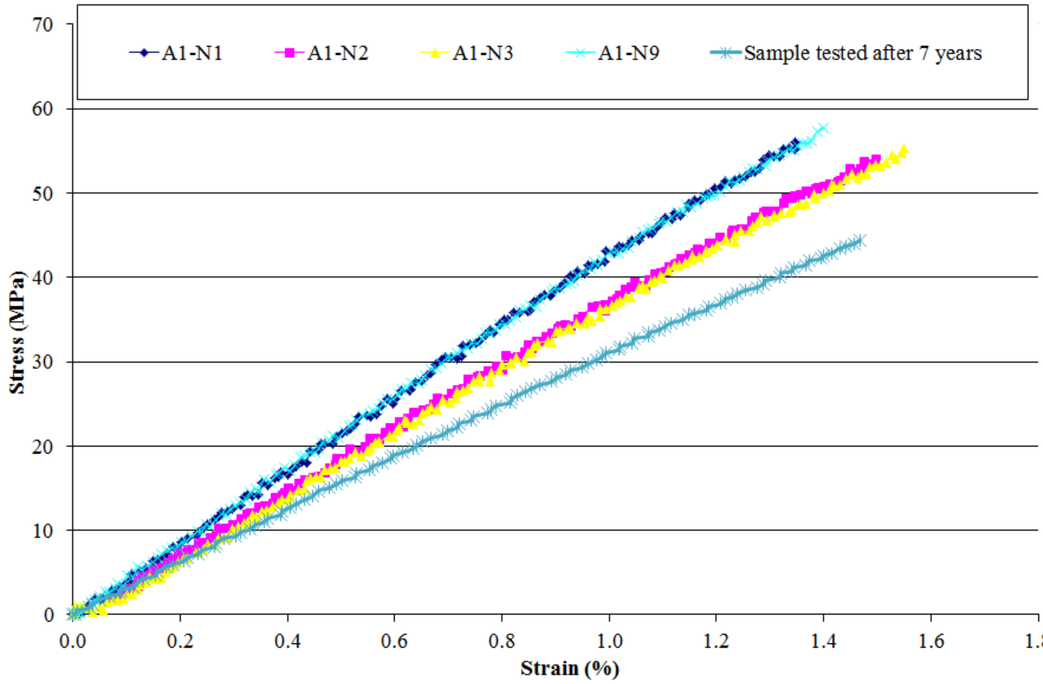


Figure 2.21 - AOC Standard - Comparison of flexural stress-strain responses

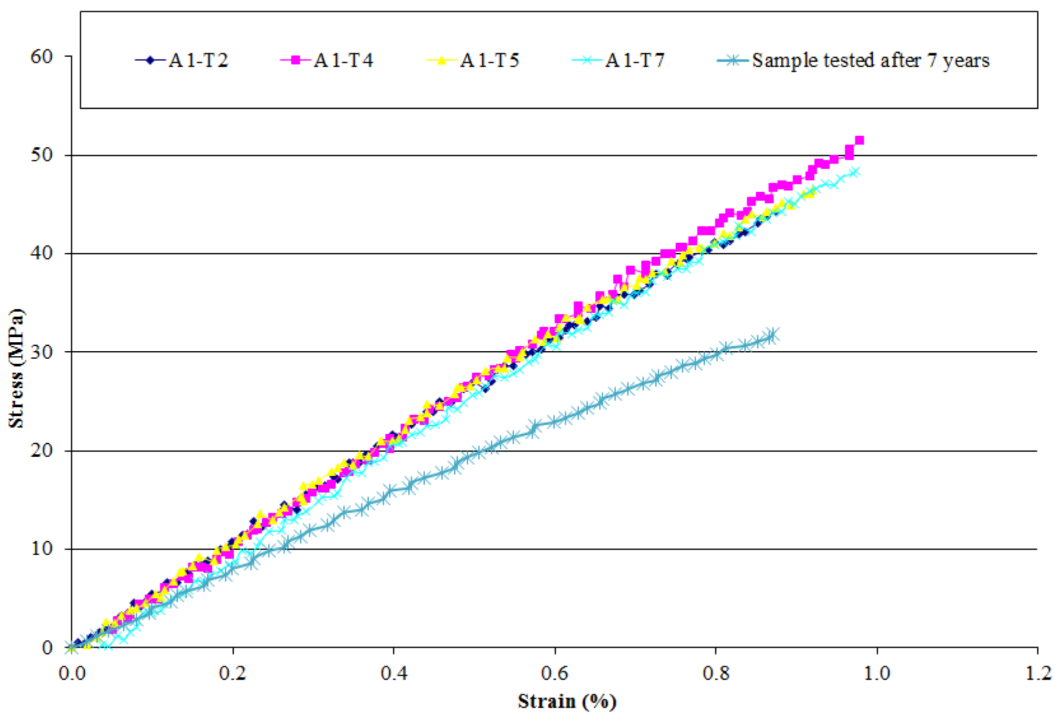


Figure 2.22 - AOC Enhanced - Comparison of flexural stress-strain responses

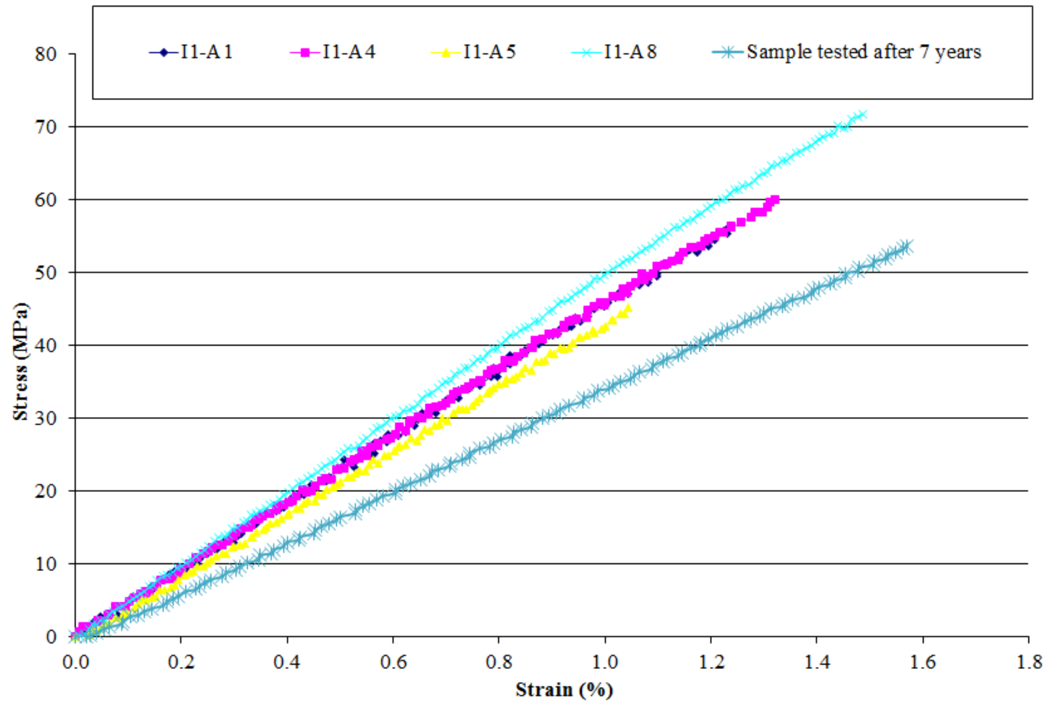


Figure 2.23 - Interplastic Corp. Standard - Comparison of flexural stress-strain responses

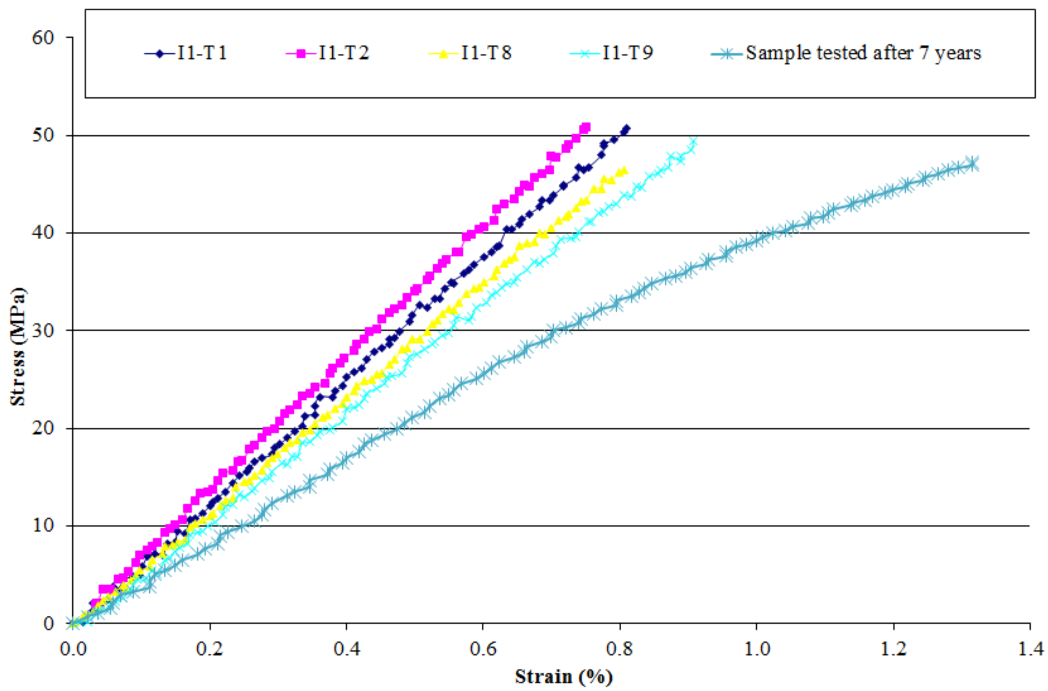


Figure 2.24 - Interplastic Corp. Enhanced - Comparison of flexural stress-strain responses

Initial ASTM D790 flexural modulus values (before the start of creep test) are compared with the values obtained after seven years of continuous loading in Table 2.9. This Table shows that the AOC and Interplastic Corp. Standard resins have higher flexural modulus retention factors compared to the Enhanced resins. The flexural modulus retention factors range from 0.70 to 0.77 after seven years of creep test.

Table 2.9 - Comparison of ASTM D790 flexural moduli values before and after undergoing creep test

Liner Type	**Sample No.**	**Initial Flexural Modulus**		**Mean**		**Standard Deviation**		**Flexural Modulus After 7 years of creep test**		**Modulus Retention Factor**
		(MPa)	(psi)	(MPa)	(psi)	(MPa)	(psi)	(MPa)	(psi)	
AOC Standard	1	4,208	610,300	3,930	570,000	294	42,640	3,042	441,200	0.77
	2	3,698	536,400							
	3	3,655	530,100							
	4	4,157	602,900							
AOC Enhanced	1	5,118	742,300	5,225	757,800	113	16,390	3,700	536,600	0.71
	2	5,369	778,800							
	3	5,156	747,800							
	4	5,256	762,300							
Interplastic Corp. Standard	1	4,550	659,900	4,594	666,300	215	31,180	3,491	506,400	0.76
	2	4,552	660,200							
	3	4,381	635,400							
	4	4,893	709,600							
Interplastic Corp. Enhanced	1	6,340	919,600	6,127	888,600	540	78,320	4,292	622,500	0.70
	2	6,768	981,600							
	3	5,864	850,500							
	4	5,536	803,000							

The flexural strength values before and after undergoing creep test, are presented in Table 2.10. This Table shows that the flexural strength retention factors for the Standard and Enhanced resins range from 0.67 to 0.96. The AOC resins have lower flexural strength retentions factors compared to the Interplastic Corp. resins. However, for the Interplastic Corp. samples, it cannot be concluded that the flexural strength values have decreased, since the strength value after seven years falls in the range of strength values obtained initially. The flexural properties after seven years presented in Table 2.10 are obtained from only one specimen. Therefore, it is not possible to analyze the test results statistically. However, the comparison is useful to develop a better understating of CIPP liners flexural properties after undergoing constant stress for a long period of time. It should be noted that the values presented in Tables 2.9 and 2.10 are only based on seven years of constant stress (equivalent to 25% of the liner initial flexural yield strength). If the 50 year design life is considered, the flexural properties may potentially decrease even more. However, based on the data presented in Tables 2.9 and 2.10, the retention factor of 0.5 which is commonly applied to the liners short-term flexural modulus and flexural strength to obtain long-term values may be considered as conservative.

Table 2.10 - Comparison of ASTM D790 flexural strength values before and after undergoing creep test

Liner Type	**Sample No.**	**Initial Flexural Strength**		**Mean**		**Standard Deviation**		**Flexural Strength After 7 years of creep test**		**Strength Retention Factor**
		(MPa)	(psi)	(MPa)	(psi)	(MPa)	(psi)	(MPa)	(psi)	
AOC Standard	1	56.0	8,120	55.8	8,090	1.53	222	44.4	6,440	0.80
	2	54.1	7,840							
	3	55.3	8,030							
	4	57.8	8,380							
AOC Enhanced	1	44.3	6,430	47.7	6,910	3.04	441	31.9	4,620	0.67
	2	51.5	7,460							
	3	46.4	6,730							
	4	48.4	7,030							
Interplastic Corp. Standard	1	56.0	8,130	58.3	8,450	10.9	1584	53.7	7,790	0.92
	2	60.1	8,710							
	3	45.3	6,560							
	4	71.7	10,400							
Interplastic Corp. Enhanced	1	50.7	7,350	49.4	7,160	2.02	293	47.2	6,850	0.96
	2	50.8	7,370							
	3	46.5	6,740							
	4	49.5	7,180							

3 Test Program

3.1 Introduction

The Interplastic Corporation, with headquarters in St. Paul, Minnesota, is a specialty chemical company that produces CIPP liners for rehabilitation of water and wastewater pipelines commonly used within North America. In 2013, the company asked the Center for Advancement of Trenchless Technologies to investigate the short-term and long-term physical properties of reinforced CIPP liners of various bag materials and thermoset resins. For the characterization of material short-term properties (i.e., tensile and flexural properties), CATT proposed the ASTM D638 and ASTM D790 test methods, respectively and ASTM D2990 for long-term properties. In the following chapters, description of the test material and the short-term and long-term test procedures along with the test results are presented.

3.2 Test Material

All of the CIPP products are manufactured by Interplastic Corporation. There are a total of nine different CIPP samples constructed using three different resins and three different fiberglass containing reinforced bag materials that are analyzed in this research project. Eighteen test plates, two from each product are provided. Test plates are labelled as follows:

Resin 1 / Reinforced CIPP Liner A
Resin 2 / Reinforced CIPP Liner A
Resin 3 / Reinforced CIPP Liner A
Resin 1 / Reinforced CIPP Liner B
Resin 2 / Reinforced CIPP Liner B
Resin 3 / Reinforced CIPP Liner B
Resin 1 / Reinforced CIPP Liner C
Resin 2 / Reinforced CIPP Liner C
Resin 3 / Reinforced CIPP Liner C

The designation of resins and CIPP bag materials are provided in Appendix A. A typical CIPP test plate (“as received” condition) showing the proposed direction for sample cutting is shown in Figure 3.1. Dimensions of the plates measured using a digital caliper are presented in Table 3.1. All of the following informtion about the CIPP components is provided by the Interplastic Corporation and presented in the paper by Hazen (2015).

Figure 3.1 - Front view of a typical CIPP plate ("as received condition")

Table 3.1 - "As received" plate dimensions

"As received" Plate Description	Depth*	Length		Width	
	(mm)	(in)	(mm)	(in)	(mm)
Resin1/Reinforced CIPP Liner B - #2	7.34	15.44	392.11	7.59	192.88
Resin1/Reinforced CIPP Liner B - #3	7.63	15.97	405.61	7.59	192.88
Resin2/Reinforced CIPP Liner B - #1	7.36	15.75	400.05	7.31	185.74
Resin2/Reinforced CIPP Liner B - #2	7.13	16.00	406.40	7.34	186.53
Resin3/Reinforced CIPP Liner B - #1	7.54	15.08	382.98	7.39	187.72
Resin3/Reinforced CIPP Liner B - #2	7.32	15.67	398.07	7.73	196.45
Average	7.39	15.65	397.54	7.49	190.37
Resin1/Reinforced CIPP Liner C - #1	4.85	15.88	403.23	8.94	227.01
Resin1/Reinforced CIPP Liner C - #2	4.85	15.88	403.23	9.09	230.98
Resin2/Reinforced CIPP Liner C - #1	4.58	15.69	398.46	8.66	219.87
Resin2/Reinforced CIPP Liner C - #2	5.22	15.41	391.32	8.72	221.46
Resin3/Reinforced CIPP Liner C - #1	5.38	15.88	403.23	8.63	219.08
Resin3/Reinforced CIPP Liner C - #2	4.92	15.72	399.26	9.13	231.78
Average	4.99	15.74	399.79	8.86	225.03
Resin1/Reinforced CIPP Liner A - #1	10.57	13.69	347.66	8.28	210.34
Resin1/Reinforced CIPP Liner A - #2	10.57	13.83	351.23	8.52	216.30
Resin2/Reinforced CIPP Liner A - #1	10.55	14.06	357.19	8.33	211.53
Resin2/Reinforced CIPP Liner A - #2	10.55	13.94	354.17	8.53	216.69
Resin3/Reinforced CIPP Liner A - #1	10.51	13.16	334.17	8.56	217.49
Resin3/Reinforced CIPP Liner A - #2	10.51	13.78	350.04	8.78	223.04
Average	10.54	13.74	349.08	8.50	215.90

*In ASTM testing, depth referes to the thickness

3.2.1 Vinyl Ester Resins

The first resin, refered to as “R1”, is a styrenated, bisphenol-A epoxy vinyl ester resin which is a versatile resin used for pipeline rehabilitation for more than 20 years (*Hazen*, 2015). The second resin, refered to as “R2”, is a styrenated, higher elongation epoxy vinyl ester resin which combines the enhanced corrosion resistant properties of vinyl ester resins with higher tensile elongation properties making it more suitable for lines requiring high pressure ratings such as forcemains and water lines. However, due to the components used in its manufacture, this resin is not recommended by Interplastic Corp. for potable water lines. The third resin, refered to as “R3”, is both styrene-free and VOC-free and has the enhanced pressure capabilities of “R2”. The tensile and flexural properties of the resins, without reinforcement, provided by Interplastic Corp. and tested in accordance with the ASTM D638 and D790 specifications are presented in Table 3.2. The flexural and tensile moduli of the resins are compared in Figure 3.2. The flexural and tensile strength values are compared in Figure 3.3.

Table 3.2 - Average resin properties without reinforcement (Adapted from *Hazen*, 2015)

Resin	**Initial Flexural Modulus**		**Ultimate Flexural Strength**		**Tensile Modulus**		**Tensile Strength**		**Tensile Elongation**
	MPa	psi	MPa	psi	MPa	psi	MPa	psi	%
R1	3,240	470,000	132	19,100	3,170	460,000	75.9	11,000	4.2
R2	3,100	450,000	114	16,500	3,100	450,000	70.0	10,000	5.6
R3	N/A	N/A	N/A	N/A	2,140	310,000	45.5	6,600	6.3

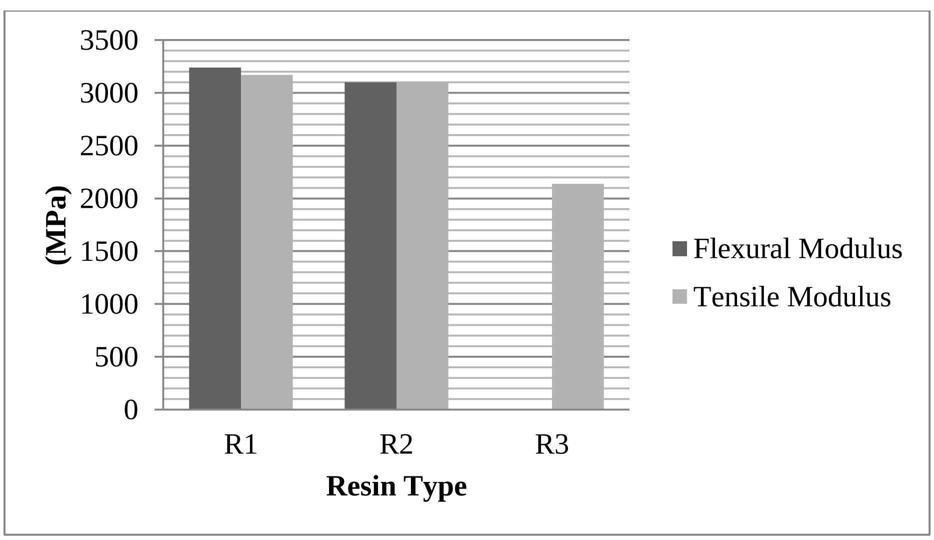


Figure 3.2 - Comparison of resins flexural and tensile moduli

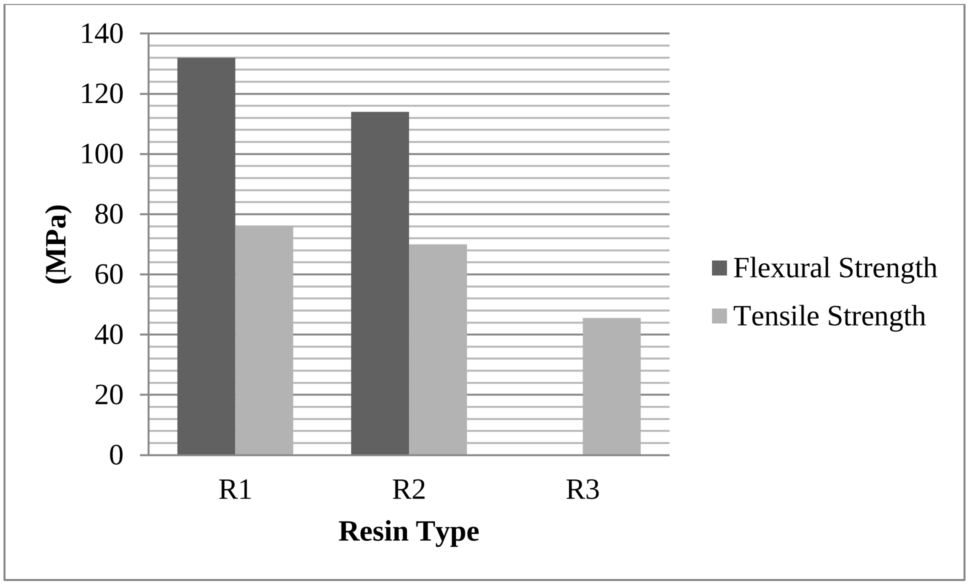


Figure 3.3 - Comparison of resins flexural and tensile strength values

Mechanical properties are specific to the resin type tested (*Kleweno*, 1994). Based on the data presented in Table 3.2, the tensile strength values are lower than the flexural strength values for Resins “1” and “2”. Resin “3” has the lowest tensile modulus and tensile strength values compared to the other two resin types. It should be noted that Resin “3” is the only VOC-free and styrene-free resin. According to Table 1 in ASTM F1216-09, a CIPP system designed for pressure pipes should have a field inspection (i.e., field cured) ASTM D638 minimum tensile strength of 3000 psi (21 MPa). The tensile strength values for all of the resin types reported in Table 3.2, exceed the ASTM F1216-09 minimum field inspection value. The minimum field inspection short-term flexural modulus and flexural strength values required by ASTM F1216-09 are 250,000 psi (1724 MPa) and 4500 psi (31 MPa), respectively. The flexural modulus and flexural strength values for Resins “1” and “2” reported in Table 3.2, exceed the ASTM F1216-09 minimum field inspection values.

3.2.2 Liner Bag Materials

The three liner bag materials are supplied by three major North American manufacturers. The photographs of each material shown in this section, are digitaly modified to remove the manufacturer’s identities (*Hazen*, 2015). The first liner bag material referred to as “Liner A” has an asymmetrical layered construction with 3.0 mm of felt on one side and 7.5 mm of felt on the other, and the fiberglass fabric that is sandwiched between the felts has alternating layers of roving with each layer orthogonal to the next. A sample of Liner "A" is illustrated in Figure 3.4. The second liner bag material referred to as Liner "B" shown in Figure 3.5, has the lowest fiberglass thickness as a percentage of total thickness. The third liner bag material referred to as Liner "C" is shown in Figure 3.6. The sandwiching felt material in this liner is thinner than 1.0 mm, making it mostly fiberglass.

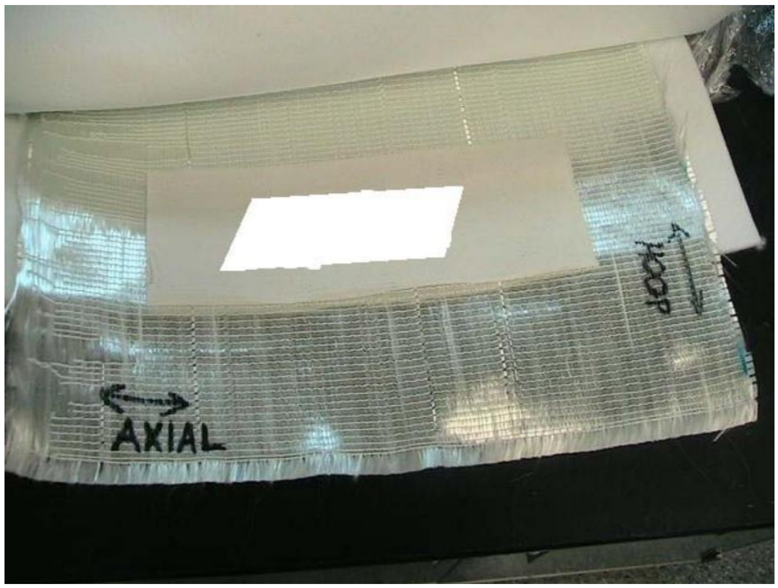


Figure 3.4 - Liner A (Adapted from *Hazen*, 2015)

Figure 3.5 - Liner B (Adapted from *Hazen*, 2015)

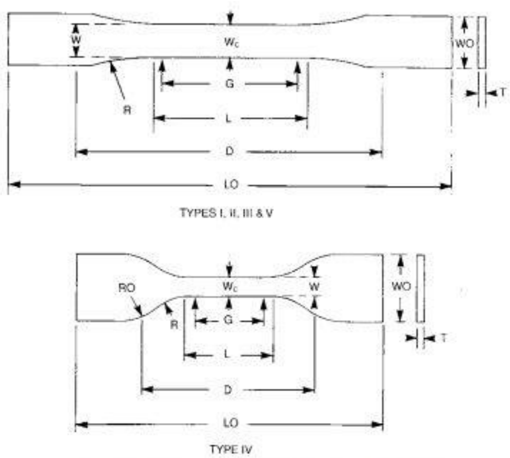
Figure 3.6 - Liner C (Adapted from *Hazen*, 2015)

4 Analysis of Nine CIPPs Short-term Tensile Properties

A tensile test is conducted to evaluate the CIPP liner short-term tensile properties. In the following, a description of the tensile test specimens, equipment, and results are provided.

4.1 Tensile Test Specifications and Specimens

Tensile tests are performed in accordance with ASTM D638–10, *Standard Test Methods for Tensile Properties of Plastics*. Interplastic Corp. stipulated that the test specimen be cut parallel to plate longitudinal axis shown on each CIPP plate (See Figure 3.1). A minimum of five specimens are prepared for each of the CIPP systems making a total of 45 tensile test specimens. Dog-bone shape specimens are cut based on the thickness of the CIPP plates according to the following specifications presented in Figure 4.1 adapted from ASTM D638-10.



Specimen Dimensions for Thickness, *T*, mm (in.)

Dimensions (see drawings)	7 (0.28) or under		Over 7 to 14 (0.28 to 0.55), incl	4 (0.16) or under		Tolerances
	Type I	Type II	Type III	Type IV	Type V	
W—Width of narrow section	13 (0.50)	6 (0.25)	19 (0.75)	6 (0.25)	3.18 (0.125)	±0.5 (±0.02)
L—Length of narrow section	57 (2.25)	57 (2.25)	57 (2.25)	33 (1.30)	9.53 (0.375)	±0.5 (±0.02)
WO—Width overall, min	19 (0.75)	19 (0.75)	29 (1.13)	19 (0.75)	...	+ 6.4 (+ 0.25)
WO—Width overall, min	...	...	...	...	9.53 (0.375)	+ 3.18 (+ 0.125)
LO—Length overall, min	165 (6.5)	183 (7.2)	246 (9.7)	115 (4.5)	63.5 (2.5)	no max (no max)
G—Gage length	50 (2.00)	50 (2.00)	50 (2.00)	...	7.62 (0.300)	±0.25 (±0.010)
G—Gage length	...	...	...	25 (1.00)	...	±0.13 (±0.005)
D—Distance between grips	115 (4.5)	135 (5.3)	115 (4.5)	65 (2.5)	25.4 (1.0)	±5 (±0.2)
R—Radius of fillet	76 (3.00)	76 (3.00)	76 (3.00)	14 (0.56)	12.7 (0.5)	±1 (±0.04)
RO—Outer radius (Type IV)	...	...	...	25 (1.00)	...	±1 (±0.04)

Figure 4.1 - Tensile test specimen specifications (Adapted from *ASTM D638-10*)

For Liners “B” and “C”, approximately 7 and 5 mm thick, respectively, Type II tensile specimens are cut from the plates using computer controlled abrasive water jet cutting in accordance with ASTM D638 requirements. For Liner “A”, approximately 10.5 mm thick, ASTM D638 specifies Type III specimens. However, due to limited Liner “A” plate size, number of plates, and the large Type III tensile test specimen size, it was decided and approved by Interplastic’s that Type II tensile specimens would be cut and tested for Liner “A”. The computer controlled water jet cutting method has been found by CATT to be the best cutting method for creating specimens with no heat distortion that are residual stress free. Through this cutting method, consistent specimens are prepared, and thus the test results are expected to be consistent as well. Table 4.1 provides the tensile test specimen dimensions for each liner type.

Table 4.1 - Tensile test specimen dimensions

Liner Type	Overall Length (mm)	Overall Width (mm)	Gage Length (mm)
A	205	19	50
B	183	19	50
C	183	19	50

All tensile test specimen dimensions are measured using a digital caliper with an accuracy of 0.01 mm. The width and thickness of each specimen are measured and recorded at the midpoint and within 5 mm of each end of the gage length. Average measured values are used for all calculations. Typical tensile test specimens from each liner type, before, during, and after the test are shown in Figures 4.2 to 4.4. For each test specimen the following labeling scheme is used:

X1-Y-J-Z: where X1 represents the Resin Number, Y is the Liner Type, J is the Plate No., and Z is specimen ID. For example, R2-B-1-E refers to *Resin 2-Liner B-Plate No.1-Specimen E.*

Figure 4.2 - Liner “A” specimen, before, during, and after the tensile test

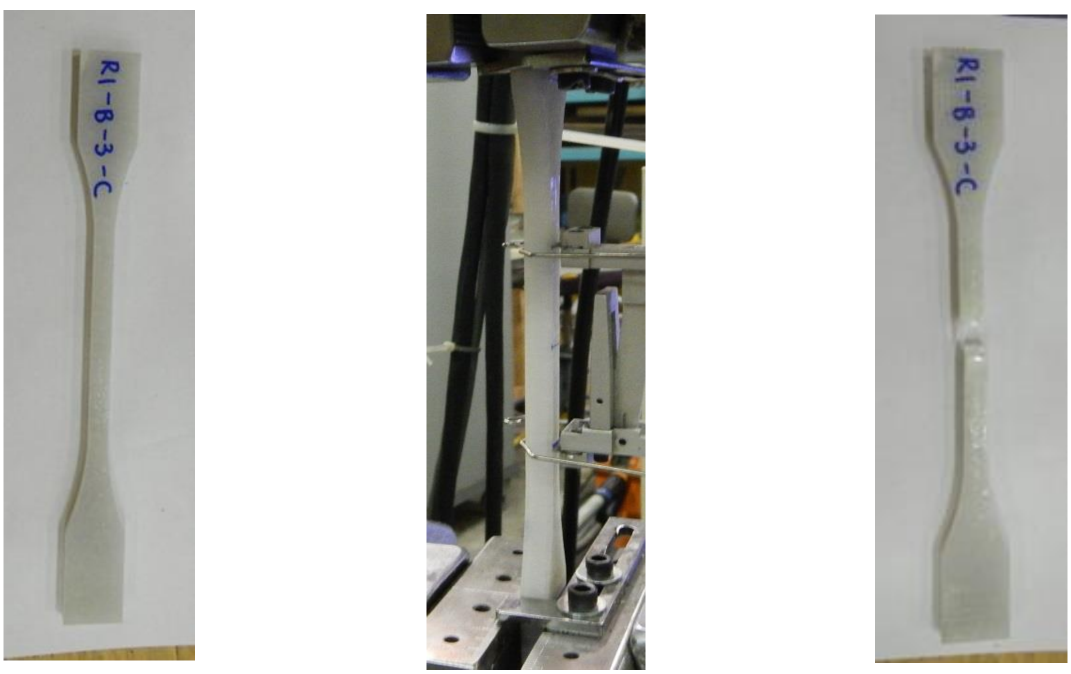


Figure 4.3 - Liner “B” specimen, before, during, and after the tensile test

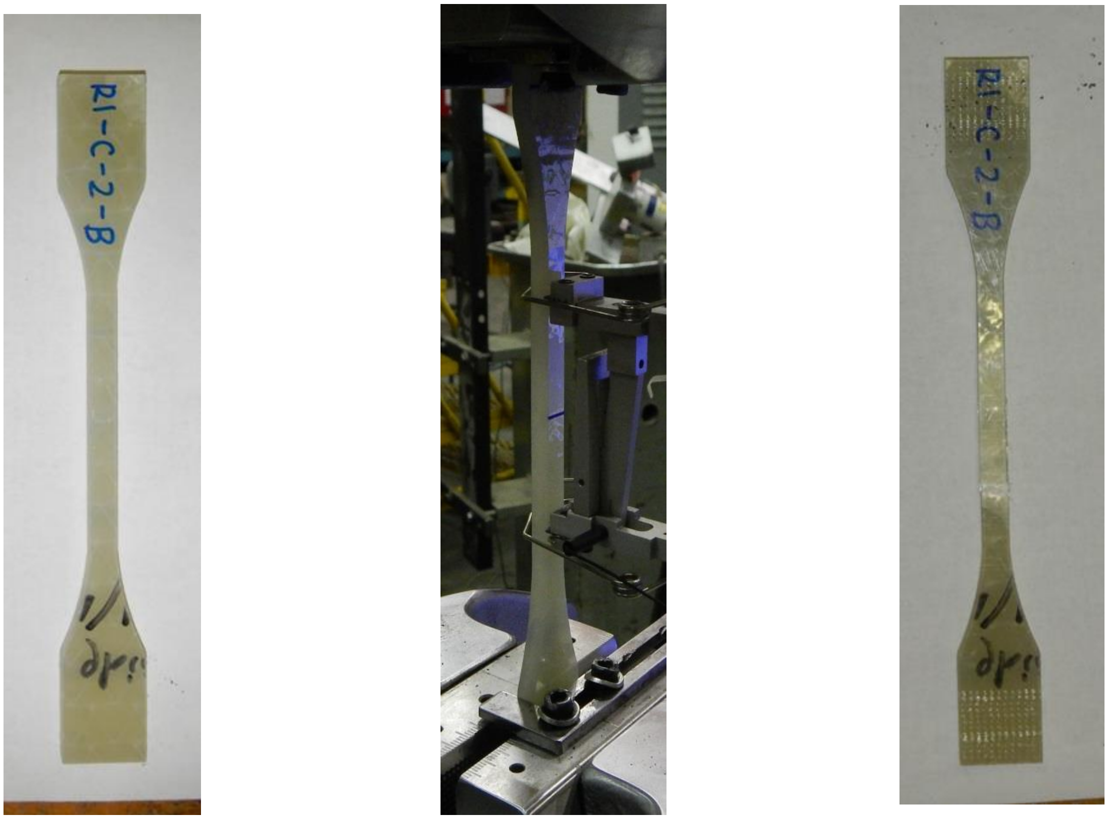


Figure 4.4 - Liner "C" specimen, before, during, and after the tensile test

4.2 Tensile Test Equipment

The tensile tests are performed using a MTS 810 test frame with a 100 kN capacity load cell and MTS 634.25E-24, 25.0 mm range, strain gage extensometer as shown in Figure 4.5. MTS Station Manager Automated Material Tester software (V3.5c 1808) is used for test data collection and test control. The test is conducted in displacement control at a rate of 5mm/min (+/- 25%) in accordance with ASTM D638-10.

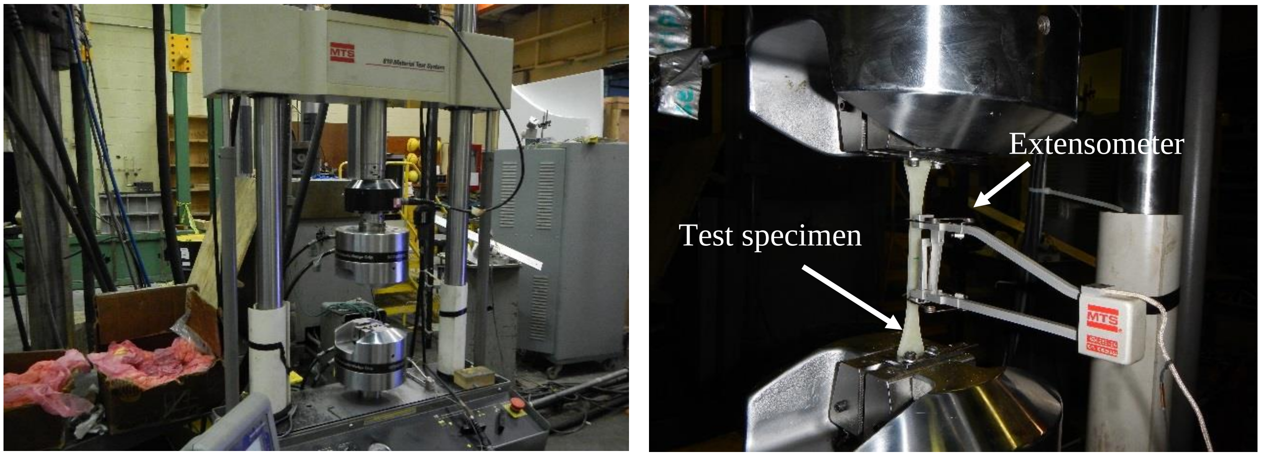


Figure 4.5 - MTS Tensile test equipment, test specimen, and strain gage extensometer

4.3 Tensile Test Results

Tensile modulus of elasticity, tensile strength at yield, and tensile strength at break values are reported for all the specimens tested from each liner system. Section A2.18 of ASTM D638-10 defines the tensile strength as the maximum tensile stress sustained by the specimen during a tension test. When the maximum stress occurs at the yield point, it is designated as the *tensile strength at yield*. When the maximum stress occurs at break, it is designated as the *tensile strength at break*. In this thesis, the tensile modulus of elasticity is defined as the slope of initial linear portion of stress-strain curve and is determined using the average specimen original cross-sectional area within the gage length. The yield stress is taken as the first sudden deviation from the initial linear portion of the stress-strain curve, while ultimate stress is taken as the peak specimen stress. Specimens for which the break occurred outside of the gage length are deemed not acceptable, and their test results are reported in separate tables. The tensile test results are presented in Tables 4.2 to 4.18. The stress-strain plots for acceptable tests (i.e., the ones which failure occurred within the gage length) from each CIPP liner system, are illustrated in Figures 4.7 to 4.15. As mentioned in Chapter 3, Liner “A” has an asymmetrical layered construction with 3.0 mm of felt on one side and 7.5 mm of felt on the other. Some specimens failed from the thick side and some from the thin side. Thus, the side which failure occurred in, during the tensile test is noted for Liner “A” specimens. A typical side view of a Liner “A” specimen showing the felt layers is illustrated in Figure 4.6.

Figure 4.6 - A typical side view of a Liner "A" specimen

Table 4.2 - Resin 1 / Liner A - Tensile properties

Test Specimen	Initial Modulus of Elasticity		Tensile Yield			Tensile Break			Notes
			Strength		Strain	Strength		Strain	
	(MPa)	(psi)	(MPa)	(psi)	(%)	(MPa)	(psi)	(%)	
R1-A-1-C	6,320	917,100	15.7	2,280	0.252	57.2	8,290	1.09	Thick side broke first
R1-A-2-A	5,450	790,000	11.8	1,710	0.216	50.5	7,320	1.12	Thick side broke first
R1-A-2-B	5,520	801,000	12.2	1,760	0.222	63.0	9,130	1.49	Thick side broke first
Min	5,450	790,000	11.8	1,710	0.216	50.5	7,320	1.09	
Max	6,320	917,100	15.7	2,280	0.252	63.0	9,130	1.49	
Average	5,760	836,000	13.2	1,920	0.230	56.9	8,250	1.23	
Standard Deviation	486	70,450	2.2	317	0.020	6.3	908	0.22	

Table 4.3 - Resin 1 / Liner A - Tensile properties of specimens that broke outside of the gage length

Test Specimen	Initial Modulus of Elasticity		Tensile Yield			Tensile Break			Notes
			Strength		Strain	Strength		Strain	
	(MPa)	(psi)	(MPa)	(psi)	(%)	(MPa)	(psi)	(%)	
R1-A-1-A	6,070	880,700	16.4	2,380	0.265	55.3	8,020	1.06	Thick side broke first
R1-A-1-B	5,660	820,500	8.48	1,230	0.146	47.0	6,820	1.04	Thick side broke first

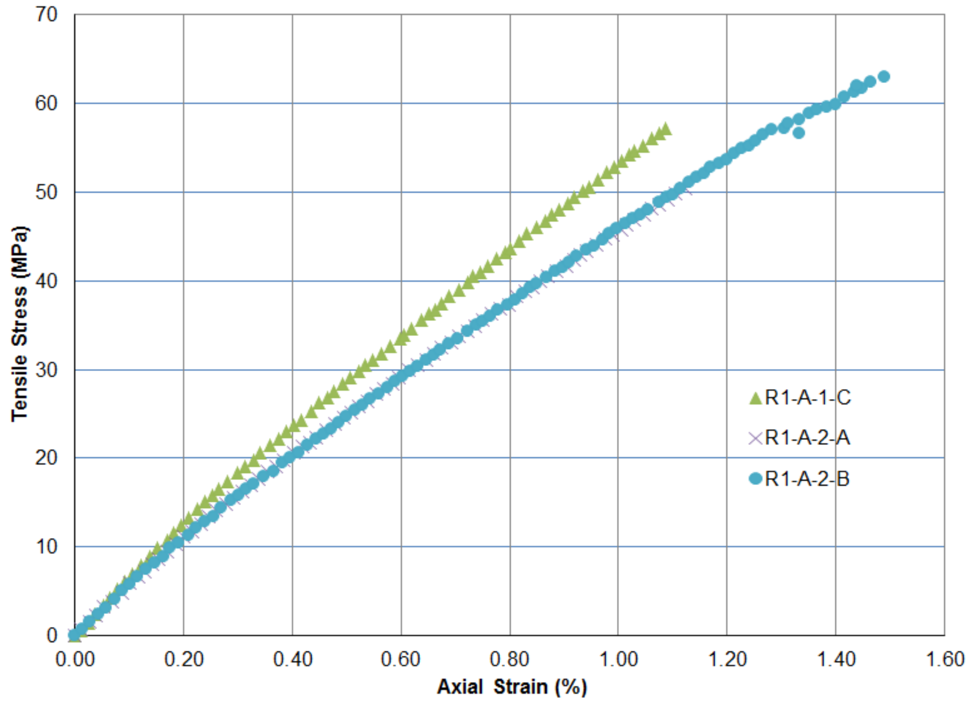


Figure 4.7 - Resin 1 / Liner A - Tensile stress - strain response for all acceptable tests

Table 4.4 - Resin 2 / Liner A - Tensile properties

Test Specimen	**Initial Modulus of Elasticity**		**Tensile Yield**			**Tensile Break**			**Notes**
			Strength		**Strain**	**Strength**		**Strain**	
	(MPa)	(psi)	(MPa)	(psi)	**(%)**	(MPa)	(psi)	**(%)**	
R2-A-1-A	5,750	833,900	27.8	4,040	0.510	66.9	9,700	1.45	Thick side broke first
R2-A-1-B	6,120	887,000	22.9	3,320	0.385	52.1	7,560	1.02	Thick side broke first
R2-A-2-B	6,160	894,000	19.7	2,850	0.325	66.9	9,710	1.44	Thick side broke first
Min	5,750	833,900	19.7	2,850	0.325	52.1	7,560	1.02	
Max	6,160	894,000	27.8	4,040	0.510	66.9	9,710	1.45	
Average	6,010	871,600	23.5	3,400	0.407	62.0	8,990	1.30	
Standard Deviation	227	32,870	4.1	596	0.094	8.5	1,240	0.25	

Table 4.5 - Resin 2 / Liner A - Tensile properties of specimens that broke outside of the gage length

Test Specimen	**Initial Modulus of Elasticity**		**Tensile Yield**			**Tensile Break**			**Notes**
			Strength		**Strain**	**Strength**		**Strain**	
	(MPa)	(psi)	(MPa)	(psi)	**(%)**	(MPa)	(psi)	**(%)**	
R2-A-1-C	6,430	933,400	20.4	2,960	0.324	83.7	12,140	1.70	Thick side broke first
R2-A-2-C	5,890	854,600	19.6	2,850	0.339	82.1	11,900	2.08	Thick side broke first

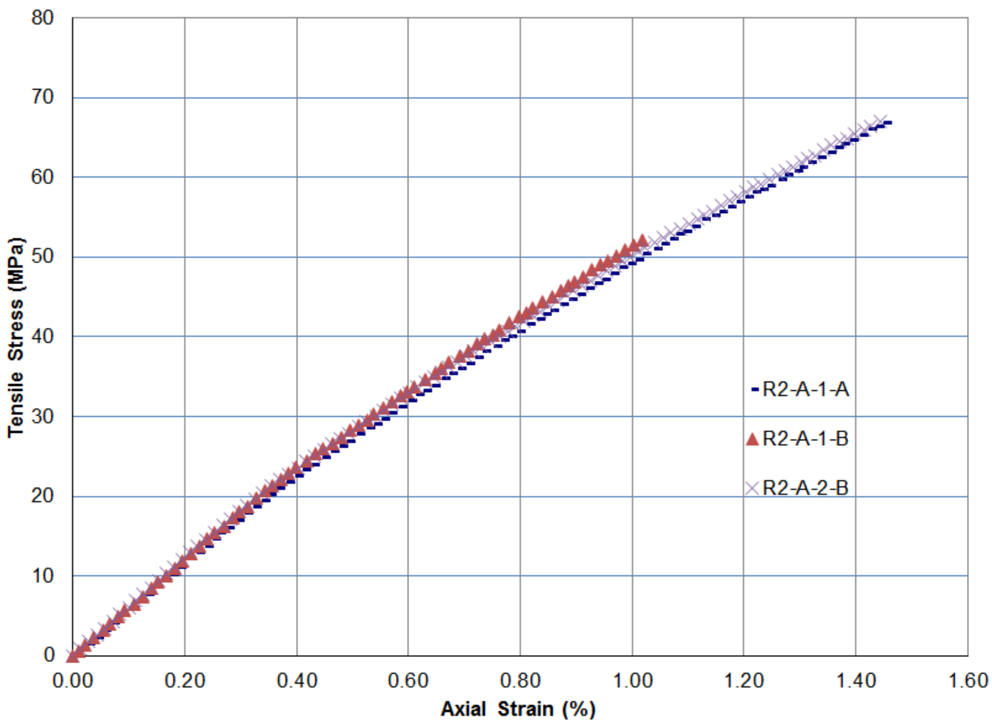


Figure 4.8 - Resin 2 / Liner A - Tensile stress - strain response for all acceptable tests

Table 4.6 - Resin 3 / Liner A - Tensile properties

Test Specimen	Initial Modulus of Elasticity		Tensile Yield			Tensile Break			Notes
			Strength		Strain	Strength		Strain	
	(MPa)	(psi)	(MPa)	(psi)	(%)	(MPa)	(psi)	(%)	
R3-A-1-C	4,900	710,100	15.2	2,200	0.307	56.5	8,200	1.36	Thin side broke first
R3-A-2-A	4,330	627,800	12.5	1,820	0.284	55.5	8,050	1.62	Thin side broke first
Min	4,330	627,800	12.5	1,820	0.284	55.5	8,050	1.36	
Max	4,900	710,100	15.2	2,200	0.307	56.5	8,200	1.62	
Average	4,610	668,900	13.8	2,010	0.296	56.0	8,130	1.49	
Standard Deviation	401	58,180	1.9	270	0.016	0.71	104	0.18	

Table 4.7 - Resin 3 / Liner A - Tensile properties of specimens that broke outside of the gage length

Test Specimen	Initial Modulus of Elasticity		Tensile Yield			Tensile Break			Notes
			Strength		Strain	Strength		Strain	
	(MPa)	(psi)	(MPa)	(psi)	(%)	(MPa)	(psi)	(%)	
R3-A-1-B	5,230	758,000	15.0	2,170	0.286	63.7	9,230	1.42	Thick side broke first
R3-A-2-B	4,810	698,400	10.9	1,580	0.229	53.4	7,740	1.37	Thin side broke first
R3-A-2-C	5,010	726,700	12.5	1,810	0.253	49.5	7,180	1.20	Thin side broke first

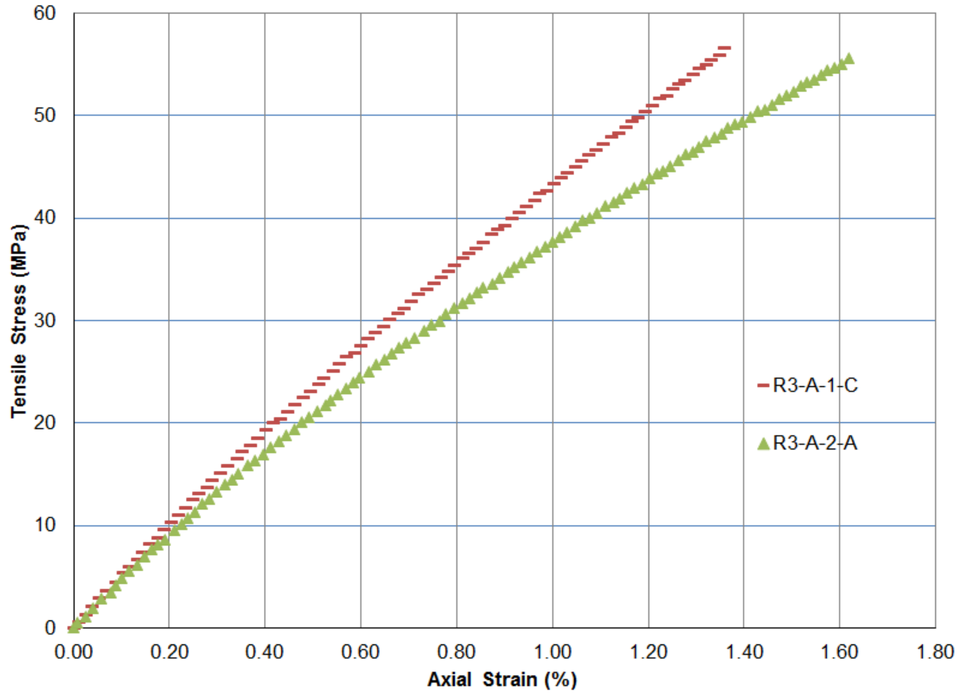


Figure 4.9 - Resin 3 / Liner A - Tensile stress - strain response for all acceptable tests

Table 4.8 - Resin 1 / Liner B - Tensile properties

Test Specimen	**Initial Modulus of Elasticity**		**At Tensile Yield**			**At Tensile Break**		
			Strength		**Strain**	**Strength**		**Strain**
	(MPa)	(psi)	(MPa)	(psi)	**(%)**	(MPa)	(psi)	**(%)**
R1-B-2-B	9,310	1,350,300	24.7	3,580	0.270	79.2	11,490	0.960
R1-B-2-C	9,220	1,338,000	31.5	4,560	0.342	82.6	11,980	0.976
R1-B-3-C	9,030	1,309,900	36.5	5,290	0.411	118	17,140	1.50
Min	9,060	1,309,900	24.7	3,580	0.270	79.2	11,490	0.960
Max	9,360	1,350,300	36.5	5,290	0.411	118	17,140	1.50
Average	9,230	1,332,800	30.9	4,480	0.341	93.3	13,540	1.14
Standard Deviation	154	20,720	5.9	858	0.071	22	3,130	0.31

Table 4.9 - Resin 1 / Liner B - Tensile properties of specimens that broke outside of the gage length

Test Specimen	Initial Modulus of Elasticity		At Tensile Yield			At Tensile Break		
			Strength		Strain	Strength		Strain
	(MPa)	(psi)	(MPa)	(psi)	(%)	(MPa)	(psi)	(%)
R1-B-3-A	10,710	1,553,200	41.6	6,030	0.387	132	19,130	1.38
R1-B-3-D	10,530	1,527,600	30.0	4,360	0.268	108	15,590	1.13

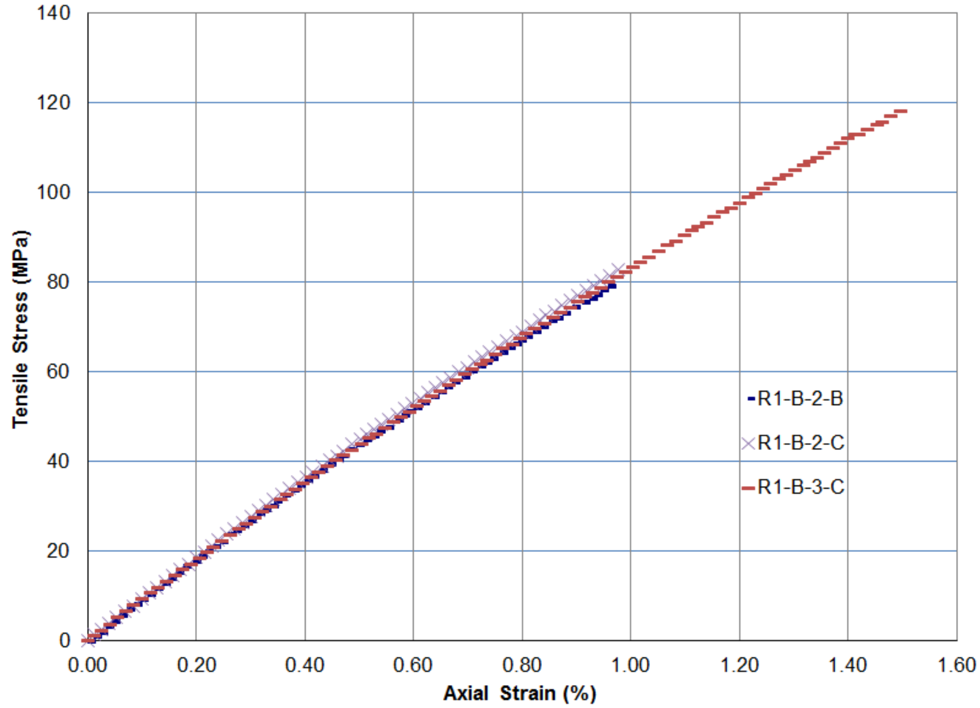


Figure 4.10 - Resin 1 / Liner B - Tensile stress - strain response for all acceptable tests

Table 4.10 - Resin 2 / Liner B - Tensile properties

Test Specimen	Initial Modulus of Elasticity		At Tensile Yield			At Tensile Break		
			Strength		Strain	Strength		Strain
	(MPa)	(psi)	(MPa)	(psi)	(%)	(MPa)	(psi)	(%)
R2-B-1-C	9,190	1,332,700	34.8	5,040	0.385	136	19,760	1.85
R2-B-1-D	7,230	1,049,000	27.8	4,030	0.393	122	17,700	2.12
Min	7,230	1,049,000	27.8	4,030	0.385	122	17,700	1.85
Max	9,190	1,332,700	34.8	5,040	0.393	136	19,760	2.12
Average	8,210	1,191,000	31.3	4,540	0.389	129	18,730	1.99
Standard Deviation	1,380	200,600	4.9	715	0.005	10	1,460	0.19

Table 4.11 - Resin 1 / Liner B - Tensile properties of specimens that broke outside of the gage length

Test Specimen	Initial Modulus of Elasticity		At Tensile Yield			At Tensile Break		
			Strength		Strain	Strength		Strain
	(MPa)	(psi)	(MPa)	(psi)	(%)	(MPa)	(psi)	(%)
R2-B-1-A	9,610	1,394,200	35.7	5,180	0.380	130	18,830	1.59
R2-B-2-A	9,760	1,415,800	43.7	6,340	0.456	150	21,820	1.89
R2-B-2-B	10,370	1,504,800	38.1	5,530	0.366	155	22,440	1.86

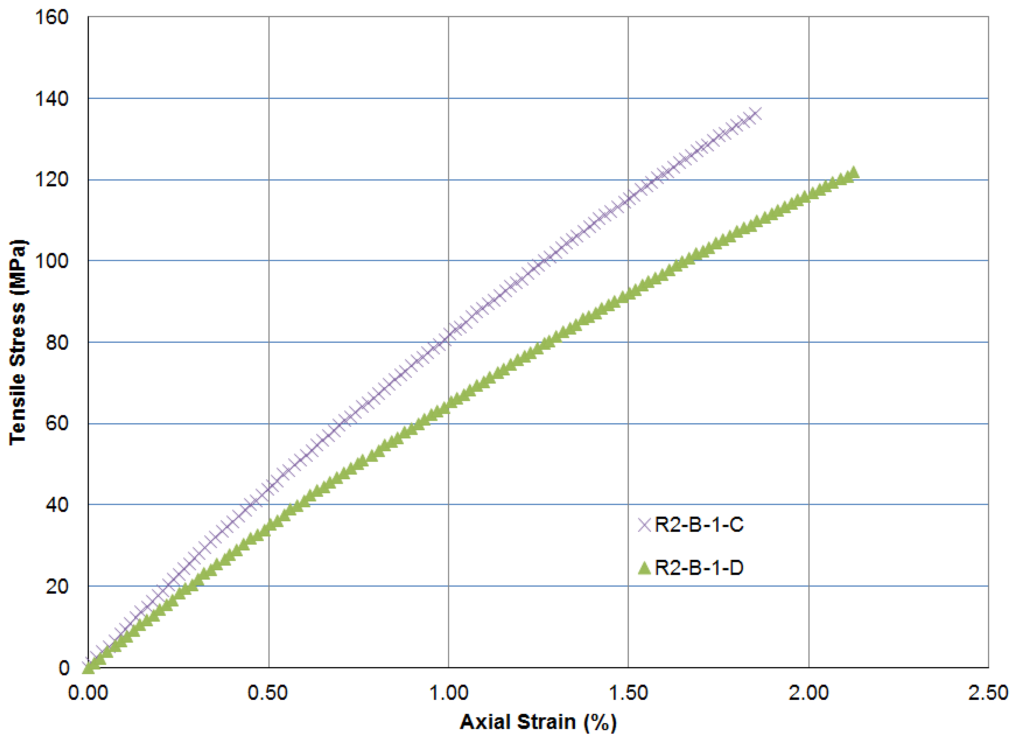


Figure 4.11 - Resin 2 / Liner B - Tensile stress - strain response for all acceptable tests

Table 4.12 - Resin 3 / Liner B - Tensile properties

Test Specimen	Initial Modulus of Elasticity		At Tensile Yield			At Tensile Break		
			Strength		Strain	Strength		Strain
	(MPa)	(psi)	(MPa)	(psi)	(%)	(MPa)	(psi)	(%)
R3-B-1-D	7,310	1,060,400	38.0	5,500	0.527	120	17,470	2.16
R3-B-2-A	6,820	988,700	35.1	5,090	0.513	96.2	13,960	1.60
R3-B-2-D	10,180	1,476,800	33.2	4,820	0.329	148	21,400	1.97
Min	6,810	988,700	33.2	4,820	0.329	96.2	13,960	1.60
Max	10,180	1,476,800	38.0	5,500	0.527	148	21,400	2.16
Average	8,100	1,175,300	35.4	5,140	0.457	121	17,610	1.91
Standard Deviation	1,820	263,600	2.4	347	0.11	26	3,720	0.28

Table 4.13 - Resin 3 / Liner B - Tensile properties of specimens that broke outside of the gage length

Test Specimen	Initial Modulus of Elasticity		At Tensile Yield			At Tensile Break		
			Strength		Strain	Strength		Strain
	(MPa)	(psi)	(MPa)	(psi)	(%)	(MPa)	(psi)	(%)
R3-B-1-A	7,420	1,076,100	27.2	3,950	0.366	98.5	14,290	1.55
R3-B-2-B	7,950	1,152,400	38.4	5,570	0.481	117	16,980	1.78

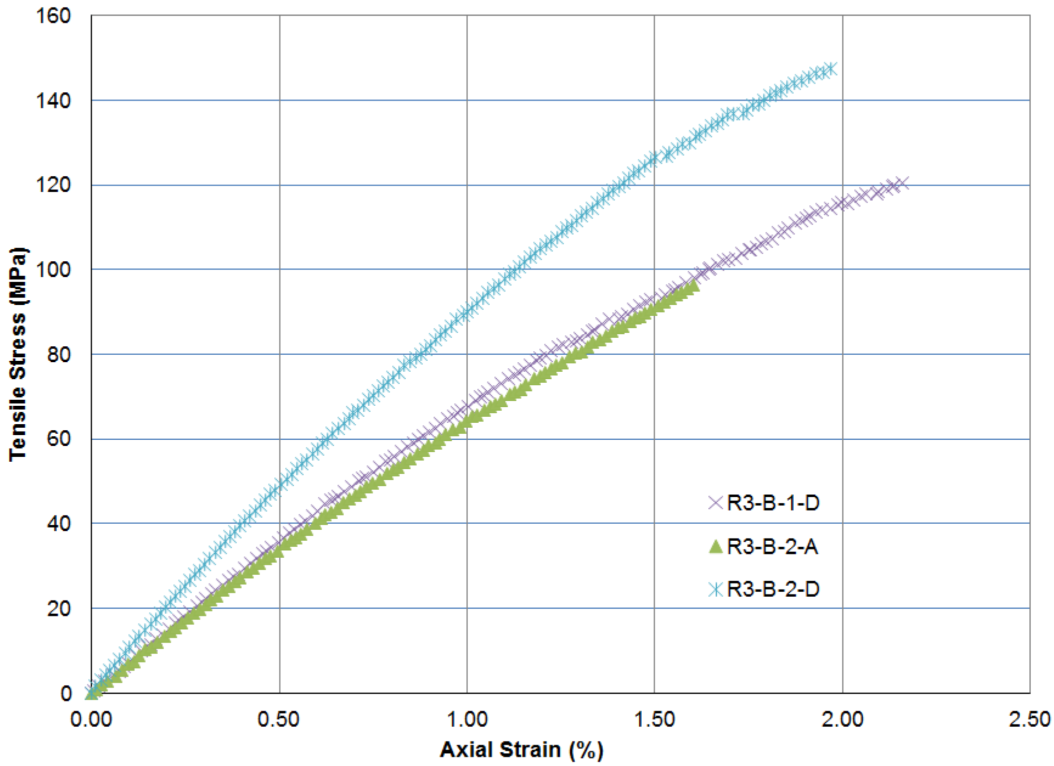


Figure 4.12 - Resin 3 / Liner B - Tensile stress - strain response for all acceptable tests

Table 4.14 - Resin 1 / Liner C - Tensile properties

Test Specimen	**Initial Modulus of Elasticity**		**At Tensile Yield**			**At Tensile Break**		
			Strength		**Strain**	**Strength**		**Strain**
	(MPa)	(psi)	(MPa)	(psi)	**(%)**	(MPa)	(psi)	**(%)**
R1-C-1-B	11,870	1,721,900	42.7	6,190	0.361	160	23,190	2.17
R1-C-1-C	12,420	1,801,500	33.2	4,810	0.262	154	22,400	2.02
R1-C-1-E	12,390	1,797,400	32.8	4,750	0.262	160	23,260	2.42
R1-C-2-B	10,260	1,488,600	31.8	4,610	0.307	108	15,710	1.83
R1-C-2-D	9,280	1,346,000	17.1	2,470	0.185	85.4	12,380	1.56
Min	9,280	1,343,000	17.1	2,470	0.185	85.4	12,380	1.56
Max	12,420	1,801,500	42.7	6,190	0.361	160	23,260	2.42
Average	11,250	1,631,100	31.5	4,570	0.275	134	19,390	2.00
Standard Deviation	1,410	204,000	9.2	1,330	0.065	35	5,030	0.33

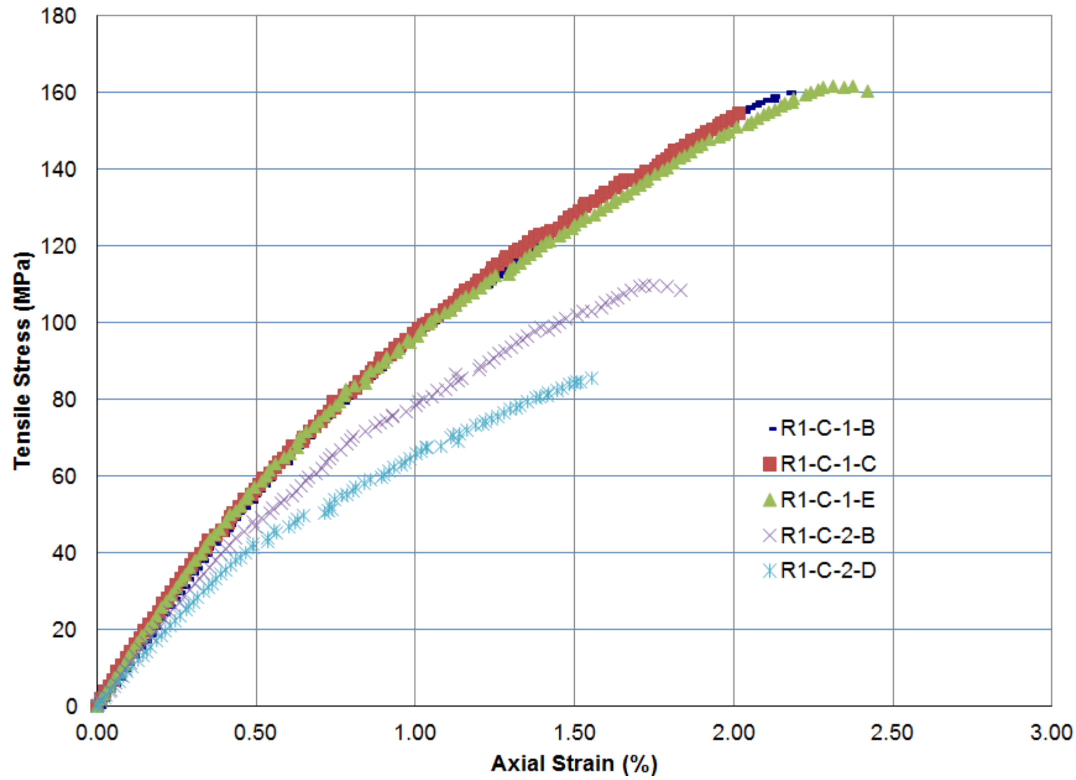


Figure 4.13 - Resin 1 / Liner C - Tensile stress - strain response for all acceptable tests

Table 4.15 - Resin 2 / Liner C - Tensile properties

Test Specimen	**Initial Modulus of Elasticity**		**At Tensile Yield**			**At Tensile Break**		
			Strength		**Strain**	**Strength**		**Strain**
	(MPa)	(psi)	(MPa)	(psi)	**(%)**	(MPa)	(psi)	**(%)**
R2-C-1-D	11,160	1,618,200	37.9	5,490	0.338	158	22,960	2.22
R2-C-2-D	9,470	1,374,200	29.7	4,310	0.319	140	20,300	2.36
R2-C-2-F	9,410	1,365,000	36.0	5,230	0.383	117	16,930	1.86
Min	9,410	1,365,000	29.7	4,310	0.319	117	16,930	1.86
Max	11,160	1,618,200	37.9	5,490	0.383	158	22,960	2.36
Average	10,010	1,452,500	34.5	5,010	0.347	138	20,060	2.15
Standard Deviation	990	143,600	4.3	618	0.033	21	3,020	0.26

Table 4.16 - Resin 2 / Liner C - Tensile properties of specimens that broke outside of the gage length

Test Specimen	Initial Modulus of Elasticity		At Tensile Yield			At Tensile Break		
			Strength		Strain	Strength		Strain
	(MPa)	(psi)	(MPa)	(psi)	(%)	(MPa)	(psi)	(%)
R2-C-1-E	11,030	1,599,200	40.7	5,900	0.370	112	16,260	1.29
R2-C-2-G	10,210	1,480,200	29.5	4,280	0.293	133	19,240	1.85

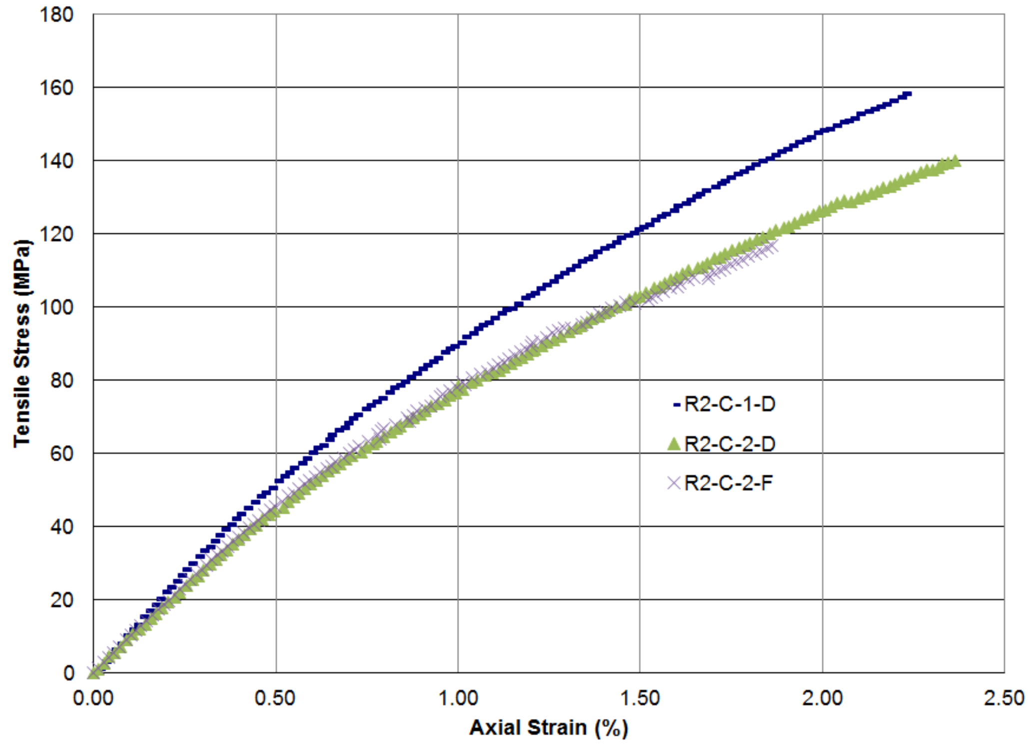


Figure 4.14 - Resin 2 / Liner C - Tensile stress - strain response for all acceptable tests

Table 4.17 - Resin 3 / Liner C - Tensile properties

Test Specimen	Initial Modulus of Elasticity		At Tensile Yield			At Tensile Break		
			Strength		Strain	Strength		Strain
	(MPa)	(psi)	(MPa)	(psi)	(%)	(MPa)	(psi)	(%)
R3-C-1-A	7,960	1,155,000	23.6	3,430	0.298	95.5	13,850	1.95
R3-C-1-D	8,580	1,243,000	22.9	3,320	0.266	129	18,680	2.22
R3-C-2-C	9,260	1,336,100	23.6	3,420	0.256	134	19,480	2.22
Min	6,920	1,155,000	22.9	3,320	0.256	95.5	13,850	1.95
Max	9,260	1,336,100	23.6	3,430	0.298	134	19,480	2.22
Average	8,250	1,244,700	23.4	3,390	0.273	120	17,340	2.13
Standard Deviation	1,200	90,560	0.40	58	0.022	21	3,050	0.16

Table 4.18 - Resin 3 / Liner C - Tensile properties of specimens that broke outside of the gage length

Test Specimen	Initial Modulus of Elasticity		At Tensile Yield			At Tensile Break		
			Strength		Strain	Strength		Strain
	(MPa)	(psi)	(MPa)	(psi)	(%)	(MPa)	(psi)	(%)
R3-C-2-B	9,650	1,399,500	19.8	2,880	0.206	120	17,460	1.89
R3-C-2-G	8,970	1,300,700	22.7	3,300	0.255	127	18,360	2.06

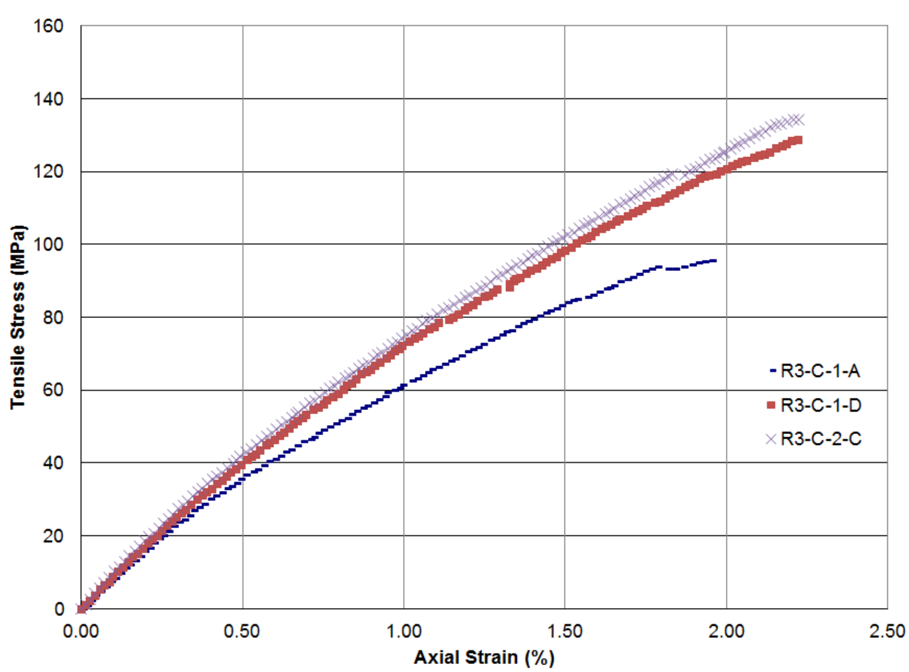


Figure 4.15 - Resin 3 / Liner C - Tensile stress - strain response for all acceptable tests

4.4 Discussion of Tensile Test Results

The term "elastic modulus" refers to the "stiffness" or "rigidity" of plastic materials (*ASTM D638-10*). Stress-strain characteristics of plastic materials are highly dependent on various factors such as rate of application of stress, temperature, and previous loading history of specimen (*ASTM D638-10*). The stress-strain curves generated using ASTM D638-10 specifications, demonstrated a linear region at low stresses. The elastic modulus is estimated by drawing a straight line tangent to the linear portion of the stress-strain curve. Such a constant is useful if its arbitrary nature and dependence on time, temperature, and similar factors are realized (*ASTM D638-10*). The average tensile test results for each resin/liner type are tabulated in Table 4.19.

Table 4.19 - Average tensile test results for each resin/liner type

Resin / Liner Type	**Initial Modulus of Elasticity**		**Strength at Yield**		**Strength at Break**	
	(MPa)	(psi)	(MPa)	(psi)	(MPa)	(psi)
Resin 1 / Liner A	5,760	836,000	13.2	1,920	56.9	8,250
Resin 2 / Liner A	6,010	871,600	23.5	3,400	62.0	8,990
Resin 3 / Liner A	4,610	668,900	13.8	2,010	56.0	8,130
Resin 1 / Liner B	9,230	1,332,800	30.9	4,480	93.3	13,540
Resin 2 / Liner B	8,210	1,190,900	31.3	4,540	129	18,730
Resin 3 / Liner B	8,100	1,175,300	35.4	5,140	121	17,610
Resin 1 / Liner C	11,250	1,631,100	31.5	4,570	134	19,390
Resin 2 / Liner C	10,010	1,452,500	34.5	5,010	138	20,060
Resin 3 / Liner C	8,250	1,244,700	23.4	3,390	120	17,340

The initial tensile moduli of elasticity values for all resin/liner types are compared in Figure 4.16. Liner "A" products have lower tensile moduli of elasticity compared to Liners "B" and "C". Liner "A" is the only CIPP system which have an asymmetrical layered construction. The fiberglass fabric that is sandwiched between the felts in Liner "A", has alternating layers of roving with each layer orthogonal to the next. It is noticed in Figure 4.16 that the liner bag materials, especially Liner "C", have substantially added to the tensile stiffness of the resin only samples. It should be noted that Liner "C" specimens have the lowest thickness compared to Liners "A" and "B". The sandwiching felt material in Liner "C" is thinner than 1.0 mm making it mostly fiberglass.

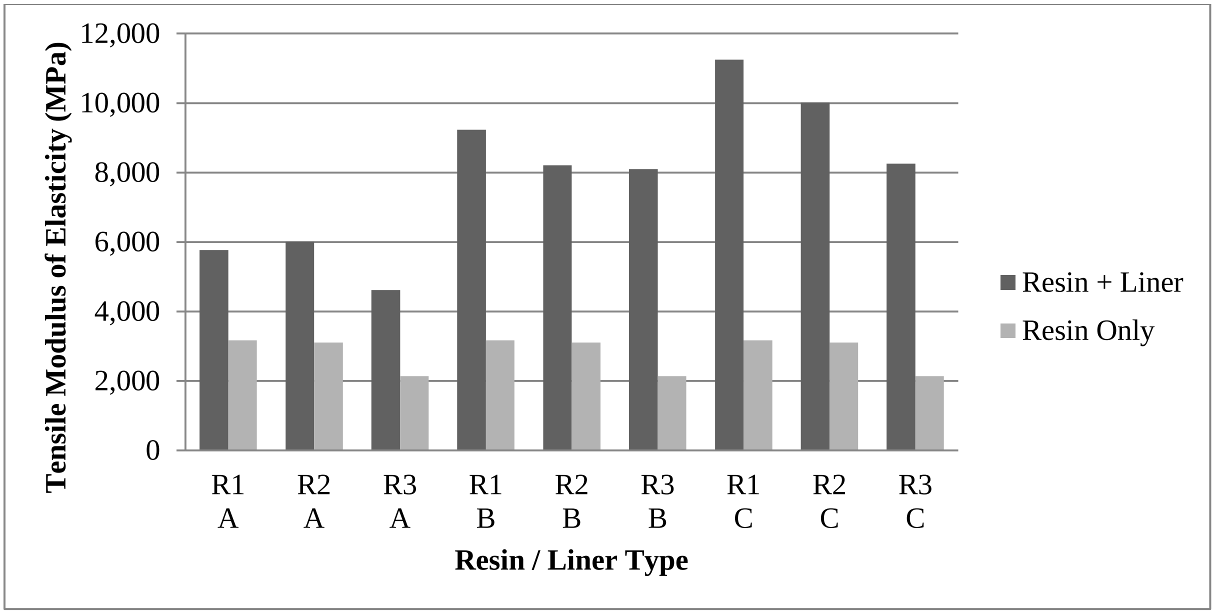


Figure 4.16 - Comparison of tensile moduli of elasticity values

The tensile strength at yield and at break values for all resin/liner types are compared in Figure 4.17. Liner "A" products have lower strength values compared to Liners "B" and "C". The asymmetry of the felt layers in Liner "A" has caused differential shrinkage when cured resulting in panels with curvature (*Hazen*, 2015). The curvature of Liner "A" dog-bone shape specimens may have affected the tensile test results for this liner system, since the specimens could not be placed perfectly straight within the grips of the tensile test machine. It is noticeable in Figure 4.17 that the liner bag materials have increased the ultimate (at break) tensile strength of resin only samples except for "Resin 1/Liner A" and "Resin 2/Liner A" products.

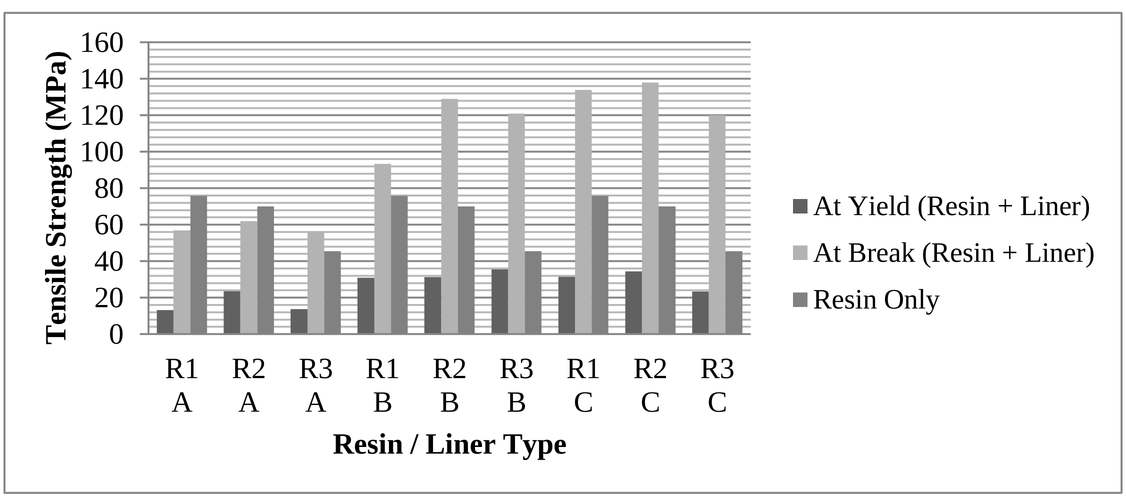


Figure 4.17 - Comparison of tensile strength values

For a reinforced CIPP, liner properties are specific to resin-reinforcement-carrier matrix and cannot be generalized from resin only properties (*Richard*, 1993). Compared to some other reinforced CIPP products previously tested by CATT, the tensile properties reported in Table 4.19 seem reasonable. According to Table 1 in ASTM F1216-09, a CIPP system designed for pressure pipes should have a field inspection ASTM D638 minimum tensile strength of 3000 psi (21 MPa). The strength at break values for all of the CIPP products reported in Table 4.19, exceed the ASTM F1216-09 minimum field inspection value.

Some degree of variability is observed in the tensile properties of the specimens in each liner system. The variability is also observed in tensile properties of some other CIPP liners tested previously by CATT. The variation in tensile properties among the same type of specimens can be attributed to the existence of non-uniformity along the laboratory manufactured CIPP panels resulting in specimens with non-uniform thicknesses. The inconsistency among the center section (i.e., gage length) of the test specimens may have also contributed to the variability in the tensile test results. This is why a minimum of five specimens from each CIPP liner system are tested to obtain representative tensile properties. The tensile stress-strain curves for some of the liner systems such as “Resin 1/Liner B” are almost linear while for some others are non-linear such as “Resin 1/Liner C”. The difference is attributed to the difference in the composition of the liner systems. Some of the liner systems are ductile and some are brittle.

5 Analysis of Nine CIPPs Short-term Flexural Properties

A flexural test is conducted to evaluate the CIPP liner flexural properties. The flexural test results are used as a basis for characterization of material long-term behavior. In the following, a description of the flexural test specimens, equipment, and results are provided.

5.1 Flexural Test Specifications

Flexural tests are performed in accordance with ASTM D790-10, *Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulation Materials*, test Procedure “A” (three-point loading). The bending test consisted of placing a rectangular CIPP specimen flatwise on two rigid supports and then loading the specimen at mid-span in flexure as a beam, until it reaches failure or five percent strain in its outer fibers as specified in ASTM D790. The amount of deflection and magnitude of the applied load during the test until failure are recorded for material behavior analysis. Parameters considered in a three point loading flexural test are illustrated in Figure 5.1.

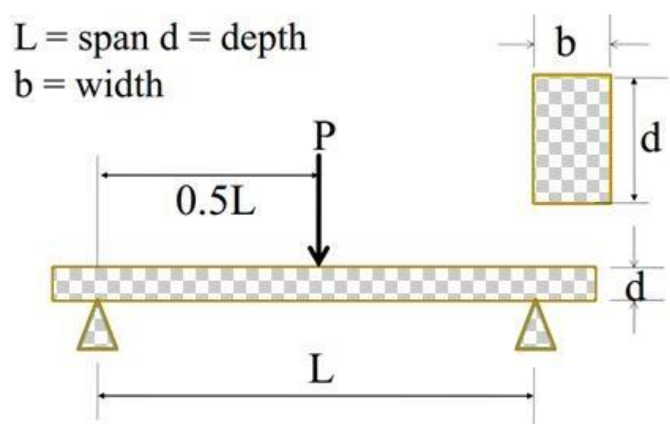


Figure 5.1 - Three-Point loading bending test

A minimum support span to depth ratio of 16:1 (tolerance +/- 1) is recommended by ASTM D790 to avoid shear stress effects in the specimen when loading at the mid-span. However, this ratio can be as high as 64:1 for composite materials depending on the level of reinforcement (*ASTM D790-10*).

5.2 Flexural Test Specimens

The rectangular test specimens for the flexural test are cut from resin plates in accordance with ASTM D790-10 Section 7.2.1 requirements using water jet technology with a minimum support span to depth ratio of 16 to 1. The width of the specimens are selected to be less than or equal to one fourth of the support span. The length of the specimens are selected to allow for overhanging on each end for at least 10% of the support span, but in no case less than 6.4 mm on each end to prevent the specimen from slipping through the supports. The specimens are cut in the direction specified by Interplastic Corp. to obtain flexural properties in the hoop direction. Sample dimensions are measured using a digital caliper accurate to 0.01 mm. Specimen dimensions are presented in Table 5.1. The average sample width and depth (thickness) values are used in all calculations. For each plate sample, at least five flexural specimens are tested. All test specimens are labeled using the following scheme:

X1-Y-J-K: where X1 stands for the resin type (e.g., R1 stands for Resin 1, R2 stands for Resin 2, R3 stands for Resin 3), Y stands for the liner type (three liners labeled as A, B, or C), J represents the plate number, and K stands for the coupon/specimen number. For example, R2-A-1-1 refers to *Resin 2-Liner A-Plate No.1-Specimen #1.*

Table 5.1 - Flexural test specimen dimensions, test span, and span to depth ratio

Test Specimen	**Specimen Dimensions (mm)**			**Test Span (mm)**	**Span to Depth Ratio**
	Length	**Width**	**Depth**		
Liner A	205	25	10.24 to 10.31	169	16.4 to 16.5
Liner B	150	20	7.08 to 7.43	125	16.88 to 17.75
Liner C	105	15	4.73 to 5.17	87	16.97 to 18.57

It is stated in Hazen (2015) that all the CIPP systems have shrunk when impregnated with resin and cured. However, the asymmetry of the felt layers in Liner “A” has caused differential shrinkage when cured resulting in panels with curvature (*Hazen*, 2015). A typical Liner “A” panel having a curvature caused by differential shrinkage is shown in Figure 5.2.

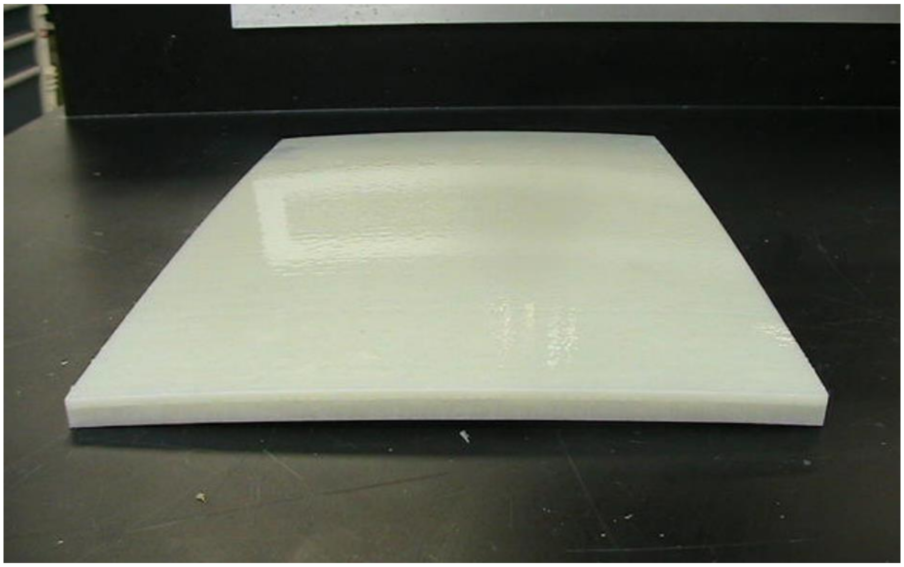
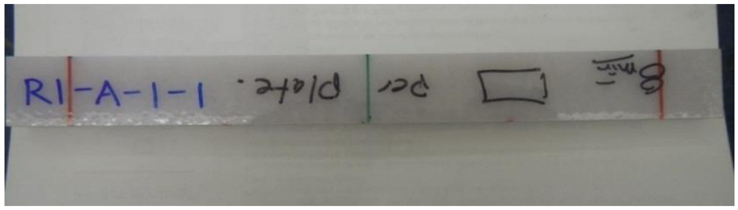
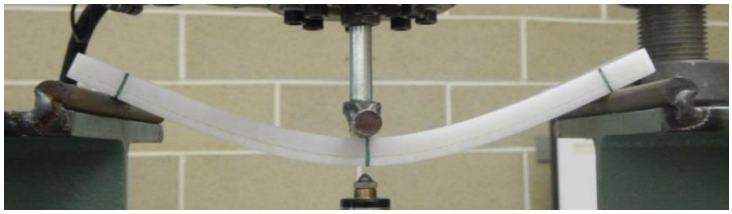


Figure 5.2 - Typical Liner “A” panel with curvature (Adapted from *Hazen*, 2015)

It was decided and approved by the Interplastic Corp. to test three of the specimens from each Liner “A” resins with the 3 mm felt side (concave surface) facing downwards and two specimens with the 7.5 mm felt side (convex surface) facing downwards to evaluate the difference in flexural properties between the two surfaces. A specimen from each liner type before, during, and after the flexural test is illustrated in Figures 5.3 to 5.6.



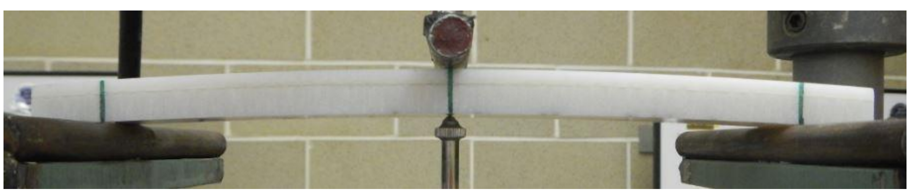
Before test



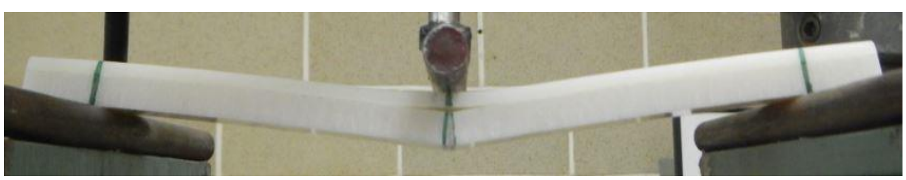
During test

After test (bottom side)

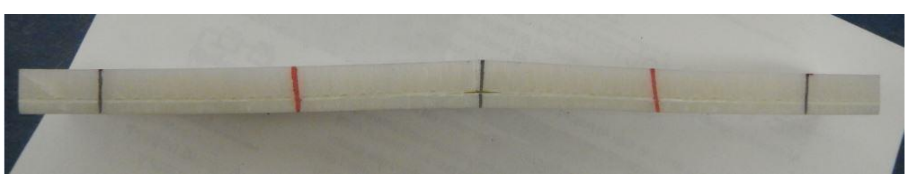
Figure 5.3 - Liner “A” specimen (tested with the concave surface facing downwards) before, during and after the flexural test



Before test

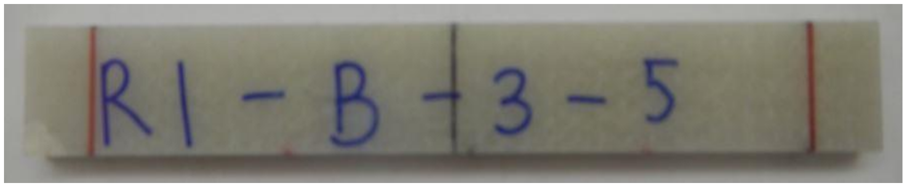


During test

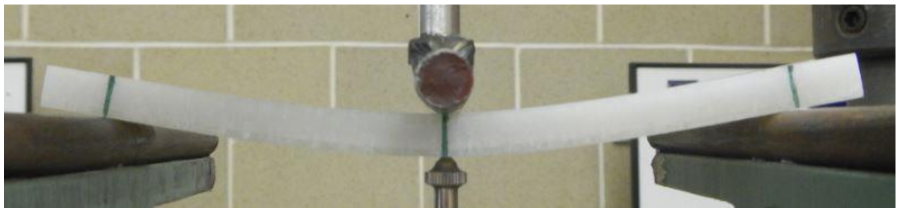


After test (side view)

Figure 5.4 - Liner “A” specimen (tested with the convex surface facing downwards) before, during and after the flexural test



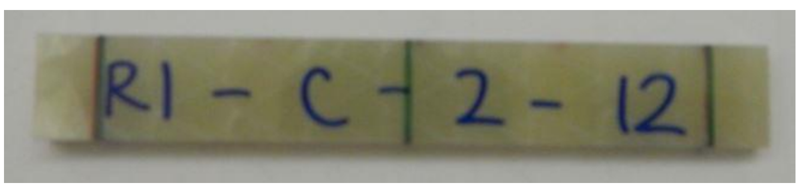
Before test



During test

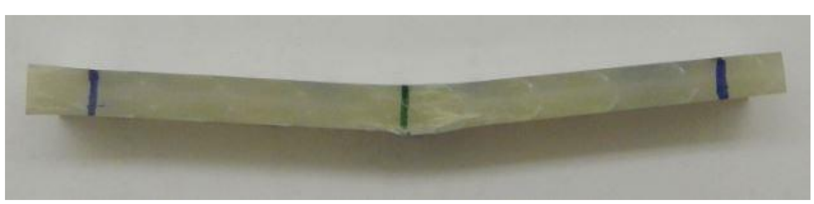
After test (side view)

Figure 5.5 - Liner “B” specimen before, during and after the flexural test



Before test

During test



After test (side view)

Figure 5.6 - Liner “C” specimen before, during and after the flexural test

5.3 Flexural Test Equipment

The three-point bending tests are performed using test equipment manufactured by Wykenham Farrance Engineering Ltd., Slough, England. The test equipment uses a gear-driven piston that moves the test platform up or down at a constant rate. Load readings from a calibrated Strain-Sert 1000 lbf (4.45kN) load cell, and displacement readings from a calibrated 25mm LVDT are recorded at 0.2 second intervals using an "eDAQ" data acquisition system. Figure 5.7 shows the test equipment and set-up. The radius of the loading nose is 4.9 mm and the crosshead motion is set at 0.15 in/min for the "A" liners, and at 0.1 in/min for the "B" and "C" liners. The loading rate is selected based on the support span and the depth of the specimen in accordance with ASTM D790-10 requirements.

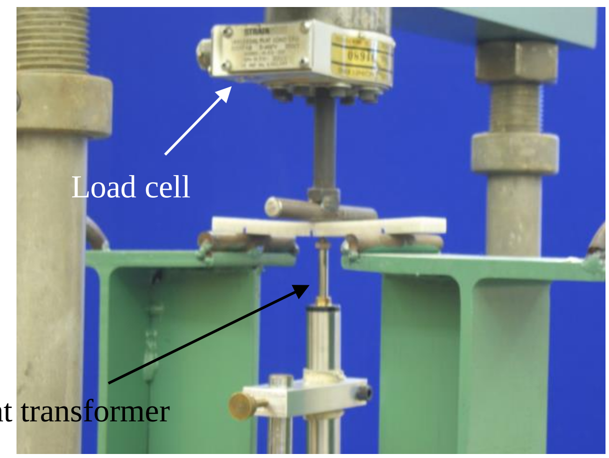


Figure 5.7 - Typical flexural test setup

5.4 Flexural Test Results

CIPP liners depending on the application, level of reinforcement, and resin type could behave differently under flexural stress (*Richard*, 1993). Some samples show a brittle response and some ductile. From the recorded test results, stress-strain plots are generated to determine the flexural properties of the CIPP products. Typical flexural stress-strain responses are shown in Figure 5.8.

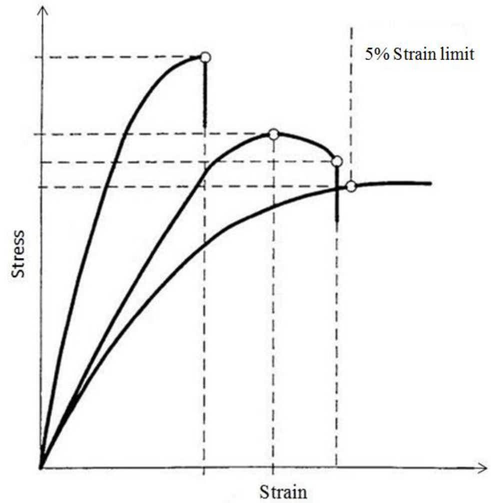


Figure 5.8 - Typical flexural stress-strain responses
(Adapted from *ASTM D790-10*)

ASTM D790-10 defines *flexural strength* as the maximum flexural stress sustained by the test specimen during a bending test. The tangent modulus of elasticity, often called the "*modulus of elasticity*," is defined as the ratio, within the elastic limit, of stress to corresponding strain. In this thesis, the elastic modulus is estimated by drawing a tangent to the steepest initial straight-line portion of the stress-strain curve. *Yield stress* is defined by ASTM D790-10 as a point at which the load does not increase with an increase in strain. However, for the analysis of CIPP liner stress-strain response, yield stress is defined as the first sudden deviation from the initial linear portion of the stress-strain curve. Furthermore, flexural strength (ultimate stress) is taken as the peak specimen stress. The average flexural test values obtained for each CIPP resin plate are summarized in Tables 5.2, 5.9, and 5.13. The flexural stress-strain responses for each of the liner systems are illustrated in Figures 5.9 to 5.17.

Table 5.2 - Liner "A" Flexural testing summary

Flexural Test Results Summary	Resin 1 – Liner A		Resin 2 – Liner A		Resin 3 – Liner A	
	Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation
Span to Depth Ratio	16.5	0.04	16.4	0.07	16.4	0.23
Average Depth (mm)	10.2	0.03	10.3	0.04	10.3	0.14
Slope (N/mm)	107	4.5	103	1.5	67.0	0.9
Initial Tangent Modulus of Elasticity (MPa)	4,850	151	4,580	78	3,000	95
Initial Tangent Modulus of Elasticity (psi)	703,300	21,930	663,600	11,370	435,400	13,840
Flexural Strength (Ultimate) (MPa)	151	3.8	139	2.1	82	2.9
Flexural Strength (Ultimate) (psi)	21,930	550	20,130	311	11,870	424
Flexural Strain (Ultimate) (%)	4.84	0.01	4.91	0.04	4.79	0.18
Flexural Strength (Yield) (MPa)	79.8	6.8	58.9	2.8	32.7	5.30
Flexural Strength (Yield) (psi)	11,570	992	8,540	405	4,740	770
Flexural Strain (Yield) (%)	1.68	0.21	1.31	0.09	1.09	0.15

Table 5.3 - Resin 1 / Liner A - Flexural properties

Test Specimen	Initial Tangent Modulus of Elasticity		At Flexural Yield			At Flexural Break		
			Strength		Strain (%)	Strength		Strain (%)
	(MPa)	(psi)	(MPa)	(psi)		(MPa)	(psi)	
R1-A-1-1	4,950	718,300	74	10,790	1.52	153	22,190	4.85
R1-A-1-5	4,920	713,400	77	11,230	1.59	154	22,310	4.85
R1-A-1-8	4,680	678,100	87	12,680	1.92	147	21,300	4.83
Min	4,680	678,100	74	5,553	1.52	147	21,300	4.83
Max	4,950	718,300	87	12,680	1.92	154	22,310	4.85
Average	4,850	703,300	79	11,570	1.68	151	21,930	4.84
Standard Deviation	151	21,930	7	991	0.21	4	550	0.01

Table 5.4 - Resin 1 / Liner A - Flexural properties of specimens tested with convex surface facing downwards

Test Specimen	Initial Tangent Modulus of Elasticity		At Flexural Yield			At Flexural Break		
			Strength		Strain (%)	Strength		Strain (%)
	(MPa)	(psi)	(MPa)	(psi)		(MPa)	(psi)	
R1-A-2-1	4,950	717,600	40	5,770	0.821	74	10,770	1.75
R1-A-2-3	4,970	721,400	38	5,550	0.790	77	11,210	1.88

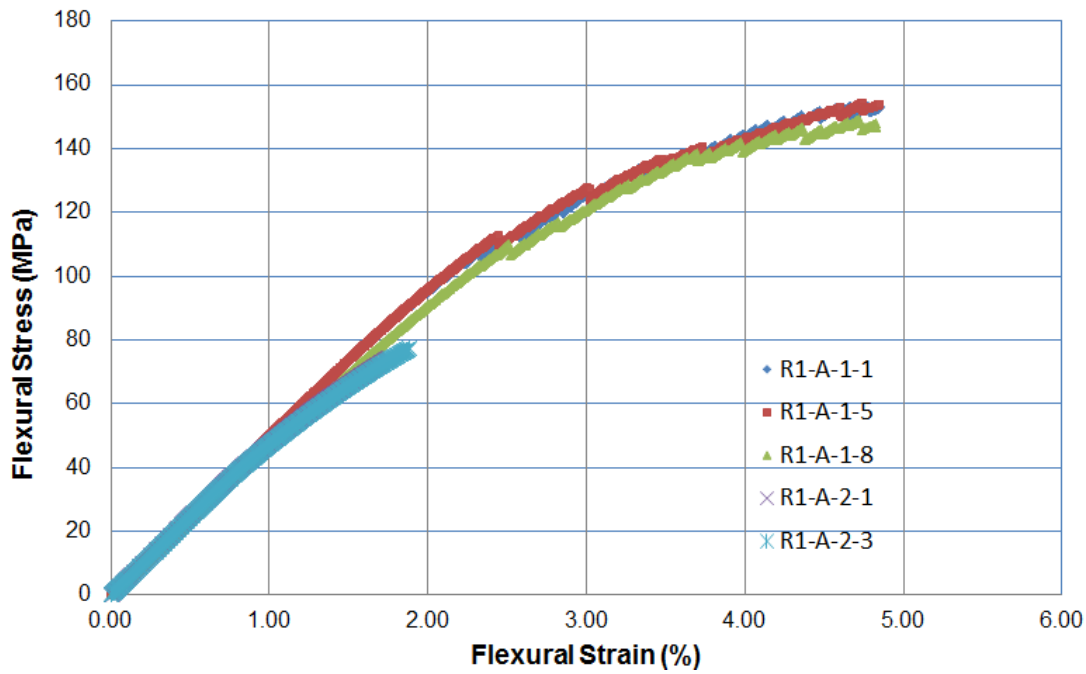


Figure 5.9 - Resin 1 / Liner A - Flexural stress-strain response

Table 5.5 - Resin 2 / Liner A - Flexural properties

Test Specimen	**Initial Tangent Modulus of Elasticity**		**At Flexural Yield**			**At Flexural Break**		
			Strength		**Strain (%)**	**Strength**		**Strain (%)**
	(MPa)	(psi)	(MPa)	(psi)		(MPa)	(psi)	
R2-A-1-1	4,650	674,800	56.0	8,120	1.22	140	20,250	4.87
R2-A-1-5	4,500	652,000	61.5	8,920	1.40	136	19,780	4.90
R2-A-1-6	4,580	664,100	59.2	8,580	1.31	140	20,360	4.95
Min	4,500	652,000	56.0	8,120	1.22	136	19,780	4.87
Max	4,650	674,800	61.5	8,920	1.40	140	20,360	4.95
Average	4,580	663,600	58.9	8,540	1.31	139	20,130	4.91
Standard Deviation	78	11,370	3	405	0.09	2	311	0.0

Table 5.6 - Resin 2 / Liner A - Flexural properties of specimens tested with convex surface facing downwards

Test Specimen	**Initial Tangent Modulus of Elasticity**		**At Flexural Yield**			**At Flexural Break**		
			Strength		**Strain (%)**	**Strength**		**Strain (%)**
	(MPa)	(psi)	(MPa)	(psi)		(MPa)	(psi)	
R2-A-2-1	4,720	684,400	42.2	6,120	0.93	72.5	10,510	1.95
R2-A-2-8	4,500	653,100	36.6	5,300	0.83	70.4	10,210	1.91

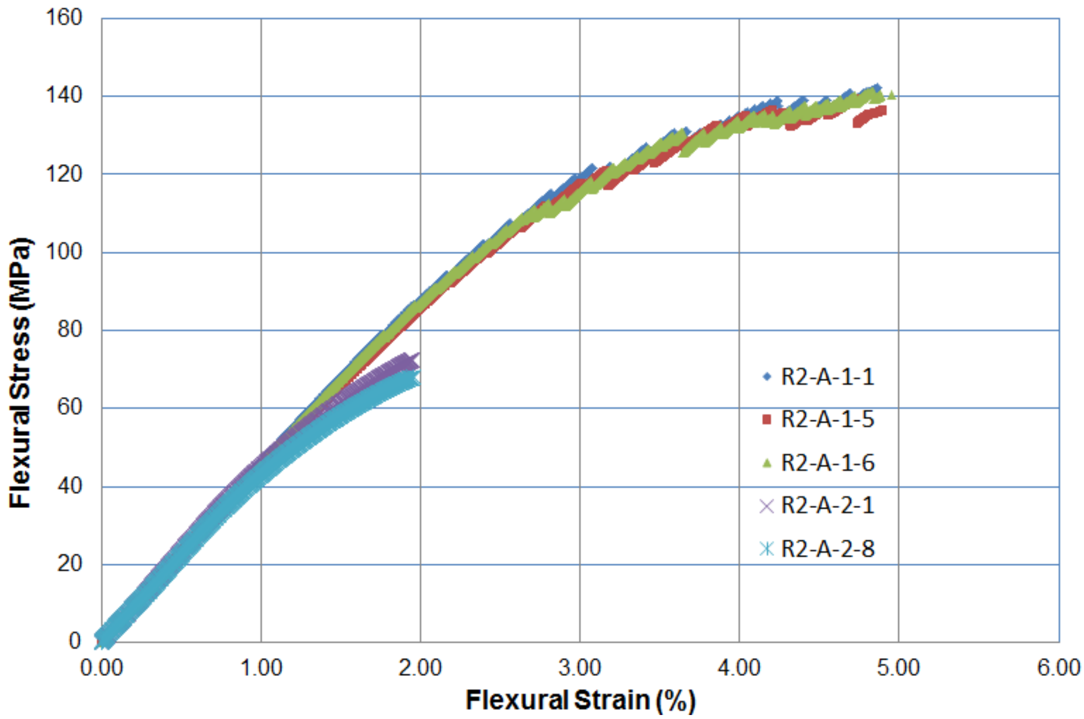


Figure 5.10 - Resin 2 / Liner A - Flexural stress-strain response

Table 5.7 - Resin 3 / Liner A - Flexural properties

Test Specimen	Initial Tangent Modulus of Elasticity		At Flexural Yield			At Flexural Break		
			Strength		Strain (%)	Strength		Strain (%)
	(MPa)	(psi)	(MPa)	(psi)		(MPa)	(psi)	
R3-A-1-1	3,010	437,300	35.3	5,110	1.15	83.0	12,040	4.83
R3-A-1-2	2,900	420,700	26.6	3,860	0.92	78.5	11,390	4.94
R3-A-2-3	3,090	448,200	36.2	5,250	1.19	84.0	12,180	4.58
Min	2,900	420,700	26.6	3,860	0.92	78.5	11,390	4.58
Max	3,090	448,200	36.2	5,250	1.19	84.0	12,180	4.94
Average	3,000	435,400	32.7	4,740	1.09	81.8	11,870	4.79
Standard Deviation	95	13,840	5	769	0.15	3	424	0.2

Table 5.8 - Resin 3 / Liner A - Flexural properties of specimens tested with convex surface facing downwards

Test Specimen	Initial Tangent Modulus of Elasticity		At Flexural Yield			At Flexural Break		
			Strength		Strain (%)	Strength		Strain (%)
	(MPa)	(psi)	(MPa)	(psi)		(MPa)	(psi)	
R3-A-2-5	3,120	452,900	23.0	3,340	0.75	44.0	6,400	1.85
R3-A-2-6	3,100	450,200	21.5	3,120	0.70	44.3	6,420	1.75

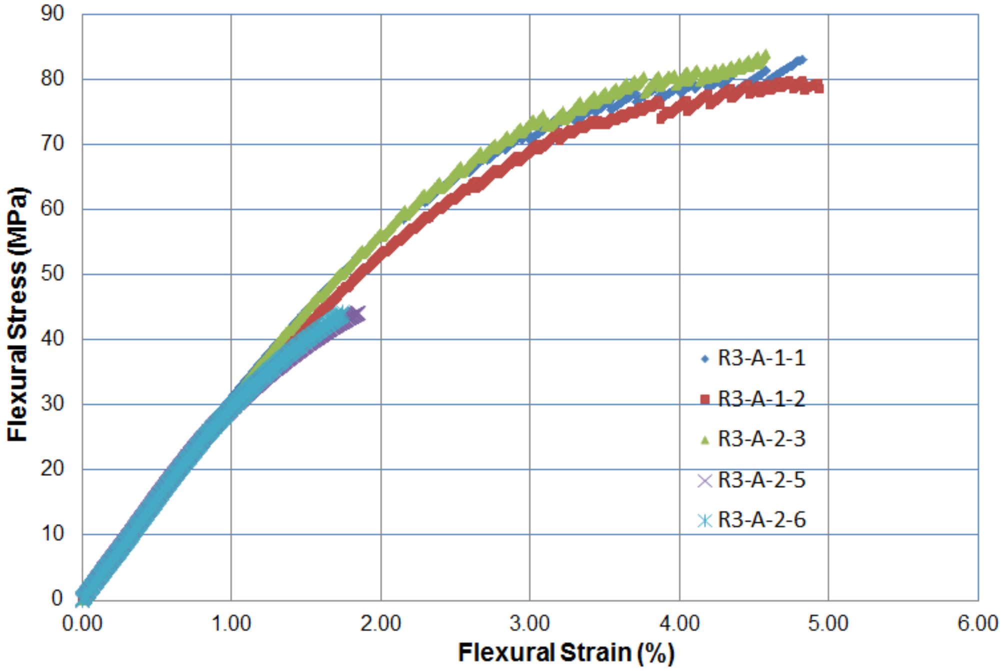


Figure 5.11 - Resin 3 / Liner A - Flexural stress-strain response

Table 5.9 - Liner “B” Flexural testing summary

Flexural Test Results Summary	Resin 1 – Liner B		Resin 2 – Liner B		Resin 3 – Liner B	
	Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation
Span to Depth Ratio	16.9	0.86	17.8	1.1	17.6	0.95
Average Depth (mm)	7.43	0.37	7.08	0.42	7.12	0.38
Slope (N/mm)	261	36	208	28	186	15
Initial Tangent Modulus of Elasticity (MPa)	15,530	521	15,210	1,415	12,820	1,462
Initial Tangent Modulus of Elasticity (psi)	2,252,200	75,500	2,206,400	205,300	1,859,700	212,100
Flexural Strength (Ultimate) (MPa)	365	29	354	46	250	31
Flexural Strength (Ultimate) (psi)	52,930	4,200	51,280	6,730	36,300	4,540
Flexural Strain (Ultimate) (%)	2.48	0.26	2.48	0.22	2.06	0.15
Flexural Strength (Yield) (MPa)	236	37	219	35	162	11
Flexural Strength (Yield) (psi)	34,240	5,320	31,790	5,140	23,500	1,570
Flexural Strain (Yield) (%)	1.53	0.27	1.45	0.11	1.30	0.17

Table 5.10 - Resin 1 / Liner B - Flexural properties

Test Specimen	**Initial Tangent Modulus of Elasticity**		**At Flexural Yield**			**At Flexural Break**		
			Strength		**Strain (%)**	**Strength**		**Strain (%)**
	(MPa)	(psi)	(MPa)	(psi)		(MPa)	(psi)	
R1-B-2-2	15,180	2,202,100	289	41,980	1.93	394	57,130	2.73
R1-B-2-3	16,340	2,369,700	227	32,950	1.43	326	47,250	2.10
R1-B-2-4	15,770	2,287,300	197	28,520	1.27	393	57,040	2.71
R1-B-3-5	15,170	2,200,100	212	30,820	1.36	354	51,310	2.45
R1-B-3-6	15,180	2,201,900	255	36,950	1.67	358	51,920	2.42
Min	15,170	2,200,100	197	28,520	1.27	326	47,250	2.10
Max	16,340	2,369,700	289	41,980	1.93	394	57,130	2.73
Average	15,530	2,252,200	236	34,240	1.53	365	52,930	2.48
Standard Deviation	521	75,500	37	5,320	0.27	29	4,200	0.26

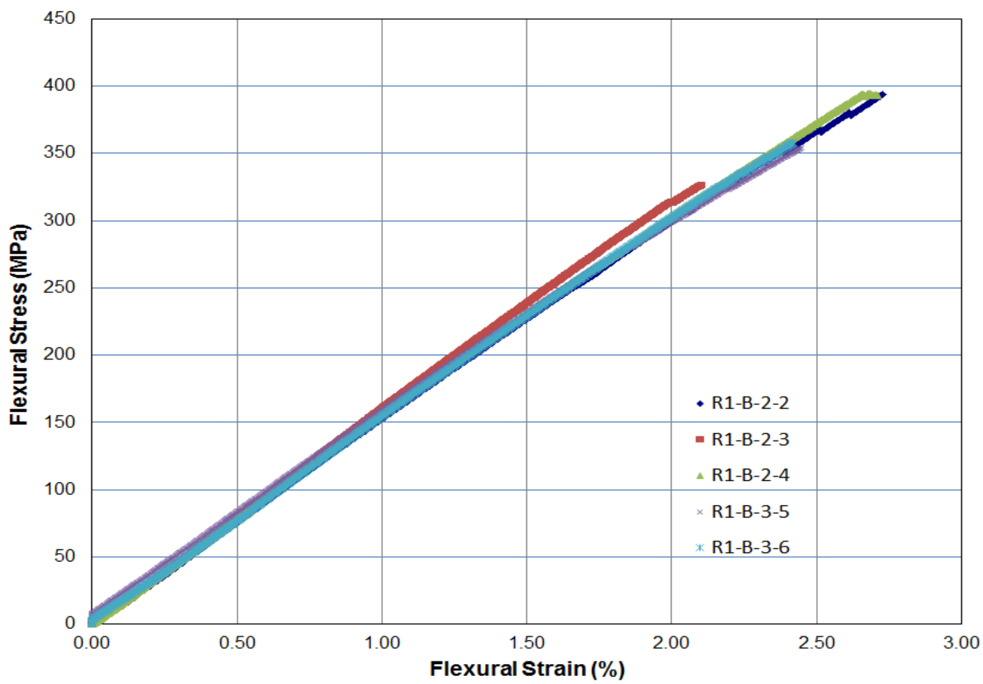


Figure 5.12 - Resin 1 / Liner B - Flexural stress-strain response

Table 5.11 - Resin 2 / Liner B - Flexural properties

Test Specimen	Initial Tangent Modulus of Elasticity		At Flexural Yield			At Flexural Break		
			Strength		Strain (%)	Strength		Strain (%)
	(MPa)	(psi)	(MPa)	(psi)		(MPa)	(psi)	
*R2-B-1-4	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
R2-B-1-6	16,970	2,461,400	272	39,430	1.60	418	60,610	2.62
R2-B-1-7	14,850	2,154,200	206	29,890	1.40	310	45,010	2.16
R2-B-2-3	13,560	1,967,000	195	28,290	1.46	332	48,190	2.63
R2-B-2-5	15,460	2,242,800	204	29,570	1.34	354	51,320	2.49
Min	13,560	1,967,000	195	28,290	1.34	310	45,010	2.16
Max	16,970	2,461,400	272	39,430	1.60	418	60,610	2.63
Average	15,210	2,206,400	219	31,790	1.45	354	51,280	2.48
Standard Deviation	1,415	205,300	35	5,140	0.11	46	6,730	0.22

***** Specimen R2-B-1-4 was removed from analysis due to existence of anomaly in the test result

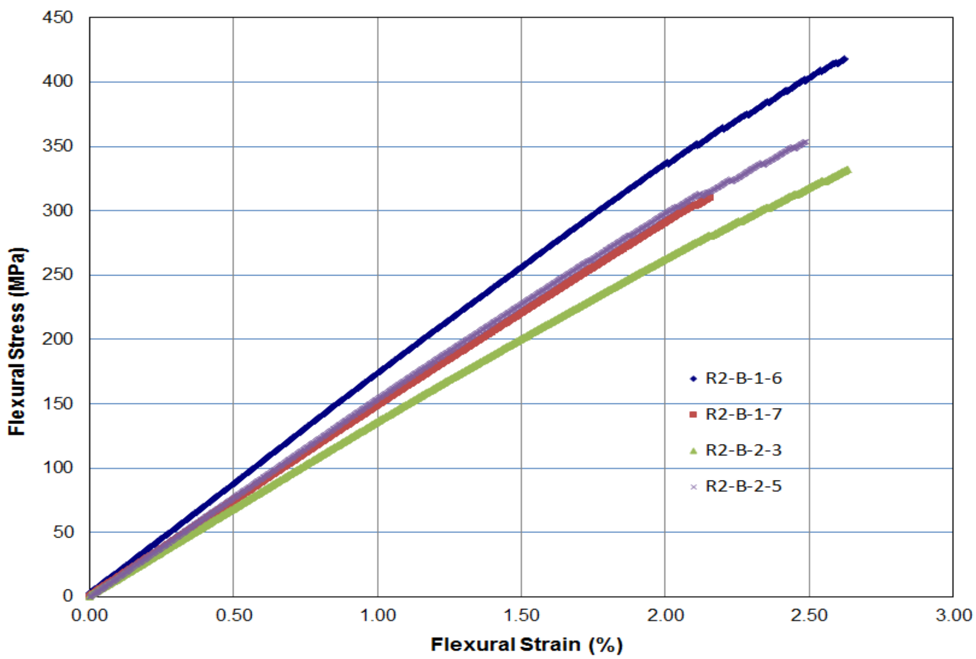


Figure 5.13 - Resin 2 / Liner B - Flexural stress-strain response

Table 5.12 - Resin 3 / Liner B - Flexural properties

Test Specimen	Initial Tangent Modulus of Elasticity		At Flexural Yield			At Flexural Break		
			Strength		Strain (%)	Strength		Strain (%)
	(MPa)	(psi)	(MPa)	(psi)		(MPa)	(psi)	
R3-B-1-1	14,870	2,156,400	158	22,890	1.08	275	39,950	1.96
R3-B-1-2	12,430	1,802,800	164	23,820	1.33	232	33,580	1.95
R3-B-1-4	11,700	1,697,200	146	21,110	1.27	215	31,240	1.93
R3-B-2-6	13,740	1,993,100	171	24,810	1.26	290	42,090	2.21
R3-B-2-7	11,370	1,648,900	172	24,890	1.55	239	34,650	2.23
Min	11,370	1,648,900	146	21,110	1.08	215	31,240	1.93
Max	14,870	2,156,400	172	24,890	1.55	290	42,090	2.23
Average	12,820	1,859,700	162	23,500	1.30	250	36,300	2.06
Standard Deviation	1,460	212,100	11	1,570	0.17	31	4,540	0.15

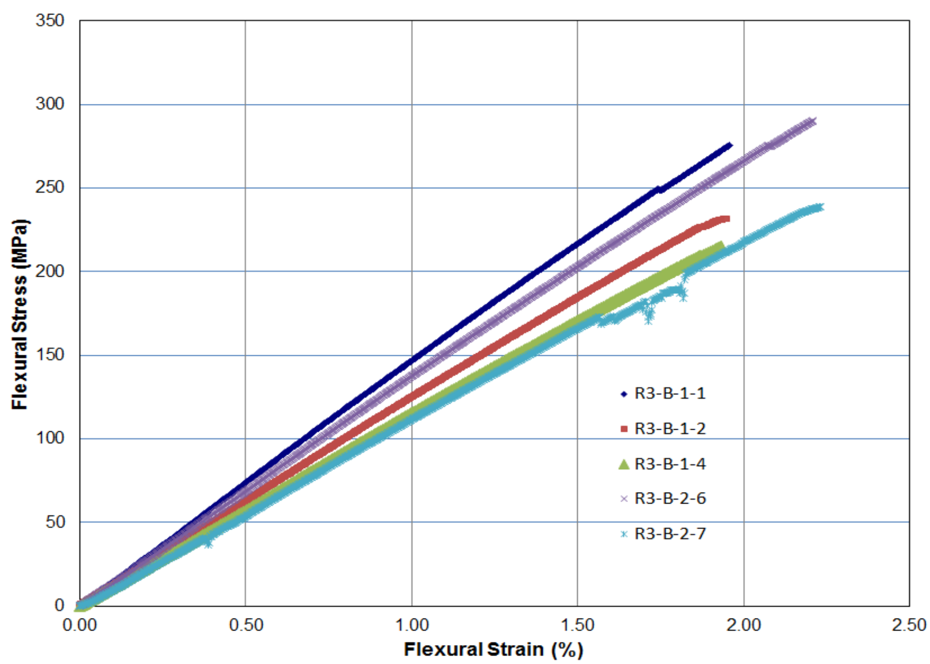


Figure 5.14 - Resin 3 / Liner B - Flexural stress-strain response

Table 5.13 - Liner "C" Flexural testing summary

Flexural Test Results Summary	**Resin 1 – Liner C**		**Resin 2 – Liner C**		**Resin 3 – Liner C**	
	Average	**Standard Deviation**	**Average**	**Standard Deviation**	**Average**	**Standard Deviation**
Span to Depth Ratio	16.97	1.6	18.57	1.8	17.66	1.6
Average Depth (mm)	5.17	0.50	4.73	0.47	5.01	0.47
Slope (N/mm)	165	33	122	34	118	32
Initial Tangent Modulus of Elasticity (MPa)	13,390	1,256	12,420	656	10,410	1,173
Initial Tangent Modulus of Elasticity (psi)	1,942,600	182,200	1,801,100	95,210	1,509,400	170,200
Flexural Strength (Ultimate) (MPa)	336	36	321	14	257	36
Flexural Strength (Ultimate) (psi)	48,720	5,240	46,500	1,960	37,350	5,150
Flexural Strain (Ultimate) (%)	3.40	0.31	3.61	0.52	3.23	0.16
Flexural Strength (Yield) (MPa)	108	26	95	6	63	5
Flexural Strength (Yield) (psi)	15,610	3,760	13,780	908	9,140	772
Flexural Strain (Yield) (%)	0.85	0.24	0.77	0.09	0.62	0.07

Table 5.14 - Resin 1 / Liner C - Flexural properties

Test Specimen	Initial Tangent Modulus of Elasticity		At Flexural Yield			At Flexural Break		
			Strength		Strain (%)	Strength		Strain (%)
	(MPa)	(psi)	(MPa)	(psi)		(MPa)	(psi)	
R1-C-1-1	14,040	2,036,100	116	16,760	0.861	360	52,220	3.54
R1-C-1-8	15,240	2,210,900	77	11,190	0.530	363	52,650	3.73
R1-C-2-5	12,970	1,881,000	144	20,920	1.15	362	52,430	3.50
R1-C-2-11	12,080	1,752,500	112.1	16,250	0.975	309	44,880	3.33
R1-C-2-12	12,630	1,832,600	89.2	12,940	0.720	285	41,390	2.90
Min	12,080	1,752,500	77.1	11,190	0.530	285	41,390	2.90
Max	15,240	2,210,900	144	20,920	1.15	363	52,650	3.73
Average	13,390	1,942,600	108	15,610	0.846	336	48,720	3.40
Standard Deviation	1,260	182,200	25.9	3,760	0.24	36.1	5,240	0.31

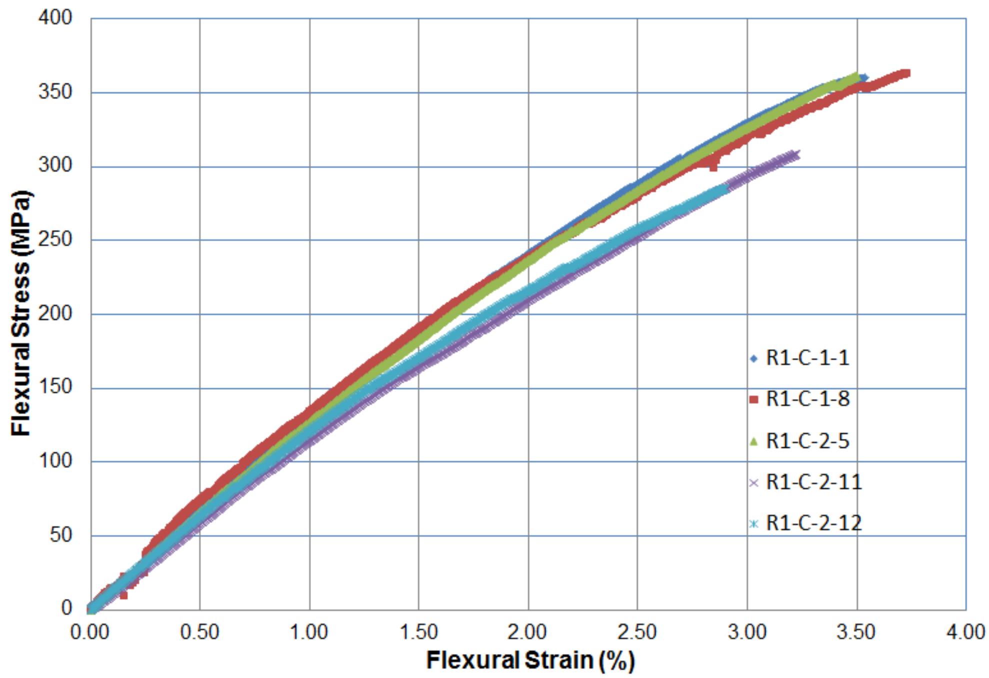


Figure 5.15 - Resin 1 / Liner C - Flexural stress-strain response

Table 5.15 - Resin 2 / Liner C - Flexural properties

Test Specimen	Initial Tangent Modulus of Elasticity		At Flexural Yield			At Flexural Break		
			Strength		Strain (%)	Strength		Strain (%)
	(MPa)	(psi)	(MPa)	(psi)		(MPa)	(psi)	
R2-C-1-1	13,310	1,931,000	92	13,320	0.676	306	44,420	2.99
*R2-C-1-8	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
R2-C-1-11	11,810	1,713,400	97	14,060	0.830	327	47,480	4.19
R2-C-2-1	12,470	1,809,400	88	12,830	0.731	336	48,730	3.83
R2-C-2-8	12,070	1,750,500	103	14,910	0.859	313	45,360	3.43
Min	11,810	1,713,400	88	12,830	0.68	306	44,420	2.99
Max	13,310	1,931,000	103	14,910	0.859	336	48,730	4.19
Average	12,420	1,801,100	95	13,780	0.770	321	46,500	3.61
Standard Deviation	656	95,210	6	908	0.090	14	1,960	0.52

***** Specimen R2-C-1-8 was removed from analysis due to existence of anomaly in the test result

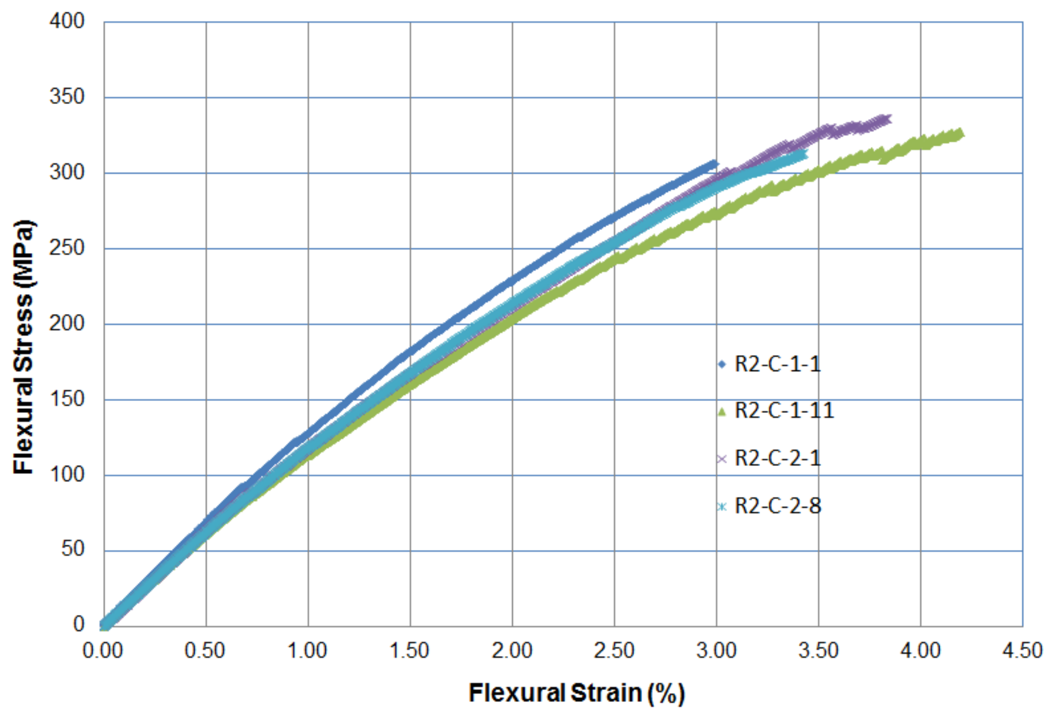


Figure 5.16 - Resin 2 / Liner C - Flexural stress-strain response

Table 5.16 - Resin 3 / Liner C - Flexural properties

Test Specimen	Initial Tangent Modulus of Elasticity		At Flexural Yield			At Flexural Break		
			Strength		Strain (%)	Strength		Strain (%)
	(MPa)	(psi)	(MPa)	(psi)		(MPa)	(psi)	
R3-C-1-1	9,160	1,329,000	65	9,400	0.730	231	33,450	3.35
R3-C-1-9	11,960	1,734,000	68	9,860	0.574	312	45,300	3.33
R3-C-1-11	10,300	1,494,700	67	9,740	0.639	264	38,270	3.06
R3-C-2-8	9,430	1,367,600	55	8,030	0.609	222	32,170	3.34
R3-C-2-9	11,180	1,621,400	60	8,670	0.539	259	37,540	3.05
Min	9,160	1,329,000	55	8,030	0.539	222	32,170	3.05
Max	11,960	1,734,000	68	9,860	0.730	312	45,300	3.35
Average	10,410	1,509,400	63	9,140	0.618	257	37,350	3.23
Standard Deviation	1,170	170,200	5	772	0.073	36	5,150	0.16

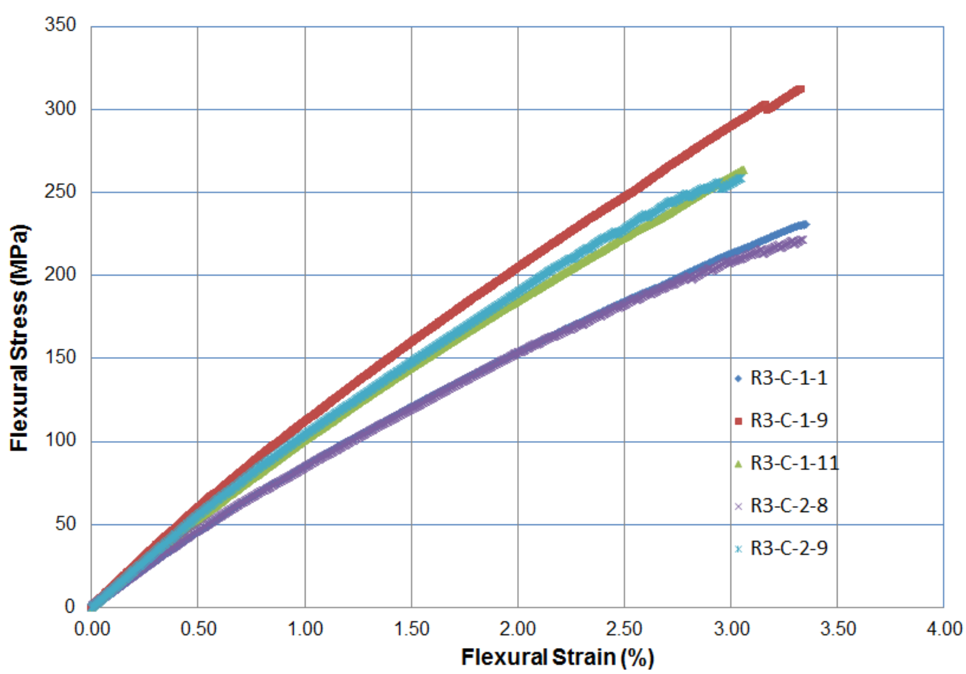


Figure 5.17 - Resin 3 / Liner C - Flexural stress-strain response

5.5 Discussion of Flexural Test Results

ASTM D790-10 specifies five percent strain in specimen outer fibers as the failure limit. Liner "A" specimens demonstrated the highest strain values at the flexural break point. However, none of the specimens from the nine CIPP products had strain values above five percent at the flexural break point. The average initial modulus of elasticity, strength at yield, and strength at break values for each resin/liner type are reported in Table 5.17.

Table 5.17 - Average flexural test results for each resin/liner type

Resin / Liner Type	Initial Modulus of Elasticity		Strength at Yield		Strength at Break	
	(MPa)	(psi)	(MPa)	(psi)	(MPa)	(psi)
Resin 1 / Liner A	4,890	709,800	63	9,210	121	17,560
Resin 2 / Liner A	4,580	663,600	59	8,540	139	20,130
Resin 3 / Liner A	3,000	435,400	33	4,740	82	11,870
Resin 1 / Liner B	15,530	2,252,200	236	34,240	365	52,930
Resin 2 / Liner B	15,210	2,206,400	219	31,790	354	51,280
Resin 3 / Liner B	12,820	1,859,700	162	23,500	250	36,300
Resin 1 / Liner C	13,390	1,942,600	108	15,610	336	48,720
Resin 2 / Liner C	12,420	1,801,100	95	13,780	321	46,500
Resin 3 / Liner C	10,410	1,509,400	63	9,140	257	37,350

The asymmetry of the felt layers in Liner "A" has caused differential shrinkage when cured resulting in panels with curvature (*Hazen*, 2015). The Liner "A" specimens tested with the convex surface facing downwards demonstrated a brittle behavior compared to the specimens tested with the concave surface facing downwards. It should be noted that for the specimens tested with the concave surface facing downwards, the load applied at the mid-span is in the direction of specimen curvature as oppose to the specimens tested with the convex surface facing downwards which the load is applied against the specimen curvature. It should also be noted that the thinner layer (i.e., the 3.0 mm felt layer) is at the bottom when the concave surface faced downwards and the thicker layer (i.e., the 7.5 mm felt layer) is at the bottom when the convex surface faced downwards. Thus, the asymmetry of the felt layers may have contribued to this difference in the behavior of the Liner "A" specimens. The test results from the specimens tested with the concave surface down are considered as the material flexural properties.

The initial flexural moduli of elasticity values of all resin/liner types are compared in Figure 5.18. It is noticed that the liner bag materials, especially Liner "B", have substantially added to the flexural stiffness of the resin only samples. Liner "B" bag material has the lowest fiberglass thickness as a percentage of total thickness. Figure 5.18 also shows that the Resin "3" products have lower flexural moduli of elasticity values compared to the other two resins in each liner system. Liner "A" products have considerably lower flexural moduli of elasticity compared to Liners "B" and "C".

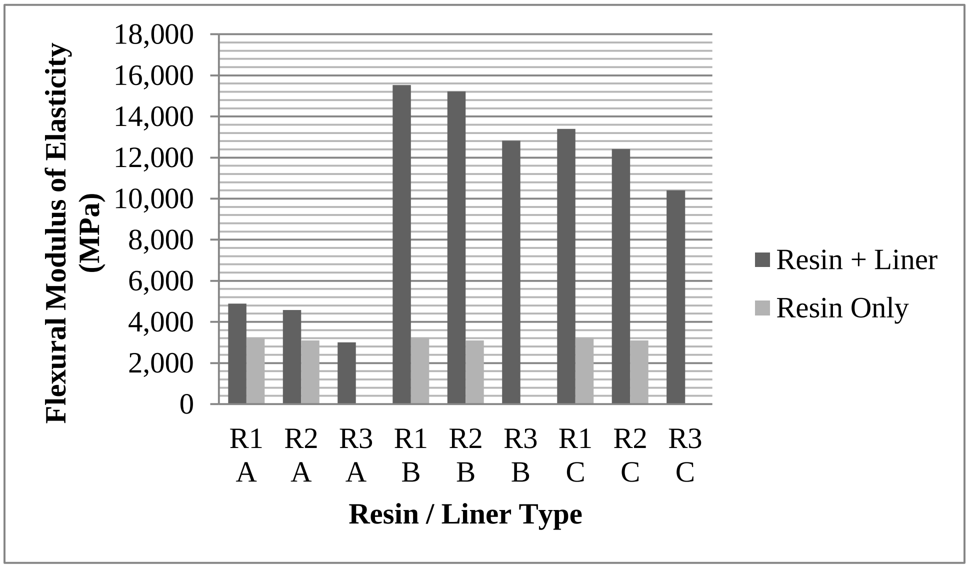


Figure 5.18 - Comparison of flexural moduli of elasticity values

The flexural strength at yield and at break values of all resin/liner types are compared in Figure 5.19. Liner "A" products have lower strength values compared to Liners "B" and "C". It is noticed that the Liner "A" bag material has not increased the ultimate (at break) flexural strength of the Resin "1" only sample. Figure 5.19 shows that Liner "B" products have higher flexural strength at yield and at break values compared to Liners "A" and "C". Flexural properties of Liner "A" systems are lower than Liners "B" and "C". This difference is due to the differing construction of each liner resulting in panels with different thicknesses and fiberglass content, two variables which have a significant impact on flexural properties of CIPP liners (*Hazen*, 2015). Resin "3" products demonstrated lower flexural properties compared to Resins "1" and "2". This difference is attributed to the differing polymer properties and the fiberglass to resin interaction on the molecular level (*Hazen*, 2015). Resin "3" is the only VOC-free and styrene-free resin and had a significantly different composition comparing to Resins "1" and "2" (*Hazen*, 2015).

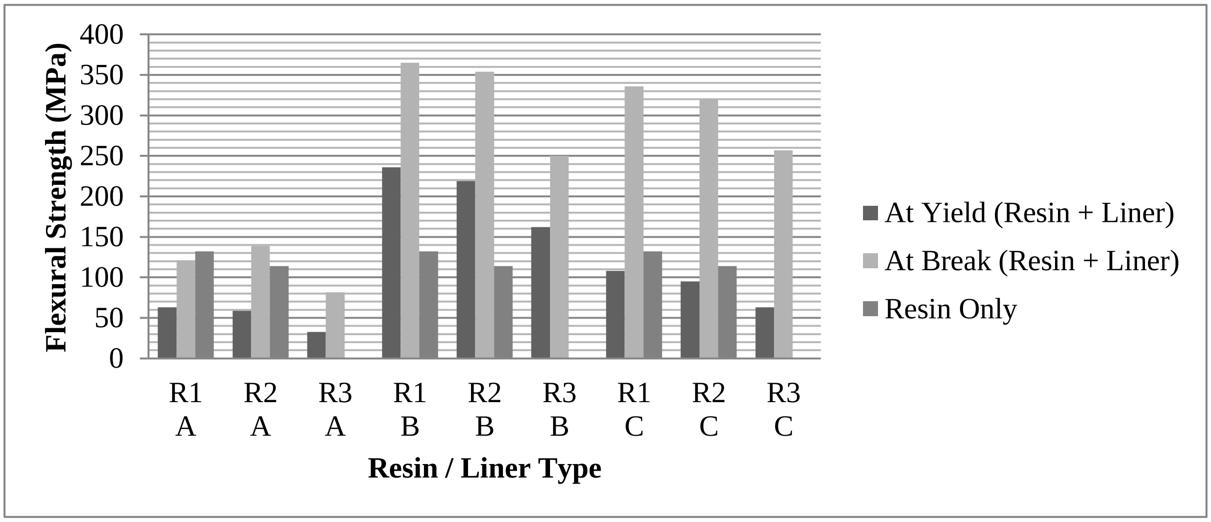


Figure 5.19 - Comparison of flexural strength values

For a reinforced CIPP, liner properties are specific to resin-reinforcement-carrier matrix and cannot be generalized from resin only properties (*Richard*, 1993). Compared to some other reinforced CIPP products previously tested by CATT, the flexural properties reported in Table 5.17 seem reasonable. Flexural strength at yield values are used as a basis for calculation of the loads required for the long-term creep tests. The minimum field inspection short-term flexural modulus and flexural strength values required by ASTM F1216-09 are 250,000 psi (1724 MPa) and 4500 psi (31 MPa), respectively. The flexural modulus and flexural strength values for all of the CIPP products reported in Table 5.17 exceed the ASTM F1216-09 minimum field inspection values.

Similar to tensile test specimens, some degree of variability is observed in the flexural properties of the specimens in each liner system. For some liner systems the variability is higher than others. The variability is also observed in flexural properties of some other CIPP liners tested previously by CATT. The variation in flexural properties among the same type of specimens can be attributed to the existence of non-uniformity along the laboratory manufactured CIPP panels resulting in specimens with non-uniform thicknesses. This is why a minimum of five specimens from each CIPP liner system are tested to obtain representative flexural properties.

6 Analysis of Nine CIPPs Long-term Flexural Creep Behavior

As mentioned in Chapter 2, CIPP liners creep under stress. The rate of creep is influenced by resin type, applied load, degree of cure, and the environmental conditions (*Richard*, 1993). A long-term flexural creep test is conducted to evaluate the CIPP liner long-term behavior. In the following, a description of the creep test, specimens, equipment, and the results are provided.

6.1 Creep Test Specifications and Procedure

ASTM D2990-09, *Standard Test Methods for Tensile, Compressive, and Flexural Creep and Creep-Rupture of Plastics*, outlines the test procedure for determining the long-term flexural creep modulus. ASTM D2990 and ISO 899, "Determination of Creep Behavior", Parts 1 and 2 cover the same subject matter. However, it is stated in ASTM D2990-09 that the technical content of ISO 899 is different from ASTM D2990 and results cannot be directly compared between the two test methods. Flexural creep behavior is addressed in ISO 899 Part 2, "Flexural Creep by Three-Point Loading". ASTM D2990-09 specifies the test procedure for measuring the deformation of a specimen as a function of time under a constant static load applied to the specimen in selected loading configurations, (such as, tension, flexure, or compression) in a controlled temperature and humidity environment.

The flexural creep test is conducted on rectangular CIPP specimens similar to the specimens used in the bending test, prepared in accordance with ASTM D790 specifications. The test consisted of placing a rectangular specimen flatwise as a beam, on two rigid supports and applying a load at the mid-span with the long axis of the specimen perpendicular to the loading nose. The full load is applied within five seconds.

Upon application of the load, the specimen undergoes an initial rapid elongation that may consist of both elastic and plastic strain (*ASTM D2990-09*). The plastic strain may not be recoverable once the load is removed. Although the initial strain in the specimen that occurs instantaneously upon application of the load does not represent material creep, it should be included in the creep modulus calculations since it is usually a considerable fraction of the total allowable strain in design of CIPP liners (*ASTM D2990-09*). Following the initial elongation, the creep rate decreases rapidly with time (primary creep) and then it reaches a steady-state value (secondary creep) followed by a rapid increase and fracture (tertiary creep) which usually occurs at high stress levels (*ASTM D2990-09*). Figure 6.1 shows an idealized curve illustrating the three stages of creep.

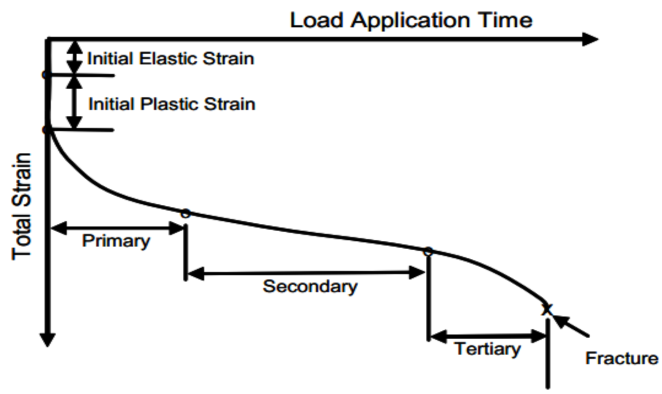


Figure 6.1 - Primary, secondary, and tertiary creep stages (Adapted from *ASTM D2990-09*)

The flexural creep test duration is not specified by ASTM D2990-09. However, the standard states that for prediction of material long-term performance undergoing constant loads for six months or longer, test duration of longer than 3,000 hours is necessary. For CIPP liners, 10,000 hours of continuous loading has become standard industry practice for extrapolation of the test results to determine the 50-year creep modulus (*TTC Report 302*, 1994). Creep behavior is noticeably affected by temperature (*Ryther and Ruggles-Wrenn*, 2011). Thus, the test is conducted in a controlled temperature and humidity room. The temperature and relative humidity of the test environment over the testing period is monitored to make sure it stays within specified limits (i.e., temperature of 23 +/- 2°C (73.4 +/- 3.6°F) and 50 +/- 10 % relative humidity).

6.2 Creep Test Specimens

According to ASTM D2990-09, at least three specimens are required for the flexural creep test at a single temperature to estimate long-term properties of a particular CIPP product. However, in this research, five specimens from each liner system are tested to obtain more representative test results. Rectangular test specimens are cut from resin plates using water jet technology in accordance with ASTM D790-10 requirements. To avoid shear stress effects, the specimens are cut with a support span to depth ratio of 16 (tolerance +/- 1). The width of the specimens are selected to be less than or equal to one fourth of the support span. The length of the specimens are selected to allow for overhanging on each end for at least 10% of the support span, but in no case less than 6.4 mm on each end to prevent the specimen from slipping through the supports. Sample dimensions are measured using a digital caliper accurate to 0.01 mm. Specimen dimensions are presented in Table 6.1. Average sample width and depth (thickness) values are used in all calculations. All test specimens are labeled using the following scheme:

X1-Y-J-K: where X1 stands for the resin type (e.g., R1 stands for Resin 1, R2 stands for Resin 2, R3 stands for Resin 3), Y stands for the liner type (three liners labeled as A, B, or C), J represents the plate number, and K stands for the coupon/specimen number. For example, R2-A-1-1 refers to *Resin 2-Liner A-Plate No.1-Specimen #1*.

Table 6.1 - Creep test specimen dimensions and span to depth ratio

Test Specimen	**Specimen Dimensions (mm)**			**Span to Depth Ratio**
	Length	**Width**	**Depth**	
Liner A	205	25	10.06 to 10.56	15.6 to 16.8
Liner B	150	20	6.64 to 7.80	16.0 to 18.8
Liner C	105	15	4.23 to 5.50	15.8 to 20.6

6.3 Creep Test Loads

Both the ASTM D2990-09 and ISO standard 889-2-2003 do not specify the required test load for the flexural creep test. ISO standard 889-2-2003, states to *select a stress value appropriate to the application envisaged for the material under test or choose the stress such that the deflection is not greater than 0.1 times the distance between the supports at any time during the test.* A load creating a flexural stress equivalent to 25 percent of material ASTM D790 yield stress is selected for the long-term creep test. A typical ASTM D790 flexural stress-strain response of a brittle CIPP liner is illustrated in Figure 6.2. In this case the flexural strength and the yield stress values are the same since a sudden failure occurs at 1.5% strain. It should also be noted that since the exact period and level of stresses (such as hydraulic surges, and hydrostatic pressures, etc.) that a liner may undergo over its design life are unknown, a factor of safety of “2” is commonly considered in CIPP design (*Knight*, 2013).

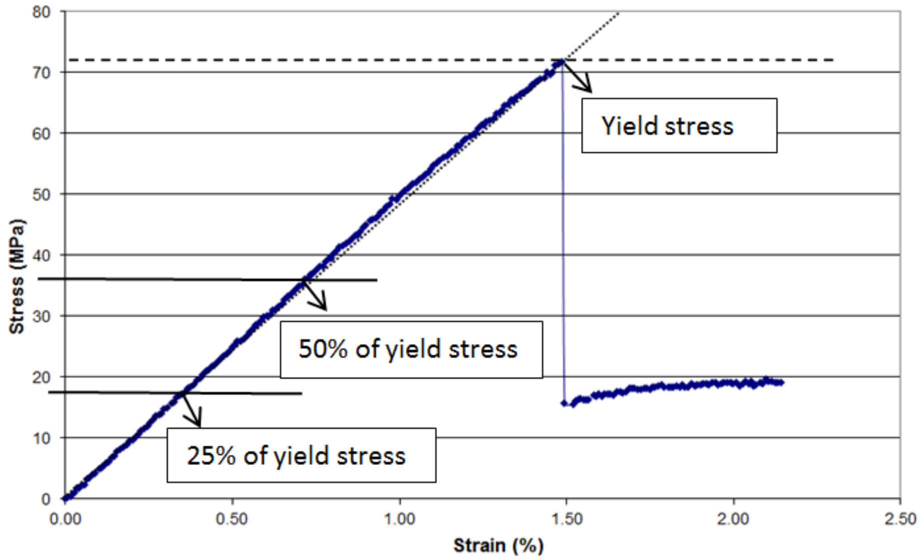


Figure 6.2 - Typical CIPP ASTM D790 flexural stress-strain response

Creep-rupture envelopes are useful for determining a stress level below which it is safe to operate given the time requirements of the end-use application (*ASTM D2990-09*). To develop a creep-rupture envelope, it is required to test a material under different stress levels and measure the time to failure (*ASTM D2990-09*). Figure 6.3 shows a typical creep-rupture envelope developed for a plastic material.

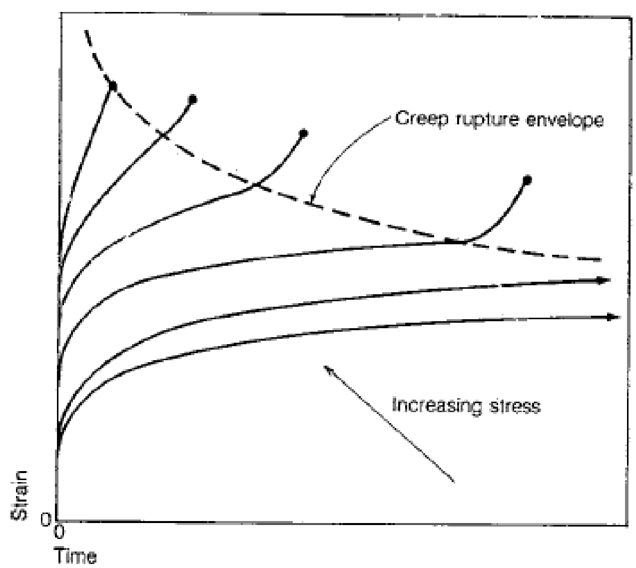


Figure 6.3 - Creep rupture envelop (Adapted from *ASTM D2990-09*)

As illustrated in Figure 6.3, as the stress level increases, the time-to-failure decreases and the material demonstrates less creep. On the other hand, at lower stress levels the time-to-failure increases and the material creep behavior can be better characterized. This better explains the reason behind the selection of 25% of material ASTM D790 yield stress as the required test load for flexural creep characterization of CIPP liners. The calculated test loads are reported in Table 6.2. All of the loads were approved by the Interplastic Corp.

Table 6.2 - Long-term flexural creep test loads

Liner Type / Resin Type	Mass (kg)
Liner A / Resin 1	20.9
Liner A / Resin 2	15.7
Liner A / Resin 3	9.3
Liner B / Resin 1	39.2
Liner B / Resin 2	31.1
Liner B / Resin 3	23.5
Liner C / Resin 1	10.1
Liner C / Resin 2	6.3
Liner C / Resin 3	5.5

6.4 Prediction of Specimens Deflection Level

Based on the calculated loads (i.e., 25% of material ASTM D790 yield stress), the maximum deflection of the rectangular beam shape specimens from each liner type is predicted using Equation 6.1.

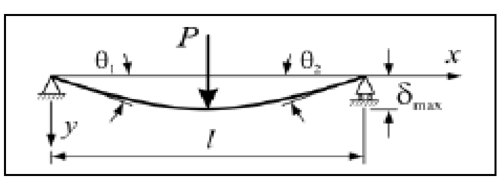


Figure 6.4 - Rectangular beam maximum deflection
(Adapted from *Canadian Concrete Design Handbook*, 2005)

$$\delta_{max} = \frac{Pl^3}{48\,EI} \tag{6.1}$$

where,

δ_{max} = specimen maximum deflection (mm),

P = load applied on the specimen (N),

l = specimen span (mm),

E = short-term flexural modulus (MPa),

I = moment of inertia ($\mathrm{mm}^4/\mathrm{mm}$).

The estimated maximum deflection values for each liner type are provided in Table 6.3. The values presented in Table 6.3 are estimated based on average properties of five specimens from each CIPP product. For the estimation of specimen deflection, the flexural modulus is taken as 50% of initial value, assuming that the specimen loses 50% of its initial flexural modulus under constant stress over the test period (i.e., creep of 50%). This doubled the values of the predicted maximum deflections.

Table 6.3 - Predicted specimen maximum deflection values

Resin / Liner Type	50% Flexural Modulus, E (MPa)	L (mm)	Depth, h (mm)	Width, b (mm)	I (mm^4)	P (N)	Max. Deflection (mm)
Liner A / Resin 1	2,425	169	10.24	25	2,237	205.5	3.81
Liner A / Resin 2	2,288	169	10.31	25	2,283	154.3	2.97
Liner A / Resin 3	1,527	169	10.29	25	2,270	91.7	2.66
Liner B / Resin 1	7,589	125	7.43	20	684	384.0	3.01
Liner B / Resin 2	7,564	125	7.08	20	591	305.0	2.77
Liner B / Resin 3	6,156	125	7.12	20	602	230.0	2.53
Liner C / Resin 1	6,281	87	5.17	15	173	99.4	1.26
Liner C / Resin 2	6,209	87	4.65	15	126	61.8	1.09
Liner C / Resin 3	5,238	87	5.01	15	157	53.7	0.89

6.5 Creep Test Equipment

From each liner system, five test samples are loaded on a rigid test rack with a span equal to 16 times the sample thickness. The test racks are designed in accordance with Canadian Handbook of Steel Construction specifications to be capable of withstanding the test loads. Using a stirrup, each sample is loaded at the mid span by hanging a steel weight as shown in Figure 6.5. Mechanical dial gages accurate to 0.01 mm mounted on top of the test frame are used to monitor the deflection of four of the specimens from each liner system. From each CIPP product, deflection of one of the test specimens is monitored and recorded using a displacement transducer connected to a data acquisition system. All tests are conducted in a controlled access room located in the Engineering 2 building at the University of Waterloo.

Figure 6.5 - Typical flexural creep test setup

6.6 Creep Test Results

The test started on June 13, 2014 with a total of 45 specimens. Sample deflection measurements are recorded at approximately 0.02, 0.05, 0.1, 0.2, 0.25, 0.5, 1, 2, 5, 16, 24, 48, 96, 192, 384, 768 and 1000 hours after the load application. Additional readings are recorded at subsequent 1000 hours interval until 10,000 hours is reached on August 10, 2015. These recorded data are used to predict the CIPPs long-term behavior. The amount of measured deflection at each time step is used to calculate the creep modulus for a given specimen. According to ASTM D2990-09, creep modulus is determined by dividing the maximum fiber stress by the maximum strain at a given time step. ASTM D2990-09 defines the following two relationships for calculating the maximum fiber stress and the maximum strain, respectively. Maximum fiber stress for each specimen is calculated using Equation 6.2:

$$S = 3PL/2bd^2 \tag{6.2}$$

where,

S = stress, psi (MPa),

P = initial applied load, lbf (N),

L = span, in. (mm),

b = width, in. (mm), and

d = depth, in. (mm).

Maximum strain in the outer fibers at the mid-span is calculated as:

$$r = \frac{6Dd}{L^2} * 100 \tag{6.3}$$

where,

r = maximum strain, in./in. (mm/mm),

D = maximum deflection at mid-span, in. (mm),

d = corrected specimen depth, in. (mm), and

L = span, in. (mm).

The flexural creep test results for each of the specimens from all of the CIPP products are provided in Tables 6.4 to 6.12. The creep modulus versus time plots for all of the liner systems are presented in Figures 6.6 to 6.14.

Table 6.4 - Resin 1 / Liner A - Creep test results

Specimen	**Time**	**Deflection**	**Maximum Strain**	**Creep Modulus**	
	(Hours)	(mm)	(%)	(MPa)	(psi)
R1-A-1-2	1,000	2.42	0.532	3,590	521,000
R1-A-1-2	3,000	2.46	0.540	3,540	513,200
R1-A-1-2	6,000	2.55	0.560	3,410	494,500
R1-A-1-2	10,000	2.63	0.577	3,310	480,000
R1-A-1-6	1,000	2.54	0.540	3,740	542,000
R1-A-1-6	3,000	2.60	0.554	3,650	528,800
R1-A-1-6	6,000	2.71	0.578	3,490	507,000
R1-A-1-6	10,000	3.03	0.645	3,130	454,200
R1-A-2-5	1,000	2.21	0.491	3,780	548,400
R1-A-2-5	3,000	2.25	0.500	3,710	537,900
R1-A-2-5	6,000	2.34	0.519	3,580	518,600
R1-A-2-5	10,000	2.42	0.536	3,460	501,700
R1-A-2-6	1,000	2.20	0.487	3,850	558,400
R1-A-2-6	3,000	2.25	0.498	3,770	546,500
R1-A-2-6	6,000	2.33	0.515	3,640	528,000
R1-A-2-6	10,000	2.42	0.535	3,510	508,600
R1-A-2-7	1,000	2.16	0.480	3,880	563,200
R1-A-2-7	3,000	2.27	0.502	3,710	538,100
R1-A-2-7	6,000	2.33	0.516	3,610	523,800
R1-A-2-7	10,000	2.43	0.538	3,460	502,600

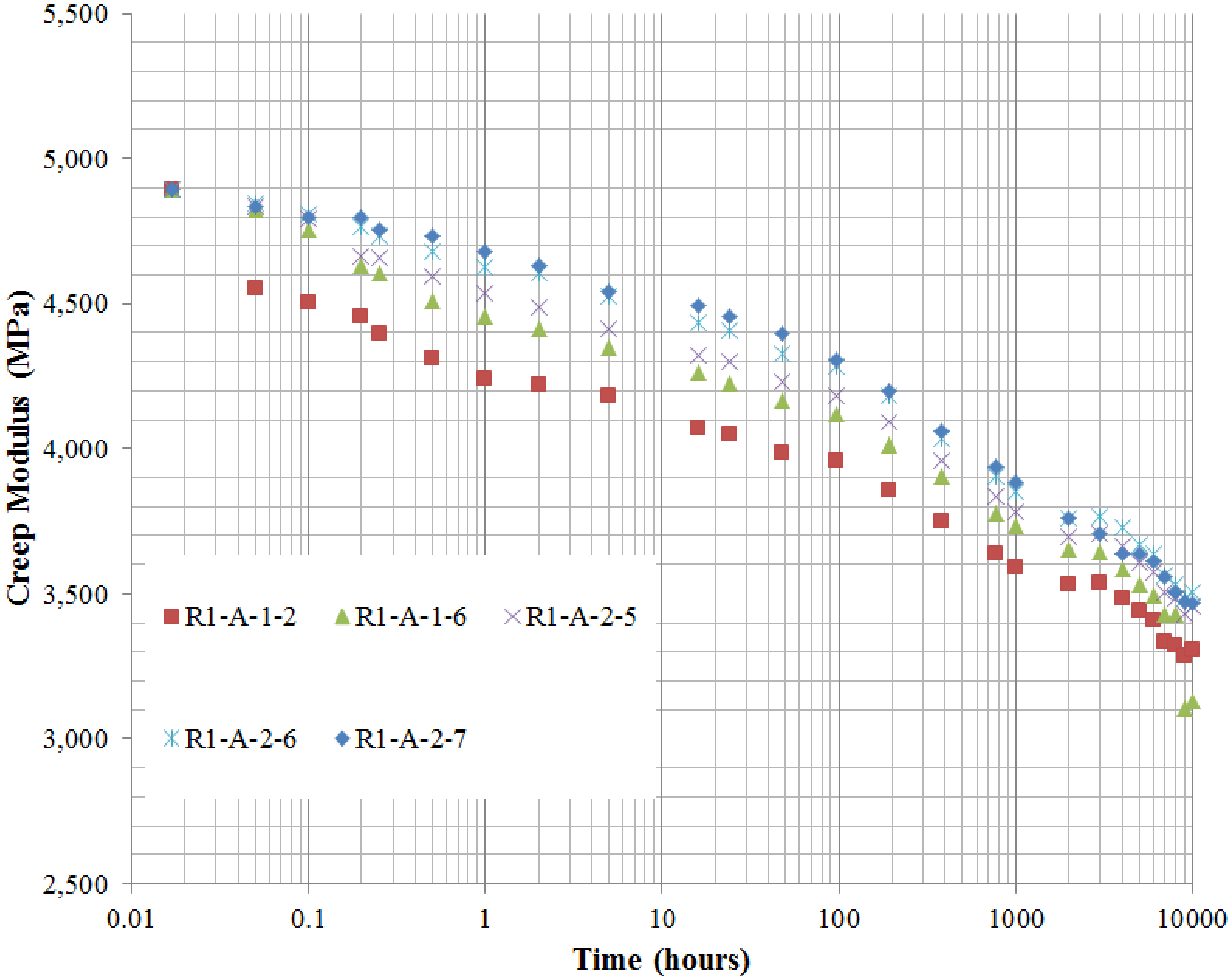


Figure 6.6 - Resin 1 / Liner A - Creep modulus over 10,000 hours of loading

Table 6.5 - Resin 2 / Liner A - Creep test results

Specimen	Time	Deflection	Maximum Strain	Creep Modulus	
	(Hours)	(mm)	(%)	(MPa)	(psi)
R2-A-1-2	1,000	1.91	0.432	3,420	496,000
R2-A-1-2	3,000	2.06	0.466	3,170	460,500
R2-A-1-2	6,000	2.19	0.496	2,980	432,800
R2-A-1-2	10,000	2.30	0.521	2,840	411,800
R2-A-1-7	1,000	1.96	0.448	3,230	469,100
R2-A-1-7	3,000	2.12	0.484	2,990	433,700
R2-A-1-7	6,000	2.23	0.510	2,840	412,000
R2-A-1-7	10,000	2.34	0.534	2,710	393,700
R2-A-2-5	1,000	1.78	0.417	3,300	478,100
R2-A-2-5	3,000	1.96	0.459	3,000	434,800
R2-A-2-5	6,000	2.06	0.481	2,860	414,900
R2-A-2-5	10,000	2.15	0.503	2,730	396,300
R2-A-2-6	1,000	1.83	0.423	3,350	485,500
R2-A-2-6	3,000	2.02	0.465	3,040	441,200
R2-A-2-6	6,000	2.12	0.488	2,900	420,400
R2-A-2-6	10,000	2.22	0.513	2,760	400,100
R2-A-2-7	1,000	1.83	0.418	3,440	498,800
R2-A-2-7	3,000	2.05	0.468	3,070	445,700
R2-A-2-7	6,000	2.36	0.539	2,670	387,500
R2-A-2-7	10,000	2.42	0.554	2,600	377,100

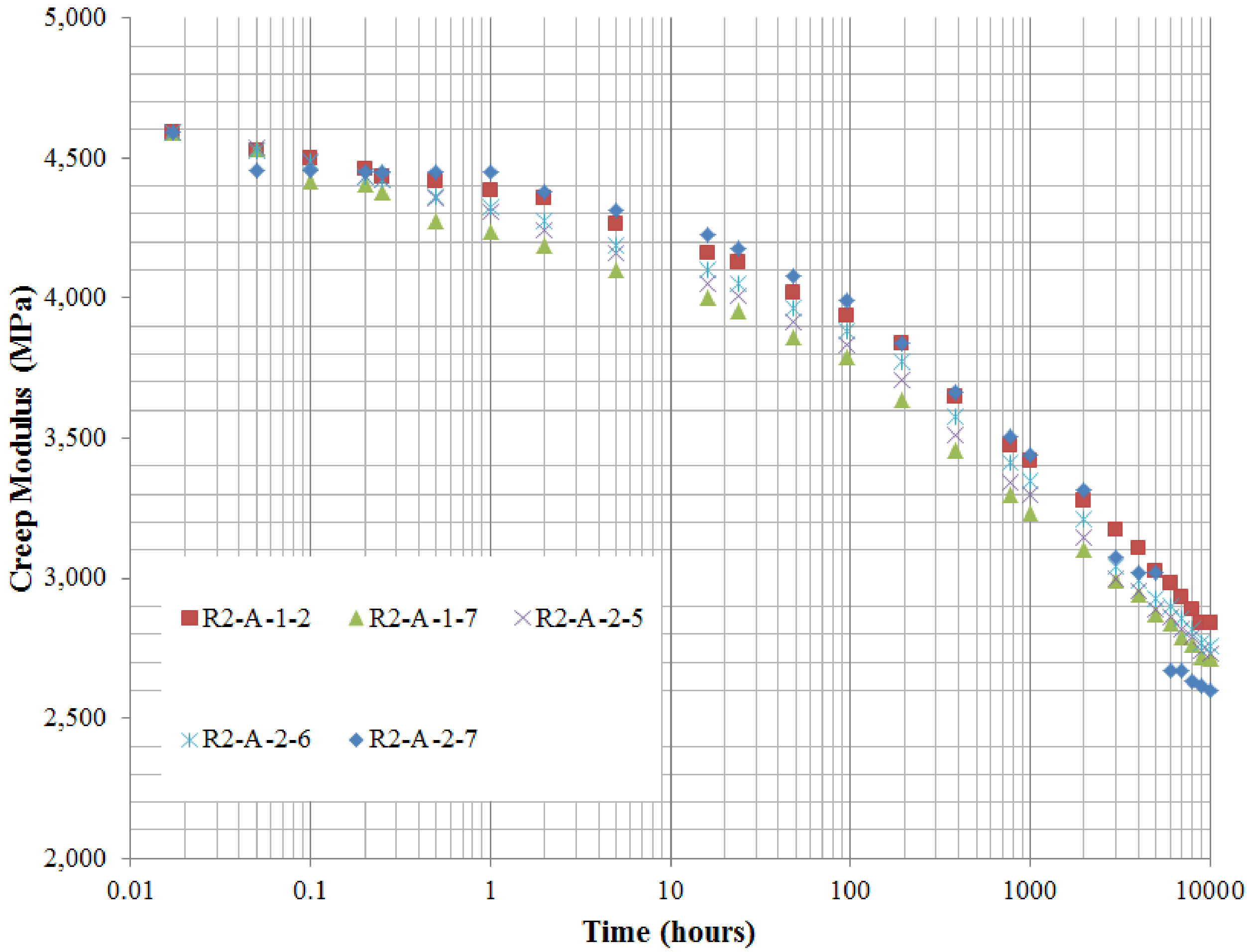


Figure 6.7 - Resin 2 / Liner A - Creep modulus over 10,000 hours of loading

Table 6.6 - Resin 3 / Liner A - Creep test results

Specimen	Time	Deflection	Maximum Strain	Creep Modulus	
	(Hours)	(mm)	(%)	(MPa)	(psi)
R3-A-1-3	1,000	3.58	0.757	1,210	176,200
R3-A-1-3	3,000	4.73	0.999	921	133,500
R3-A-1-3	6,000	5.69	1.203	765	110,900
R3-A-1-3	10,000	5.39	1.140	807	117,100
R3-A-1-4	1,000	3.42	0.739	1,190	173,200
R3-A-1-4	3,000	4.46	0.964	915	132,800
R3-A-1-4	6,000	5.31	1.147	769	111,500
R3-A-1-4	10,000	4.92	1.063	830	120,400
R3-A-2-1	1,000	3.30	0.708	1,250	180,700
R3-A-2-1	3,000	4.31	0.926	953	138,200
R3-A-2-1	6,000	5.17	1.110	795	115,300
R3-A-2-1	10,000	4.73	1.016	869	126,000
R3-A-2-2	1,000	3.32	0.714	1,240	180,200
R3-A-2-2	3,000	4.32	0.929	955	138,600
R3-A-2-2	6,000	5.23	1.123	790	114,600
R3-A-2-2	10,000	4.89	1.050	845	122,600
R3-A-2-7	1,000	3.34	0.770	1,120	162,100
R3-A-2-7	3,000	4.54	1.045	823	119,400
R3-A-2-7	6,000	5.57	1.282	671	97,280
R3-A-2-7	10,000	5.24	1.206	713	103,400

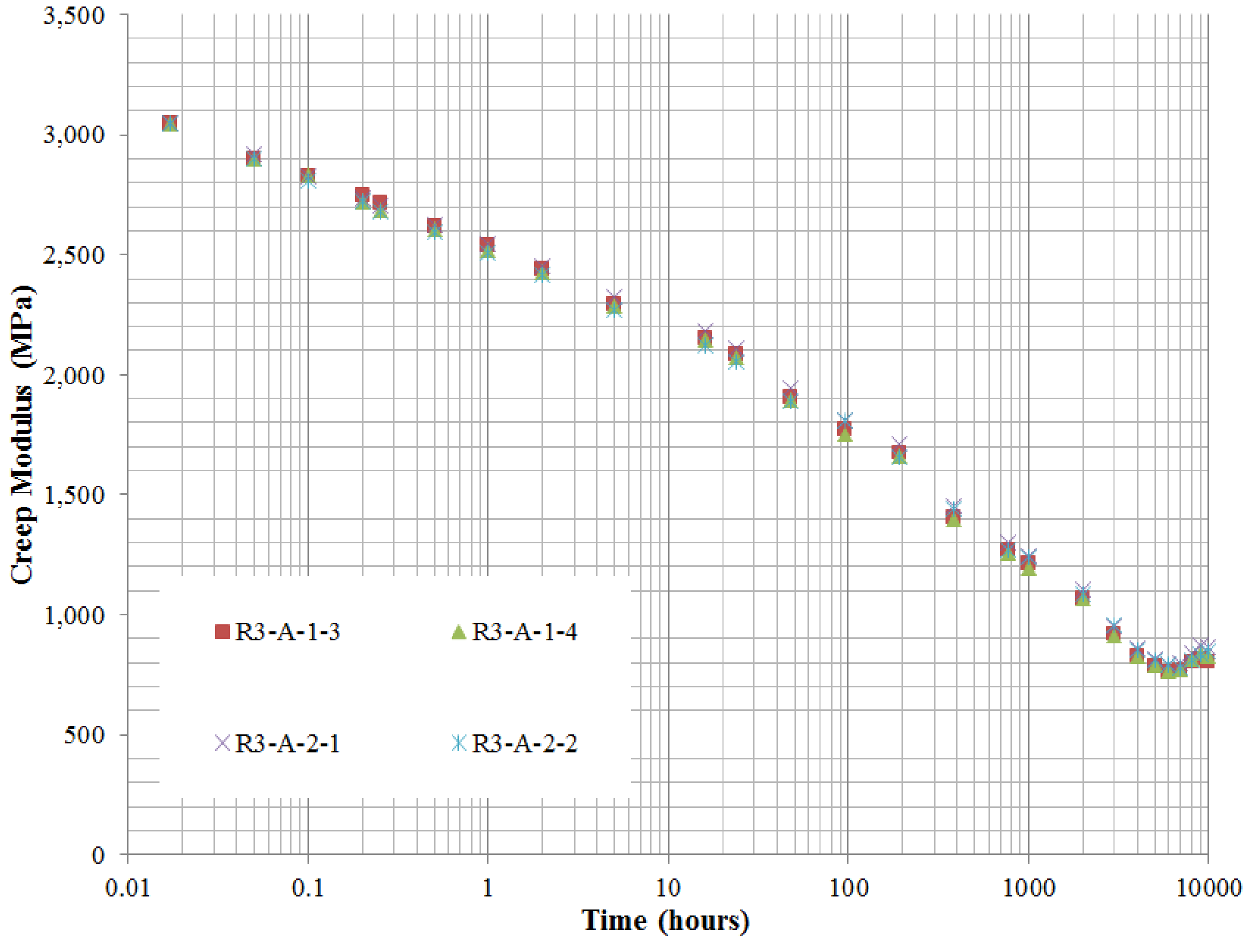


Figure 6.8 - Resin 3 / Liner A - Creep modulus over 10,000 hours of loading

Table 6.7 - Resin 1 / Liner B - Creep test results

Specimen	Time	Deflection	Maximum Strain	Creep Modulus	
	(Hours)	(mm)	(%)	(MPa)	(psi)
R1-B-2-6	1,000	1.72	0.487	13,540	1,964,400
R1-B-2-6	3,000	1.74	0.493	13,390	1,941,800
R1-B-2-6	6,000	1.73	0.490	13,460	1,951,900
R1-B-2-6	10,000	1.76	0.499	13,210	1,916,500
R1-B-2-7	1,000	2.40	0.611	13,380	1,940,200
R1-B-2-7	3,000	2.43	0.620	13,180	1,912,200
R1-B-2-7	6,000	2.42	0.617	13,250	1,922,500
R1-B-2-7	10,000	2.47	0.629	13,000	1,885,100
R1-B-3-3	1,000	1.60	0.465	13,540	1,963,700
R1-B-3-3	3,000	1.62	0.471	13,350	1,937,000
R1-B-3-3	6,000	1.62	0.471	13,340	1,934,700
R1-B-3-3	10,000	1.64	0.477	13,180	1,911,100
R1-B-3-4	1,000	1.55	0.451	13,840	2,008,000
R1-B-3-4	3,000	1.57	0.458	13,620	1,976,100
R1-B-3-4	6,000	1.59	0.463	13,470	1,953,800
R1-B-3-4	10,000	1.60	0.465	13,430	1,947,700
R1-B-3-7	1,000	1.53	0.459	12,830	1,861,600
R1-B-3-7	3,000	1.60	0.479	12,300	1,783,700
R1-B-3-7	6,000	1.84	0.550	10,710	1,553,600
R1-B-3-7	10,000	1.91	0.571	10,330	1,498,200

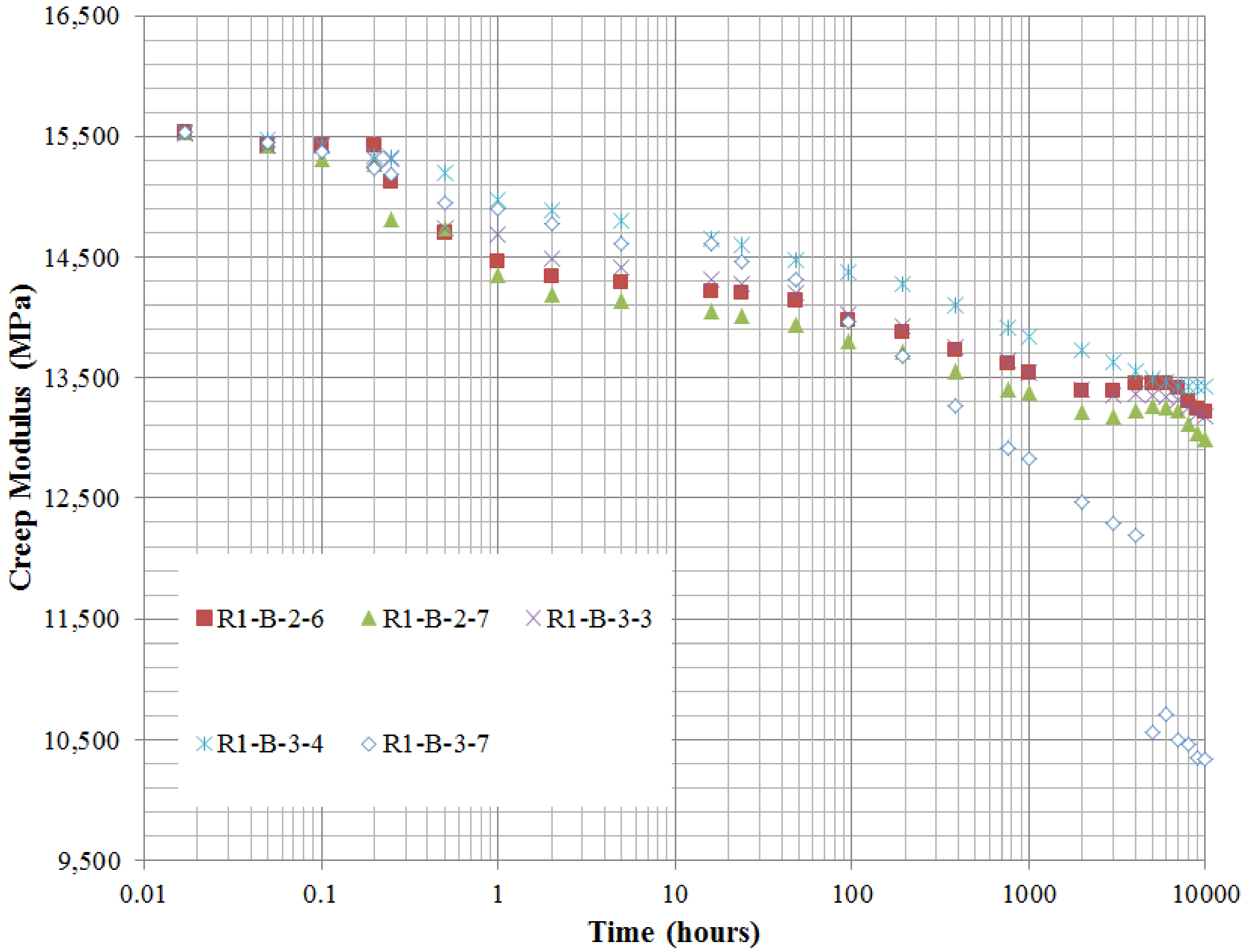


Figure 6.9 - Resin 1 / Liner B - Creep modulus over 10,000 hours of loading

Table 6.8 - Resin 2 / Liner B - Creep test results

Specimen	Time	Deflection	Maximum Strain	Creep Modulus	
	(Hours)	(mm)	(%)	(MPa)	(psi)
R2-B-1-2	1,000	1.37	0.393	12,860	1,865,800
R2-B-1-2	3,000	1.41	0.406	12,450	1,805,300
R2-B-1-2	6,000	1.42	0.407	12,400	1,798,900
R2-B-1-2	10,000	1.45	0.418	12,080	1,751,700
R2-B-1-3	1,000	1.47	0.413	12,890	1,869,800
R2-B-1-3	3,000	1.51	0.424	12,580	1,825,200
R2-B-1-3	6,000	1.54	0.431	12,360	1,792,000
R2-B-1-3	10,000	1.56	0.436	12,210	1,771,300
R2-B-2-2	1,000	1.94	0.495	12,970	1,880,900
R2-B-2-2	3,000	1.99	0.509	12,620	1,830,800
R2-B-2-2	6,000	2.01	0.513	12,520	1,815,300
R2-B-2-2	10,000	2.04	0.522	12,310	1,785,100
R2-B-2-7	1,000	1.60	0.432	13,230	1,918,600
R2-B-2-7	3,000	1.64	0.444	12,860	1,865,200
R2-B-2-7	6,000	1.66	0.450	12,700	1,842,400
R2-B-2-7	10,000	1.69	0.457	12,490	1,812,000
R2-B-2-9	1,000	1.69	0.477	11,020	1,598,900
R2-B-2-9	3,000	1.75	0.494	10,630	1,541,400
R2-B-2-9	6,000	1.78	0.502	10,480	1,519,700
R2-B-2-9	10,000	1.77	0.500	10,510	1,524,900

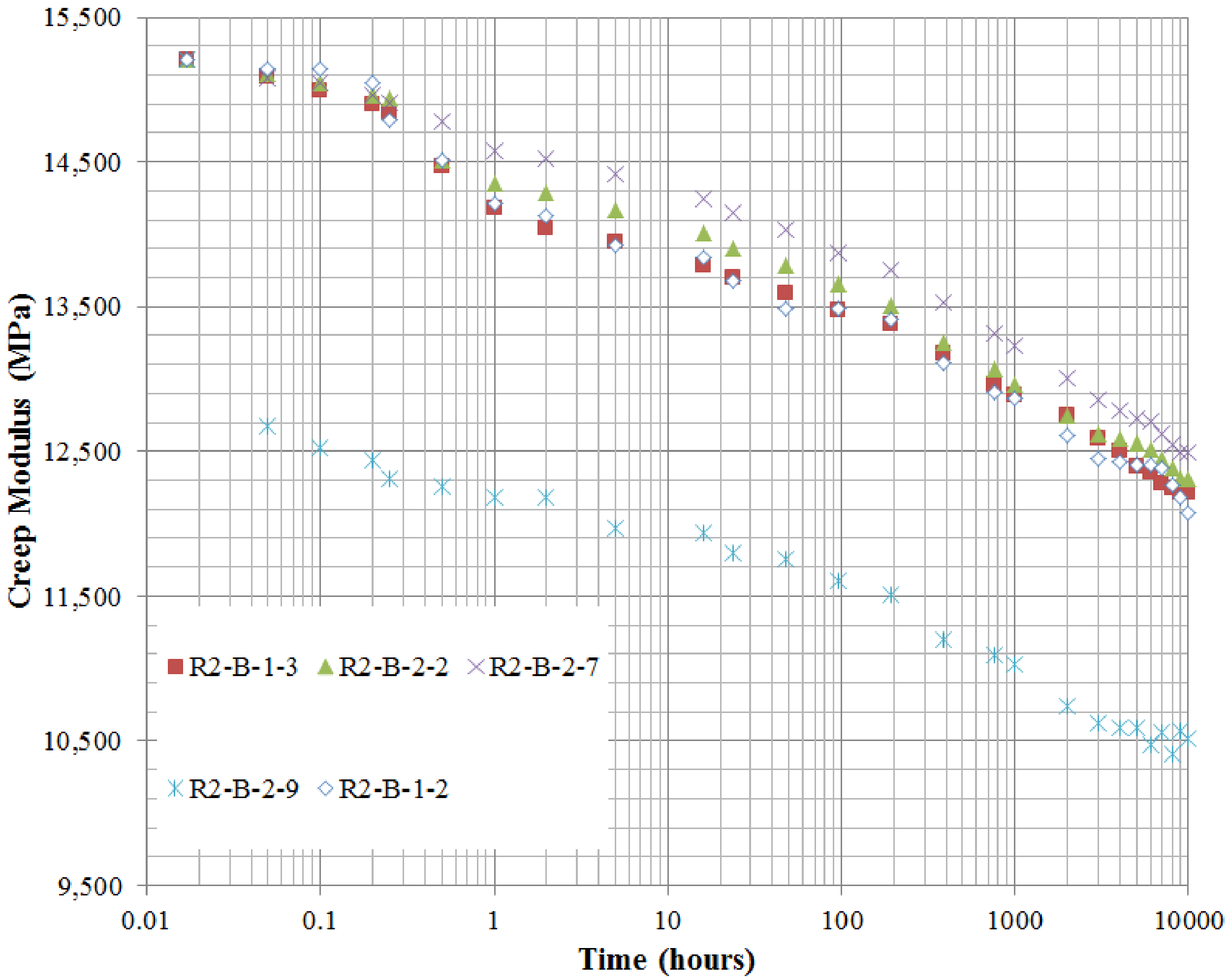


Figure 6.10 - Resin 2 / Liner B - Creep modulus over 10,000 hours of loading

Table 6.9 - Resin 3 / Liner B - Creep test results

Specimen	Time	Deflection	Maximum Strain	Creep Modulus	
	(Hours)	(mm)	(%)	(MPa)	(psi)
R3-B-1-3	1,000	1.78	0.473	9,540	1,384,400
R3-B-1-3	3,000	1.89	0.503	8,970	1,300,900
R3-B-1-3	6,000	1.96	0.520	8,680	1,258,600
R3-B-1-3	10,000	1.98	0.527	8,560	1,240,900
R3-B-1-6	1,000	1.35	0.402	8,940	1,297,300
R3-B-1-6	3,000	1.46	0.434	8,290	1,202,400
R3-B-1-6	6,000	1.51	0.450	7,980	1,158,000
R3-B-1-6	10,000	1.53	0.454	7,920	1,148,400
R3-B-2-2	1,000	1.63	0.452	9,170	1,329,900
R3-B-2-2	3,000	1.76	0.487	8,510	1,233,900
R3-B-2-2	6,000	1.77	0.489	8,470	1,228,600
R3-B-2-2	10,000	1.85	0.512	8,090	1,172,900
R3-B-2-3	1,000	1.63	0.444	9,620	1,395,200
R3-B-2-3	3,000	1.69	0.460	9,290	1,346,900
R3-B-2-3	6,000	1.83	0.500	8,540	1,238,600
R3-B-2-3	10,000	1.84	0.502	8,490	1,231,800
R3-B-2-4	1,000	1.41	0.413	8,940	1,297,300
R3-B-2-4	3,000	1.54	0.450	8,200	1,189,500
R3-B-2-4	6,000	1.60	0.467	7,900	1,146,300
R3-B-2-4	10,000	1.62	0.472	7,820	1,134,200

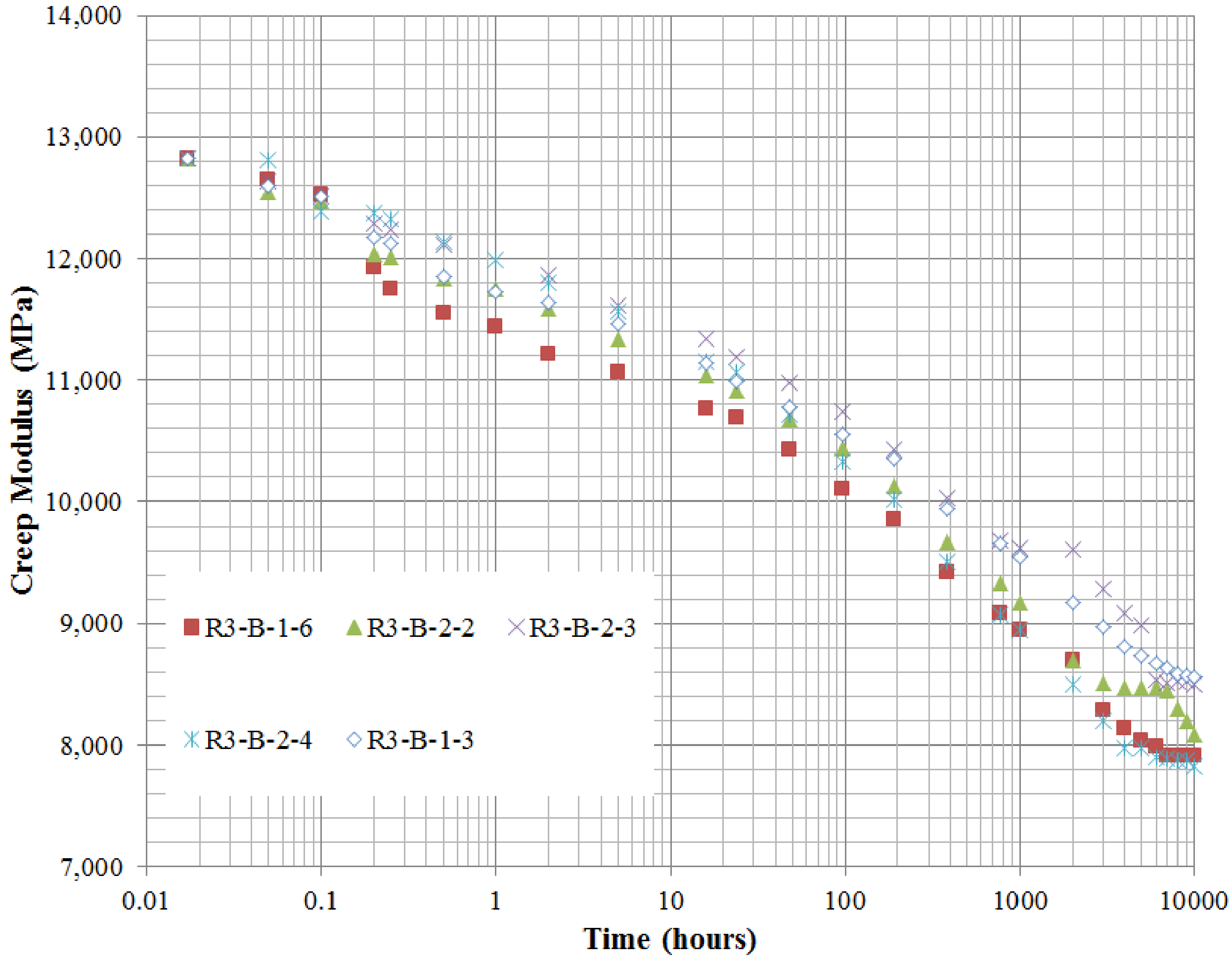


Figure 6.11 - Resin 3 / Liner B - Creep modulus over 10,000 hours of loading

Table 6.10 - Resin 1 / Liner C - Creep test results

Specimen	Time	Deflection	Maximum Strain	Creep Modulus	
	(Hours)	(mm)	(%)	(MPa)	(psi)
R1-C-1-2	1,000	1.05	0.369	11,830	1,716,500
R1-C-1-2	3,000	1.07	0.377	11,580	1,679,900
R1-C-1-2	6,000	1.08	0.379	11,530	1,672,000
R1-C-1-2	10,000	1.09	0.384	11,370	1,648,600
R1-C-1-10	1,000	0.90	0.336	11,530	1,671,900
R1-C-1-10	3,000	0.92	0.344	11,260	1,633,600
R1-C-1-10	6,000	0.93	0.348	11,130	1,614,300
R1-C-1-10	10,000	0.94	0.352	11,010	1,597,100
R1-C-1-11	1,000	0.88	0.323	12,530	1,816,700
R1-C-1-11	3,000	0.89	0.327	12,360	1,793,400
R1-C-1-11	6,000	0.89	0.327	12,380	1,796,000
R1-C-1-11	10,000	0.90	0.331	12,210	1,770,800
R1-C-2-4	1,000	0.63	0.267	11,210	1,625,800
R1-C-2-4	3,000	0.64	0.271	11,030	1,600,000
R1-C-2-4	6,000	0.64	0.272	10,990	1,593,700
R1-C-2-4	10,000	0.65	0.276	10,840	1,572,000
R1-C-2-8	1,000	0.60	0.262	10,890	1,580,200
R1-C-2-8	3,000	0.54	0.235	12,130	1,758,900
R1-C-2-8	6,000	0.54	0.236	12,100	1,755,700
R1-C-2-8	10,000	0.57	0.249	11,470	1,663,300

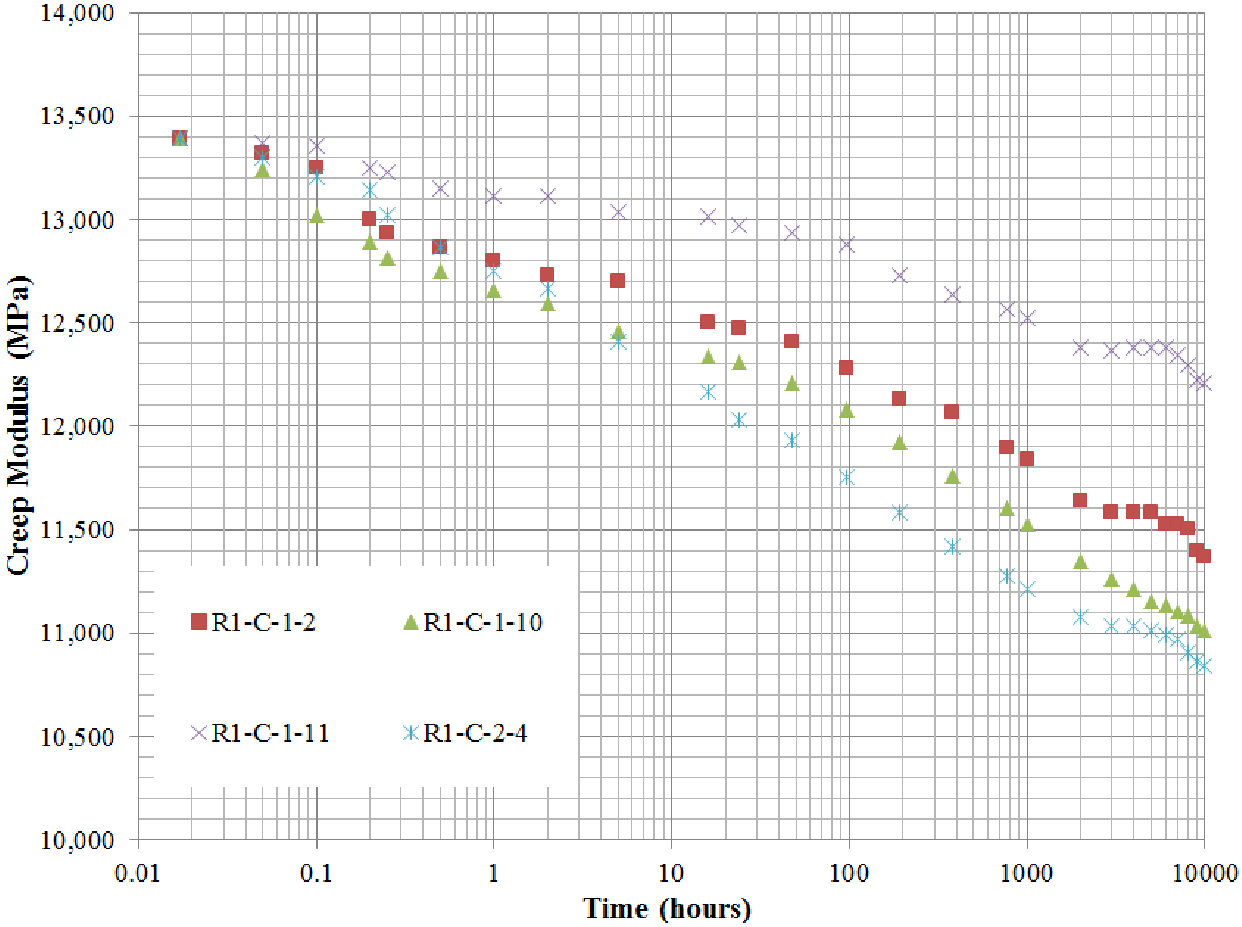


Figure 6.12 - Resin 1 / Liner C **-** Creep modulus over 10,000 hours of loading

Table 6.11 - Resin 2 / Liner C - Creep test results

Specimen	Time	Deflection	Maximum Strain	Creep Modulus	
	(Hours)	(mm)	(%)	(MPa)	(psi)
R2-C-1-5	1,000	0.85	0.285	10,420	1,511,300
R2-C-1-5	3,000	0.88	0.296	10,040	1,456,100
R2-C-1-5	6,000	0.87	0.292	10,150	1,472,900
R2-C-1-5	10,000	0.92	0.310	9,580	1,389,600
R2-C-1-12	1,000	0.79	0.269	10,680	1,548,800
R2-C-1-12	3,000	0.79	0.269	10,660	1,546,800
R2-C-1-12	6,000	0.79	0.271	10,600	1,537,000
R2-C-1-12	10,000	0.82	0.281	10,220	1,482,700
R2-C-2-3	1,000	0.43	0.180	10,700	1,551,600
R2-C-2-3	3,000	0.44	0.185	10,390	1,507,200
R2-C-2-3	6,000	0.44	0.186	10,360	1,502,900
R2-C-2-3	10,000	0.46	0.191	10,070	1,461,200
R2-C-2-7	1,000	0.49	0.204	9,420	1,366,800
R2-C-2-7	3,000	0.51	0.214	8,980	1,302,900
R2-C-2-7	6,000	0.52	0.218	8,810	1,278,000
R2-C-2-7	10,000	0.54	0.225	8,530	1,237,800
R2-C-2-13	1,000	0.54	0.224	8,750	1,269,400
R2-C-2-13	3,000	0.57	0.235	8,340	1,209,100
R2-C-2-13	6,000	0.57	0.238	8,250	1,196,500
R2-C-2-13	10,000	0.59	0.246	7,970	1,156,300

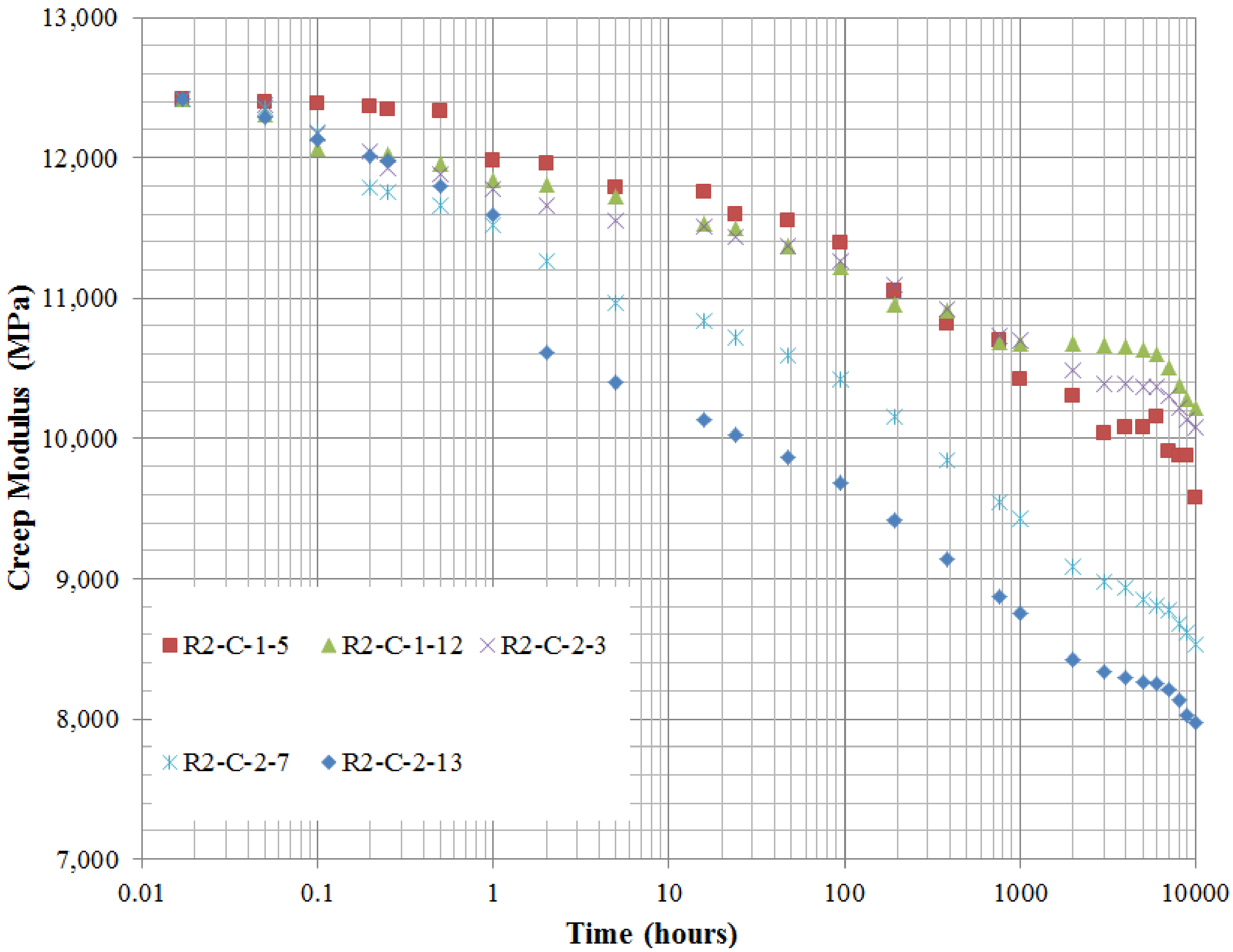


Figure 6.13 - Resin 2 / Liner C - Creep modulus over 10,000 hours of loading

Table 6.12 - Resin 2 / Liner C - Creep test results

Specimen	Time	Deflection	Maximum Strain	Creep Modulus	
	(Hours)	(mm)	(%)	(MPa)	(psi)
R3-C-1-2	1,000	0.59	0.250	6,460	936,800
R3-C-1-2	3,000	0.63	0.268	6,020	873,000
R3-C-1-2	6,000	0.64	0.274	5,900	855,400
R3-C-1-2	10,000	0.67	0.283	5,700	827,100
R3-C-1-5	1,000	0.64	0.270	6,110	885,600
R3-C-1-5	3,000	0.69	0.292	5,660	820,600
R3-C-1-5	6,000	0.71	0.298	5,540	803,300
R3-C-1-5	10,000	0.74	0.311	5,310	769,600
R3-C-2-1	1,000	0.96	0.346	6,690	970,300
R3-C-2-1	3,000	1.03	0.370	6,260	908,000
R3-C-2-1	6,000	1.05	0.377	6,140	889,900
R3-C-2-1	10,000	1.09	0.392	5,900	856,400
R3-C-2-2	1,000	1.13	0.381	6,960	1,009,400
R3-C-2-2	3,000	1.21	0.406	6,520	945,900
R3-C-2-2	6,000	1.22	0.409	6,470	938,000
R3-C-2-2	10,000	1.28	0.429	6,170	895,200
R3-C-2-11	1,000	1.00	0.350	6,850	993,800
R3-C-2-11	3,000	1.08	0.380	6,310	915,600
R3-C-2-11	6,000	1.09	0.385	6,240	904,700
R3-C-2-11	10,000	1.13	0.397	6,040	876,600

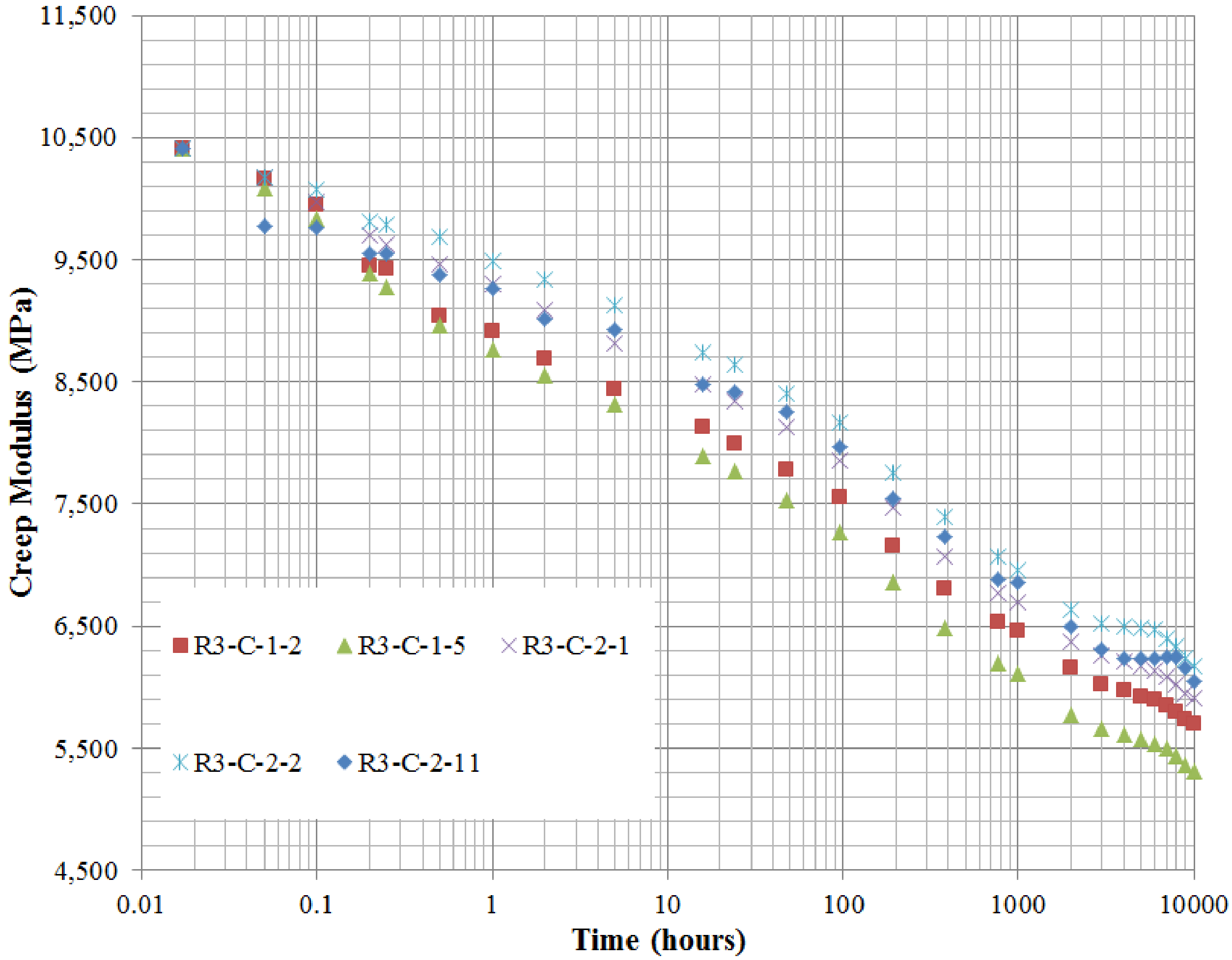


Figure 6.14 - Resin 3 / Liner C - Creep modulus over 10,000 hours of loading

6.7 Discussion of Flexural Creep Test Results

As mentioned in Chapter 2, the behavior of CIPP liners is time and stress dependent. The average 10,000 hour and maximum predicted deflection values for each resin/liner type are tabulated in Table 6.13 and compared in Figure 6.15.

Table 6.13 - 10,000 hour and maximum predicted deflection values

Resin / Liner Type	Avergae 10,000 Hour Deflection (mm)	Max. Predicted Deflection (mm)
Resin 1 / Liner A	2.58	3.81
Resin 2 / Liner A	2.29	2.97
Resin 3 / Liner A	5.03	2.66
Resin 1 / Liner B	1.88	3.01
Resin 2 / Liner B	1.70	2.77
Resin 3 / Liner B	1.76	2.53
Resin 1 / Liner C	0.83	1.26
Resin 2 / Liner C	0.67	1.09
Resin 3 / Liner C	0.98	0.89

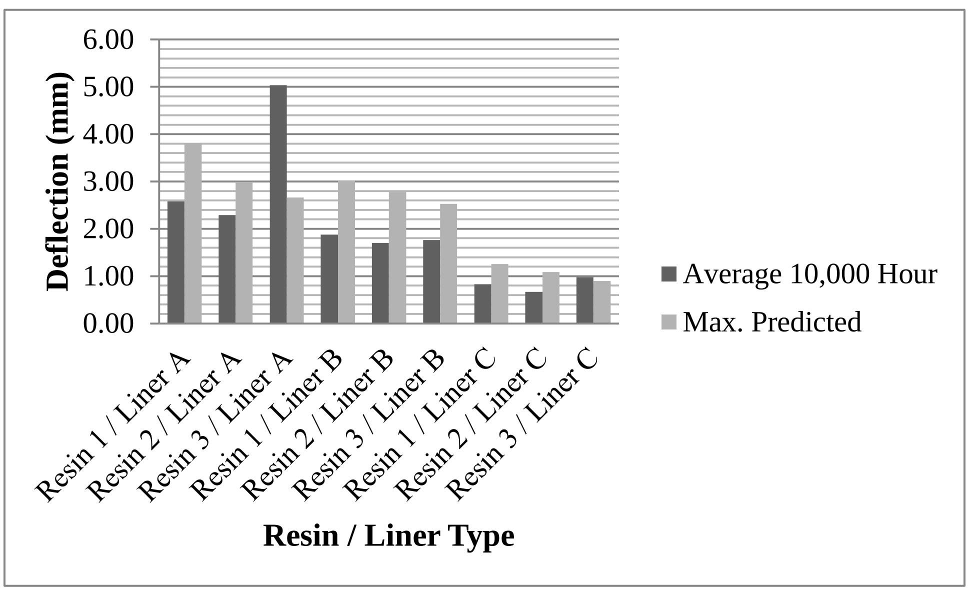


Figure 6.15 - Comparison of average 10,000 hour and maximum predicted deflection values

Figure 6.15 shows that the 10,000 hour deflection values are all below the maximum predicted values except for “Resin 3/Liner A” and “Resin 3/Liner C” products. These two liner types have deflection values higher than the maximum predicted values and this can be attributed to the properties of Resin “3” which is the only VOC-free and styrene-free resin. The deflection values can be correlated to the flexural properties of the liner systems. As discussed in Section 5.5, flexural properties of Liner “A” systems are lower than Liners “B” and “C” and Resin “3” products also demonstrated lower flexural properties compared to Resins “1” and “2”. The liner systems which have lower flexural properties, demonstrated higher deflection values. Table 6.13 shows that the combination of Liner “A” and Resin “3” products has resulted in the highest average 10,000 hour deflection value compared to the eight other CIPP systems. An unusual behavior is observed in the creep modulus versus log time plot of the “Resin 3/Liner A” product (See Figure 6.8). After the 6000 hour deflection reading, the specimens from this liner type demonstrated reverse deflection (i.e., increase in creep modulus) until the 9000 hour reading and at the 10,000 hour reading the specimens showed a positive deflection. It is not clear exactly why this liner demonstrated such behavior. However, this different behavior can be attributed to the construction of Liner “A” and properties of Resin “3”.

“Resin 3/Liner B” product is an exception and has an average 10,000 hour deflection value less than the predicted value compared to the other two Resin “3” systems. This product despite demonstrating lower flexural properties compared to “Resin 1/Liner B” product, has a slightly lower average 10,000 hour deflection value. All of the Liner “A” specimens tested in flexural creep have the concave surface facing downwards and thus the load is applied in the direction of the specimen curvature. This may have also contributed to the higher deflection values compared to the other liner systems. The 10,000 hours of creep test results are used to estimate the material 50-year (438,000 hours) creep modulus. The CIPP long-term mechanical properties are described in Chapter 7.

7 Prediction of CIPP Liners Long-term Behavior

The long-term behavior of CIPP liners are predicted based on the flexural creep test results through which the time dependent strain changes are measured under a constant static load. In the following, the methodology used for analysis of CIPP products long-term physical properties is described.

7.1 Estimation of Material 50-Year Creep Modulus

The creep test data are used to extrapolate the 50-year creep modulus as an indication of material behavior over its design life. ASTM D2990-09 does not provide a specific method for determining the 50-year creep modulus. However, it does offer several procedures for documenting creep data depending upon time, temperature and rates of loading. To evaluate the CIPP liners long-term performance, creep moduli values calculated at specified time steps are plotted versus time on a semi-logarithmic scale. The 50-year creep modulus of any specimen is estimated based on a linear regression of the observed values and projecting a value to 50 years as follows:

$$\text{Creep modulus} = a * \log(\text{time}) + b \qquad \textbf{(7.1)}$$

where “a” and “b” are regression constants. Then, by using the best fit regression equation, the 50-year creep modulus is calculated. Some CIPP samples showed a linear change in creep modulus over time, but some demonstrated a bi-linear behavior. The linear versus non-linear behavior can be attributed to the differences in resin-reinforcement-carrier matrices. Based on previous creep tests conducted on various CIPP liners by CATT, it has been found that the reinforced CIPP liners tend to demonstrate a bi-linear behavior compared to the non-reinforced CIPP liners (*Knight*, 2013). A typical bi-linear CIPP creep behavior is shown in Figure 7.1.

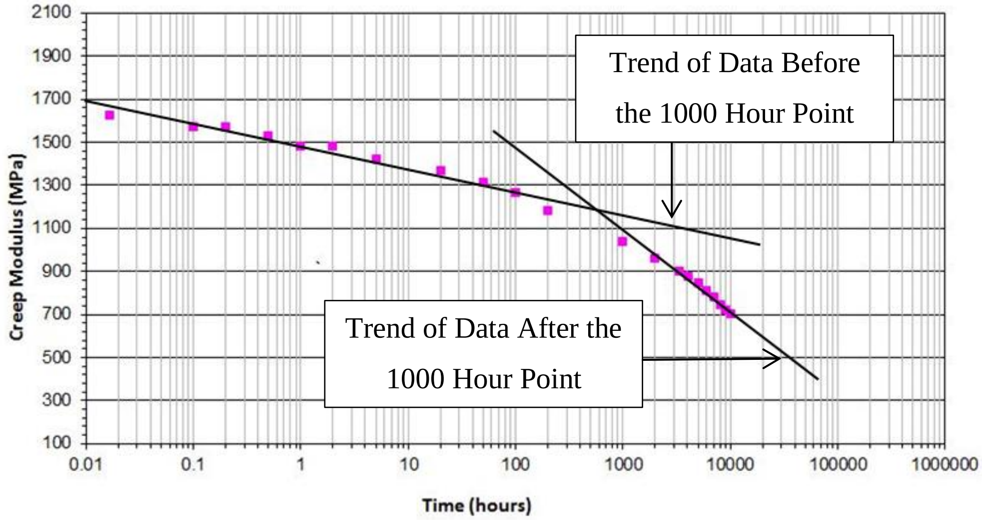


Figure 7.1 - An example of bi-linear CIPP creep behavior

As discussed in Chapter 2, the inclusion of all of the observed values from the initial (1-minute modulus) to the final (10,000 hours modulus) in the regression analysis can result in the estimation of unsubstantiated high 50-year creep modulus value for the specimens which demonstrate a bi-linear behavior. Thus, for the specimens which showed a bi-linear behavior in the creep modulus versus time plot, only the data at every 1000 hour interval are considered for the regression analysis. The creep modulus versus time plots for all the CIPP products showing the extrapolated 50-year creep modulus are provided in Appendix B. The extrapolated 50-year creep moduli values are presented in the following section.

7.2 Determination of Creep Retention Factor (CRF)

The short-term ASTM D790 flexural modulus and the 50-year extrapolated creep modulus values along with the creep retention factors for each liner system are presented in Tables 7.1 to 7.3. In this thesis, the Creep Retention Factor (CRF) for any particular CIPP sample is defined as:

CRF = Extrapolated 50-year creep modulus / ASTM D790 short-term flexural modulus **(7.2)**

Table 7.1 - Liner A, Average short-term flexural modulus, extrapolated 50-year creep moduli, and creep retention factor values

Sample	Average D790 (Short-Term) Flexural Modulus		Extrapolated 50-Year Creep Modulus		Creep Retention Factor
	(MPa)	(psi)	(MPa)	(psi)	
R1-A-1-2	4,890	709,800	2,780	403,500	0.57
R1-A-1-6			2,350	341,300	0.48
R1-A-2-5			2,880	418,100	0.59
R1-A-2-6			2,900	421,400	0.59
R1-A-2-7			2,800	406,400	0.57
Average			2,740	398,100	0.56
Standard Deviation			225	32,660	0.05
Maximum			2,900	421,400	0.59
Minimum			2,350	341,300	0.48
R2-A-1-2	4,590	665,700	1,840	266,900	0.40
R2-A-1-7			1,830	265,100	0.40
R2-A-2-5			1,790	259,400	0.39
R2-A-2-6			1,760	255,800	0.38
R2-A-2-7			1,040	150,500	0.23
Average			1,650	239,500	0.36
Standard Deviation			345	49,970	0.08
Maximum			1,840	266,900	0.40
Minimum			1,040	150,500	0.23
R3-A-1-3	3,050	441,900	23	3,320	0.01
R3-A-1-4			104	15,060	0.03
R3-A-2-1			99	14,420	0.03
R3-A-2-2			34	4,950	0.01
*R3-A-2-7			N/A	N/A	N/A
Average			65	9,440	0.02
Standard Deviation			43	6,160	0.01
Maximum			104	15,060	0.03
Minimum			23	3,320	0.01

***** Specimen R3-A-2-7 was removed from analysis due to existence of anomaly in the test result

Table 7.2 - Liner B, Average short-term flexural modulus, extrapolated 50-year creep moduli, and creep retention factor values

Sample	Average D790 (Short-Term) Flexural Modulus		Extrapolated 50-Year Creep Modulus		Creep Retention Factor
	(MPa)	(psi)	(MPa)	(psi)	
R1-B-2-6	15,530	2,252,200	12,570	1,823,600	0.81
R1-B-2-7			12,320	1,787,300	0.79
R1-B-3-3			12,500	1,812,900	0.80
R1-B-3-4			12,800	1,857,000	0.82
R1-B-3-7			9,830	1,426,300	0.63
Average			12,010	1,741,400	0.77
Standard Deviation			1,230	177,900	0.08
Maximum			12,800	1,857,000	0.82
Minimum			9,830	1,426,300	0.63
R2-B-1-2	15,210	2,206,400	11,100	1,610,600	0.73
R2-B-1-3			10,990	1,593,900	0.72
R2-B-2-2			11,290	1,637,500	0.74
R2-B-2-7			11,290	1,637,400	0.74
R2-B-2-9			9,650	1,399,000	0.63
Average			10,860	1,575,700	0.71
Standard Deviation			693	100,500	0.05
Maximum			11,290	1,637,500	0.74
Minimum			9,650	1,399,000	0.63
R3-B-1-3	12,820	1,859,700	6,860	994,400	0.53
R3-B-1-6			5,970	865,300	0.47
R3-B-2-2			6,730	976,500	0.53
R3-B-2-3			6,180	895,900	0.48
R3-B-2-4			5,940	861,700	0.46
Average			6,330	918,700	0.49
Standard Deviation			432	62,620	0.03
Maximum			6,860	994,400	0.53
Minimum			5,940	861,700	0.46

Table 7.3 - Liner C, Average short-term flexural modulus, extrapolated 50-year creep moduli, and creep retention factor values

Sample	Average D790 (Short-Term) Flexural Modulus (MPa)	Average D790 (Short-Term) Flexural Modulus (psi)	Extrapolated 50-Year Creep Modulus (MPa)	Extrapolated 50-Year Creep Modulus (psi)	Creep Retention Factor
R1-C-1-2	13,390	1,942,600	10,400	1,508,000	0.78
R1-C-1-10			9,710	1,408,300	0.72
R1-C-1-11			11,610	1,684,300	0.87
R1-C-2-4			10,010	1,451,500	0.75
*R1-C-2-8			N/A	N/A	N/A
Average			10,430	1,513,000	0.78
Standard Deviation			836	121,300	0.06
Maximum			11,610	1,684,300	0.87
Minimum			9,710	1,408,300	0.72
R2-C-1-5	12,420	1,801,100	8,060	1,168,400	0.65
R2-C-1-12			9,250	1,342,200	0.75
R2-C-2-3			8,750	1,269,700	0.70
R2-C-2-7			6,480	940,100	0.52
R2-C-2-13			6,280	910,600	0.51
Average			7,760	1,126,200	0.63
Standard Deviation			1,340	193,700	0.11
Maximum			9,250	1,342,200	0.75
Minimum			6,280	910,600	0.51
R3-C-1-2	10,410	1,509,400	3,510	509,600	0.34
R3-C-1-5			2,960	428,700	0.28
R3-C-2-1			3,810	552,800	0.37
R3-C-2-2			4,250	616,300	0.41
R3-C-2-11			4,130	599,700	0.40
Average			3,730	541,400	0.36
Standard Deviation			521	75,590	0.05
Maximum			4,250	616,300	0.41
Minimum			2,960	428,700	0.28

***** Specimen R1-C-2-8 was removed from analysis due to existence of anomaly in the test result

The long-term flexural modulus of the liner required by ASTM F1216 is defined as the short-term D790 modulus reduced by the long-term creep retention factor. The following relationship is used to determine the value of “E_L”:

$$E_L = CRF * E \tag{7.3}$$

where "CRF" is called the resin creep retention factor and “E” is the resin short-term (ASTM D790) initial tangent modulus. As mentioned in Chapter 2, the same creep retention factor is usually applied to the liner flexural strength to estimate the liner long-term time-corrected flexural strength (σ_L) used for determination of the minimum liner thickness required for rehabilitation of an oval pipe (i.e., application of Equation X1.2).

7.3 Discussion of CIPP Liners Creep Retention Factors

The long-term creep test is conducted both on specific resins and liners (i.e., resin plus tube) (*Knasel*, 1994). For a non-reinforced CIPP, liner properties are mostly related to resin properties. However, for a reinforced CIPP, liner properties are specific to resin-reinforcement-carrier matrix and cannot be generalized from resin only properties (*Richard*, 1993). The short-term flexural moduli values and the extrapolated 50-year creep moduli values for each liner system are compared in Figure 7.2.

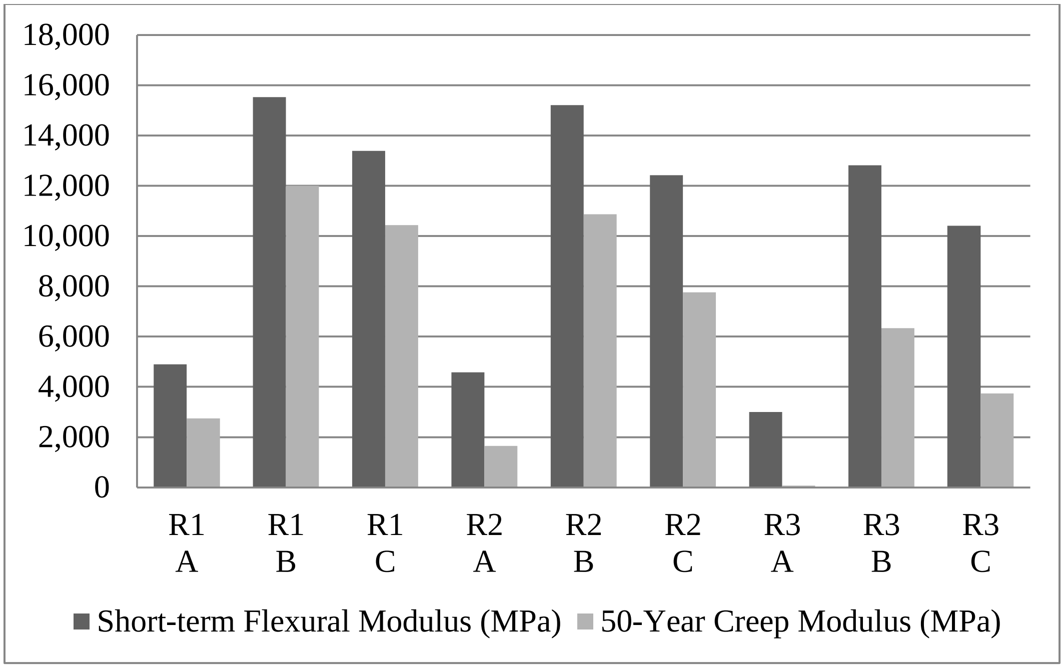


Figure 7.2 - Comparison of short-term and long-term creep moduli values

Figure 7.2 suggests that Resin "3" systems had lower 50-year creep moduli values compared to Resins "1" and "2". The above figure also shows that Liner "A" systems demonstrated lower short-term and long-term flexural moduli values compared to Liners "B" and "C". The average, minimum, and maximum creep retention factors for each liner system are presented in Table 7.4 and compared in Figure 7.3.

Table 7.4 - Summary of creep retention factors

Resin / Liner Type	Average Creep Retention Factor	Minimum Creep Retention Factor	Maximum Creep Retention Factor
Resin 1 / Liner A	0.56	0.48	0.59
Resin 1 / Liner B	0.77	0.63	0.82
Resin 1 / Liner C	0.78	0.72	0.87
Resin 2 / Liner A	0.36	0.23	0.40
Resin 2 / Liner B	0.71	0.63	0.74
Resin 2 / Liner C	0.63	0.51	0.75
Resin 3 / Liner A	0.02	0.01	0.03
Resin 3 / Liner B	0.49	0.46	0.53
Resin 3 / Liner C	0.36	0.28	0.41

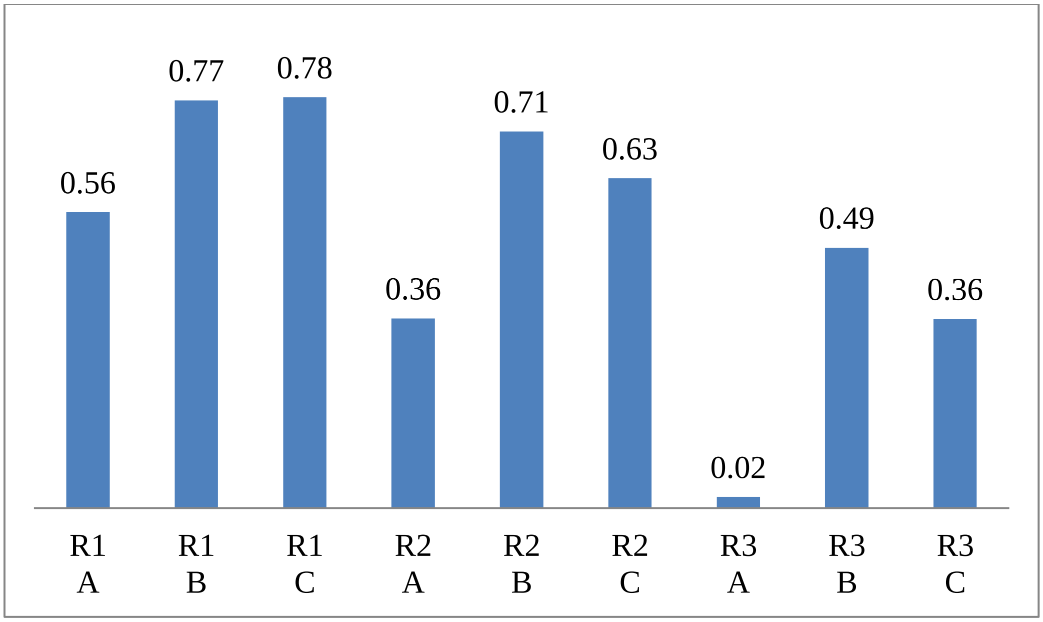


Figure 7.3 - Comparison of average creep retention factors

Based on the values provided in Table 7.4, all of the CIPP products except "Resin 2/Liner A", "Resin 3/Liner A", "Resin 3/Liner B", and "Resin 3/Liner C" have average creep retention factors higher than 0.5. In general, Liner "A" products demonstrated lower CRF values compared to Liners "B" and "C". It should be noted that Liner "A" is the only liner with an asymmetrical construction. All Resin "3" systems show a creep retention factor below 0.5, meaning that the specimens have lost more than 50% of their initial short-term flexural modulus over the test period. As discussed in Section 5.5, this can be attributed to the polymer properties and the fiberglass to resin interaction on the molecular level. Resin "3" is the only styrene-free and VOC-free resin. It should be noted that based on 10,000 hours of creep test data, the average CRF for the "Resin 3/Liner A" product is 0.02. Therefore, there is a high probability for the "Resin 3/Liner A" CIPP product to fail over its design life (i.e., 50-years) under assumed loading conditions.

Similar to tensile and flexural test specimens, some degree of variability is also observed among the creep retention factors of the specimens in each liner system. For some liner systems the variability is higher than others. The variability is also observed in creep retention factors of some other CIPP liners tested previously by CATT. The variation among the same type of specimens can be attributed to the existence of non-uniformity along the laboratory manufactured CIPP panels resulting in specimens with non-uniform thicknesses. Consistency among the specimens from each liner type is an important factor for obtaining representative results. It should be noted that the variability in the creep retention factors of the specimens from each resin/liner type can also be attributed to the long-term testing conditions. The dial gages used for deflection monitoring are highly sensitive. It is a challenging task to record a reference reading before application of the load. The difference between the reference reading and the 1-minute (after application of the load) dial gage reading demonstrates the initial elongation of the specimen which is a considerable portion of the total deflection that a specimen experiences. Due to the discrepancy associated with the dial gage reference readings, it was decided to adjust the 1-minute readings for all of the specimens from each liner system as the short-term ASTM D790 flexural modulus of that particular liner system. ASTM D2990 requires a minimum of three specimens to be tested in flexural creep. However, in this research project, five specimens from each liner system are tested for characterization of material long-term creep behavior to obtain more representative test results.

As mentioned in Chapter 2, common industry practice has been to adopt a creep retention factor of 0.5 for all CIPP materials. This has been mainly on testing of Insituform liner systems using non-reinforced resins (*Knight*, 2013). Based on the data presented in Table 7.4, a creep retention factor of 0.5 may not be applicable for all resin/liner types. Table 7.4 suggests that the creep retention factor is specific to the resin/liner type.

8 Conclusions and Recommendations

Within North America, CIPP liners used for rehabilitation of gravity pipelines are typically designed according to the design methodology provided in the non-mandatory Appendix (X1) of ASTM F1216. In the design equations provided in the standard, there are two parameters, liner long-term time-corrected modulus of elasticity and long-term time-corrected flexural strength, which are related to the CIPP long-term creep behavior. ASTM F1216 does not specify any methodology for characterizing the material long-term physical properties. Common industry practice has been to adopt a creep retention factor of 0.5 for all CIPP materials. With all the new CIPP product varieties, a creep retention factor of 0.5 may not apply. In the following, conclusions and recommendations regarding the short-term and long-term mechanical properties of CIPP liners are provided.

8.1 Conclusions

- **Analysis of previous long-term creep test results**

Based on the comparison made between the results of the hydrostatic buckling tests and the ASTM D2990 flexural creep tests, it can be concluded that both methods yield similar results. However, ASTM D2990 provides a relatively simple test procedure compared to the hydrostatic buckling test.

Based on 96,000 hours (about 11 years) of long-term test data, the estimated creep factors considering data points only after 1000 hour, are all below 0.5 except the AOC Enhanced resin which is 0.5. This suggests that the industry standard creep retention factor of 0.5 may not be applicable for all resin types.

The results of the flexural tests conducted on AOC and Interplastic Corp. resins after seven years of undergoing flexural creep test demonstrate that the flexural modulus retention factors range from 0.70 to 0.77 and the flexural strength retention factors range from 0.67 to 0.96. The AOC and Interplastic Corp. Standard resins have higher flexural modulus retention factors compared to the Enhanced resins. The AOC resins have lower flexural strength retentions factors compared to the Interplastic Corp. resins. However, for the Interplastic Corp. samples, it cannot be concluded that the flexural strength values have decreased, since the strength value after seven years falls in the range of strength values obtained initially.

- **Analysis of Nine CIPPs Short-term Tensile Properties**

Liner “A” products have lower tensile moduli of elasticity compared to Liners “B” and “C”. Liner “A” is the only CIPP system which have an asymmetrical layered construction. The liner bag materials, especially Liner “C”, have substantially added to the tensile stiffness of the resin only samples. It should be noted that Liner “C” specimens have the lowest thickness compared to Liners “A” and “B”. The sandwiching felt material in Liner “C” is thinner than 1.0 mm making it mostly fiberglass. Liner “A” products also have lower strength values compared to Liners “B” and “C”. The curvature of Liner “A” dog-bone shape specimens may have affected the tensile test results for this liner system, since the specimens could not be placed perfectly straight within the grips of the tensile test machine. The liner bag materials have increased the ultimate (at break) tensile strength of resin only samples except for “Resin 1/Liner A” and “Resin 2/Liner A” products. The tensile strength at break values for all of the nine CIPP products, exceed the ASTM F1216-09 minimum field inspection value.

- **Analysis of Nine CIPPs Short-term Flexural Properties**

The liner bag materials, especially Liner “B”, have substantially added to the flexural stiffness of the resin only samples. Liner “B” bag material has the lowest fiberglass thickness as a percentage of total thickness. It is noticed that the Liner “A” bag material has not increased the ultimate (at break) flexural strength of the Resin “1” only sample. Liner “B” products have higher flexural strength at yield and at break values compared to Liners “A” and “C”. Flexural properties of Liner “A” systems are lower than Liners “B” and “C”. This difference is attributed to the differing construction of each liner resulting in panels with different thicknesses and fiberglass content. Resin “3” products demonstrated lower flexural properties compared to Resins “1” and “2”. This difference is attributed to the differing polymer properties and the fiberglass to resin interaction on the molecular level according to Hazen (2015). Resin “3” is the only VOC-free and styrene-free resin. The flexural modulus and flexural strength values for all of the nine CIPP products exceed the ASTM F1216-09 minimum field inspection values.

- **Analysis of Nine CIPPs Long-term Flexural Creep Behavior**

All of the specimens from each CIPP product tested in flexural creep, demonstrated deflection values below the maximum predicted values except “Resin 3/Liner A” and “Resin 3/Liner C” specimens. These two liner types have deflection values higher than the maximum predicted values and this can be attributed to the properties of Resin “3”. The deflection values can be correlated to the flexural properties of the liner systems. The liner systems which have lower flexural properties, demonstrated higher deflection values.

Combination of Liner “A” and Resin “3” products has resulted in the highest average 10,000 hour deflection value compared to the eight other CIPP systems. An unusual behavior is observed in the creep modulus versus log time plot of the “Resin 3/Liner A” product (See Figure 6.8). After the 6000 hour deflection reading, the specimens from this liner type demonstrated reverse deflection (i.e., increase in creep modulus) until the 9000 hour reading and at the 10,000 hour reading the specimens showed a positive deflection. It is not clear exactly why this liner demonstrated such behavior. However, this different behavior can be attributed to the construction of Liner “A” and properties of Resin “3”.

“Resin 3/Liner B” product is an exception and has an average 10,000 hour deflection value less than the predicted value compared to the other two Resin “3” systems. This product despite demonstrating lower flexural properties compared to “Resin 1/Liner B” product, has a slightly lower average 10,000 hour deflection value. All of the Liner “A” specimens tested in flexural creep have the concave surface facing downwards and thus the load is applied in the direction of the specimen curvature. This may have also contributed to the higher deflection values compared to the other liner systems.

All of the CIPP products except “Resin 2/Liner A”, “Resin 3/Liner A”, “Resin 3/Liner B”, and “Resin 3/Liner C” have average creep retention factors higher than 0.5. In general, Liner “A” products demonstrated lower CRF values than Liners “B” and “C”. Liner “A” is the only liner with an asymmetrical construction. All Resin “3” systems have CRF values below 0.5, meaning that the specimens have lost more than 50% of their initial short-term flexural modulus over the test period. This can be attributed to the polymer properties and the fiberglass to resin interaction on the molecular level according to Hazen (2015). Resin “3” is the only styrene-free and VOC-free resin. It should be noted that based on 10,000 hours of creep test data, the average CRF for the “Resin 3/Liner A” product is 0.02. Therefore, there is a high probability for the “Resin 3/Liner A” CIPP product to fail over its design life (i.e., 50-years) under assumed loading conditions.

Similar to tensile and flexural test specimens, some degree of variability is observed among the creep retention factors of the specimens in each liner system. For some liner systems the variability is higher than others. The variation among the same type of specimens can be attributed to the existence of non-uniformity along the laboratory manufactured CIPP panels resulting in specimens with non-uniform thicknesses. Consistency among the specimens from each liner type is an important factor for obtaining representative results.

Most of the liner systems demonstrated a bi-linear behavior over the 10,000 hours of creep test. It is agreed that the regression of 1000 hour interval data results in a better prediction of the 50-year modulus and the regression of all test data is not appropriate or realistic for the materials that do not have a linear response on a creep modulus versus log time graph.

Common industry practice has been to adopt a creep retention factor of 0.5 for all CIPP materials. Based on the long-term creep test results, a creep retention factor of 0.5 may not be applicable for all resin/liner types. The test results suggest that the creep retention factor is specific to the resin/liner type.

8.2 Recommendations

Creep retention factor is dependent on the particular rehabilitation system considering factors such as the type of resin and construction of the fabric tube. Thus, it is recommended to obtain both short-term and long-term properties through experimentation for all new products before use. The CIPP samples used for analysis in this thesis are laboratory manufactured. Field installation and curing conditions can be significantly different from laboratory controlled conditions. It is recommended to test field cured CIPP samples for evaluating the properties of installed liner. Further testing is required to evaluate the material tensile/compression long-term properties to develop a better understanding of CIPP liner long-term mechanical behavior. It is also desirable to test CIPP products in flexural creep at various stress levels to generate a creep-rupture envelope. This will help the designers to have a better understanding of CIPP liner creep behavior.

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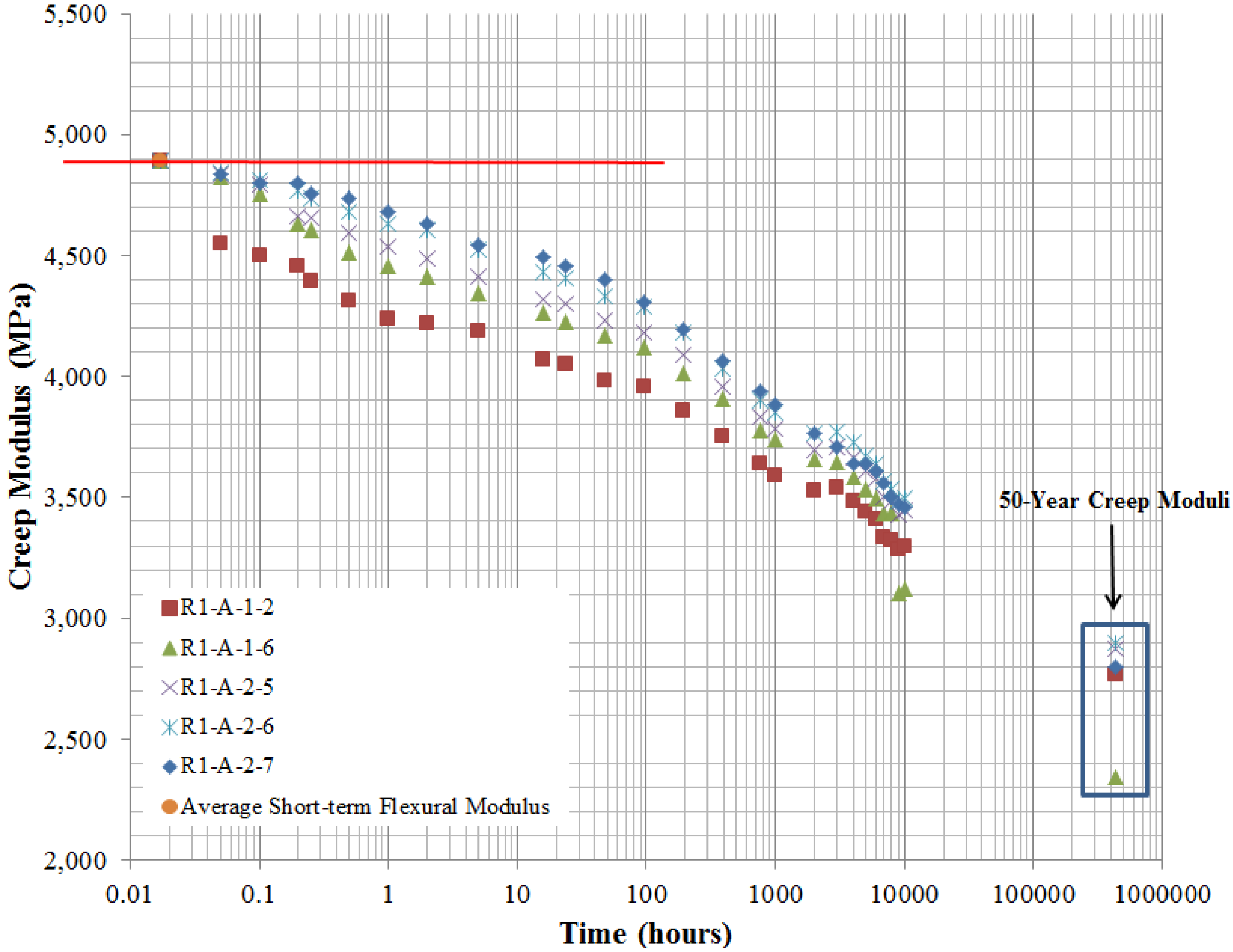
Appendix A – Designation of Resins and CIPP Bag Materials

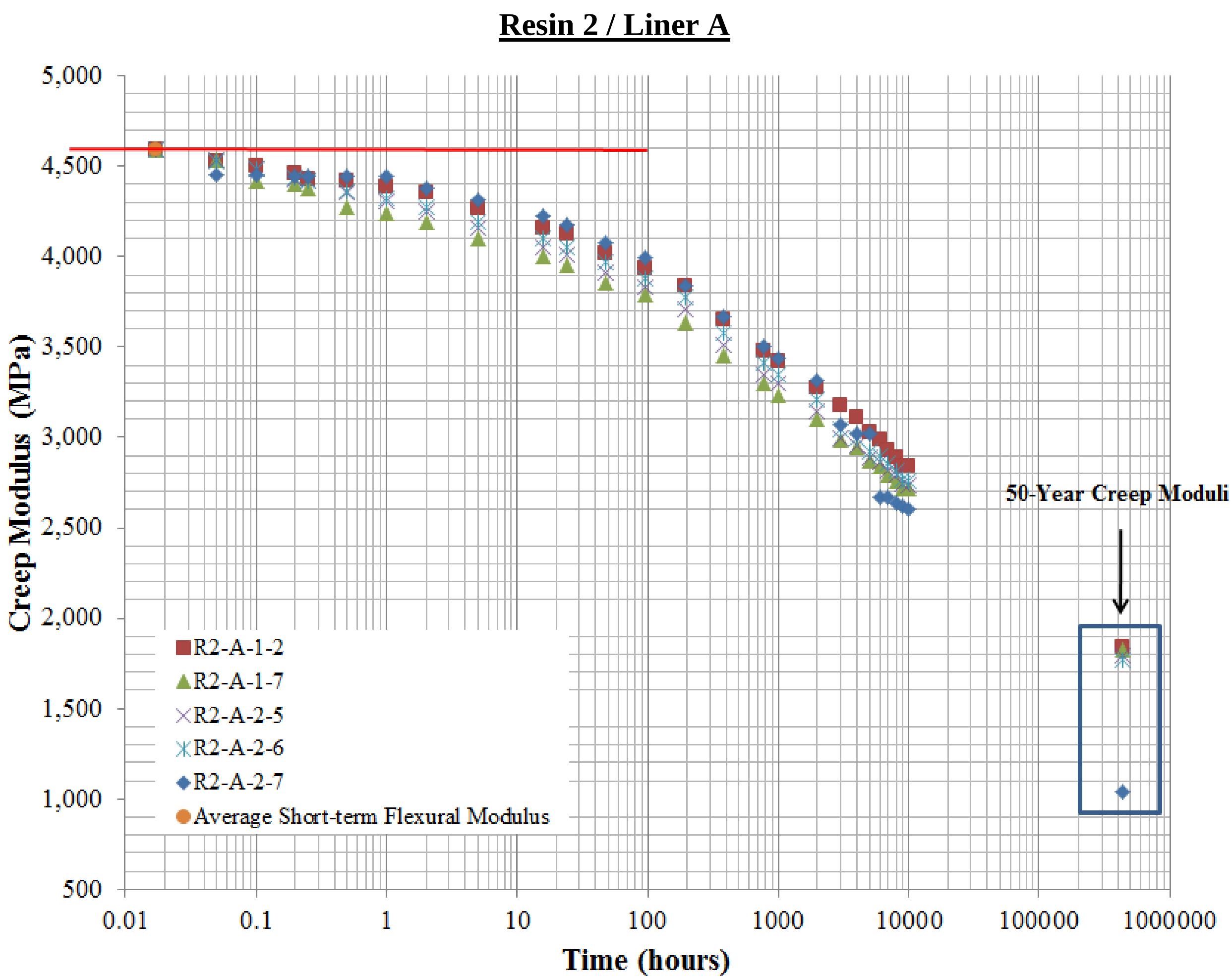
- CORVE8190 = Resin 1
- VEX216-589 = Resin 2
- CORVE8293 = Resin 3
- Norditube = Reinforced CIPP Liner A
- Applied Felts = Reinforced CIPP Liner B
- Saertex = Reinforced CIPP Liner C

Appendix B – Creep Modulus versus Time Plots

Resin 1 / Liner A

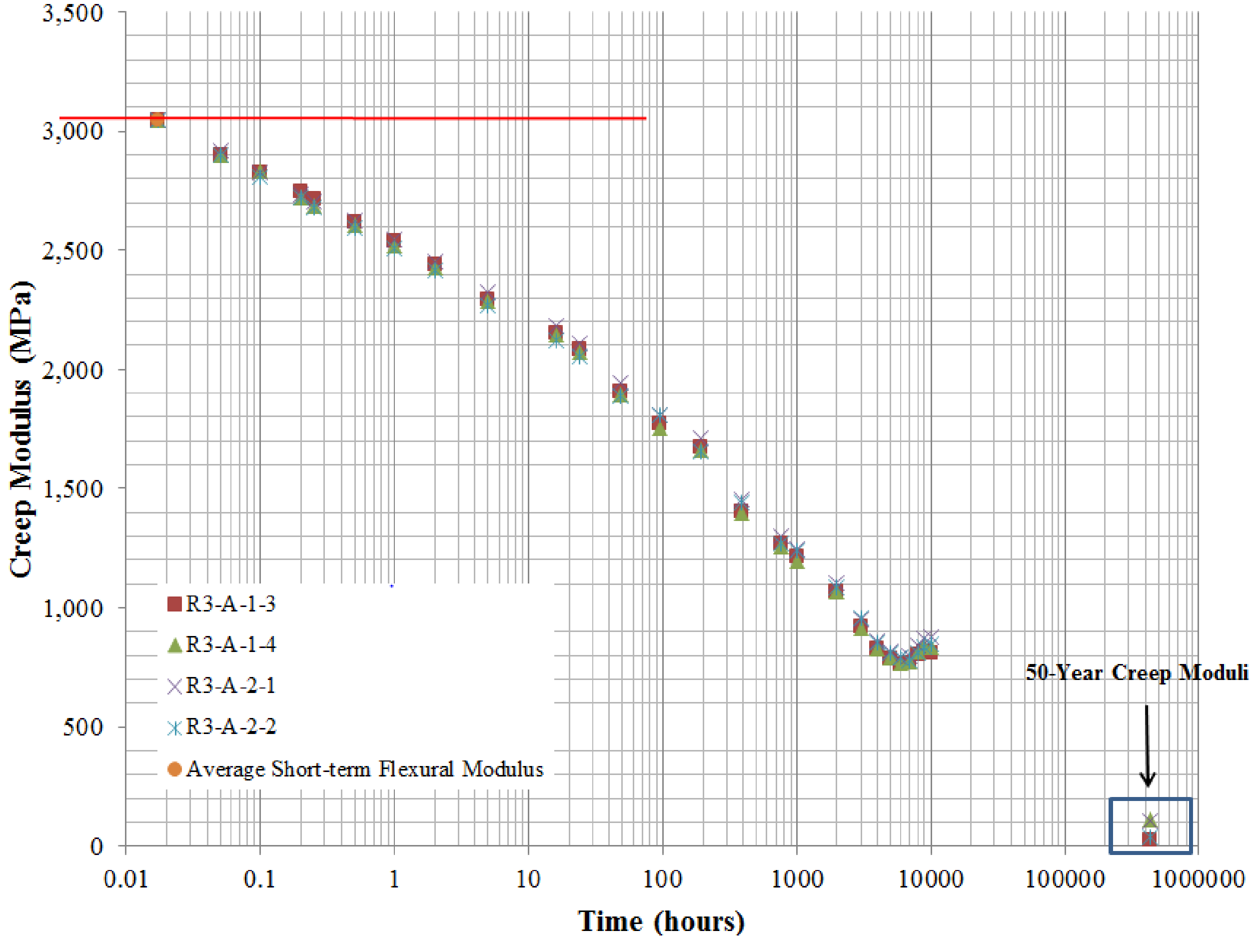


Regression Equation			
Specimen	a	b	R-Square
R1-A-1-2	-46,959	668,395	0.89
R1-A-1-6	-81,924	803,484	0.72
R1-A-2-5	-51,716	709,907	0.89
R1-A-2-6	-54,449	728,566	0.89
R1-A-2-7	-60,113	745,513	0.97



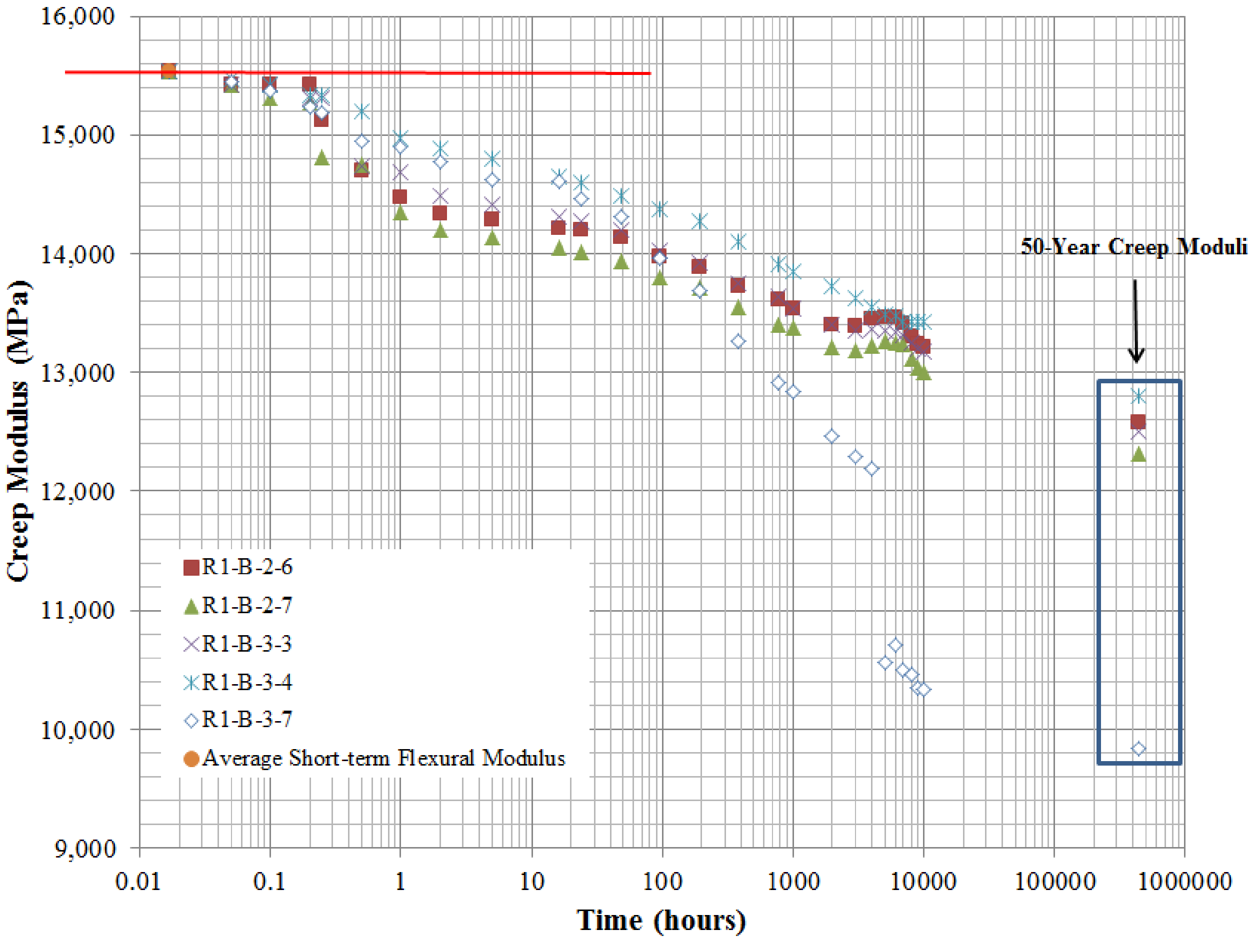
Regression Equation			
Specimen	a	b	R-Square
R2-A-1-2	-88,256	764,819	0.99
R2-A-1-7	-78,125	705,798	1.00
R2-A-2-5	-82,788	726,440	0.99
R2-A-2-6	-87,483	749,370	0.99
R2-A-2-7	-136,442	920,227	0.93

Resin 3 / Liner A



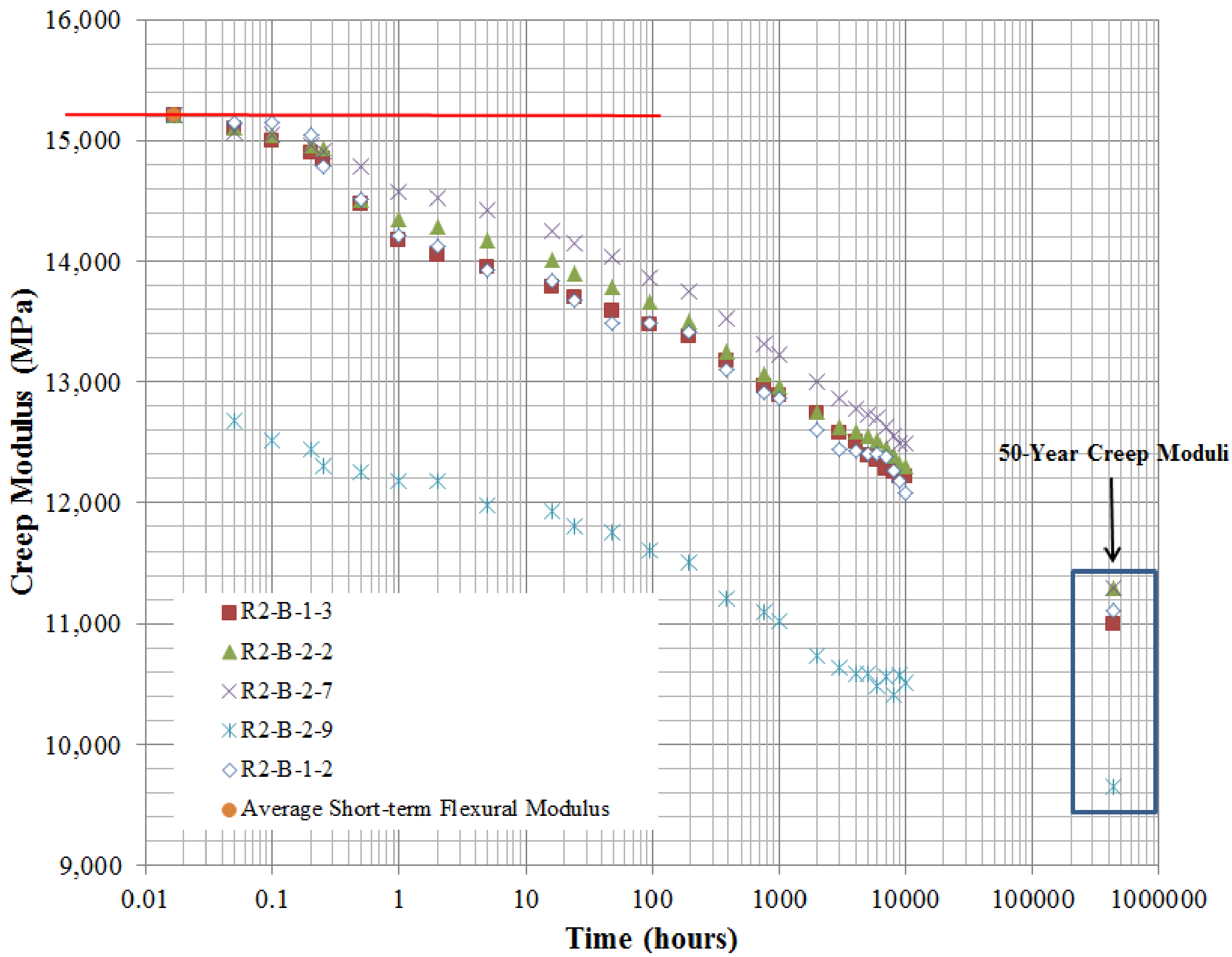
Regression Equation			
Specimen	**a**	**b**	**R-Square**
R3-A-1-3	-62,513	355,986	0.84
R3-A-1-4	-56,895	336,029	0.79
R3-A-2-1	-59,694	351,185	0.79
R3-A-2-2	-63,351	362,344	0.84

Resin 1 / Liner B



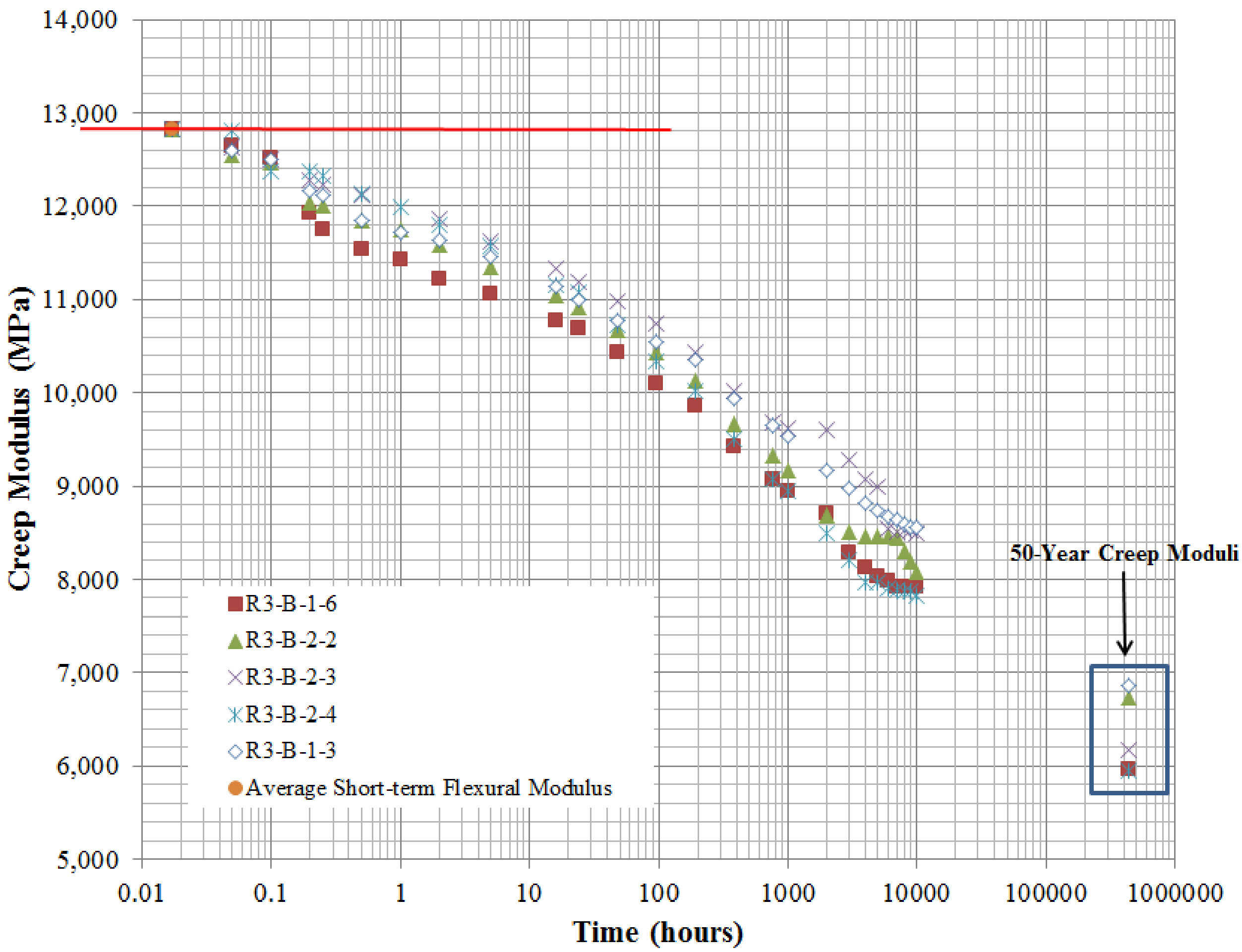
Regression Equation			
Specimen	a	b	R-Square
R1-B-2-6	-56,741	2,143,682	0.96
R1-B-2-7	-60,055	2,126,070	0.96
R1-B-3-3	-60,073	2,151,832	0.98
R1-B-3-4	-57,380	2,180,702	0.99
R1-B-3-7	-129,836	2,158,777	0.85

Resin 2 / Liner B

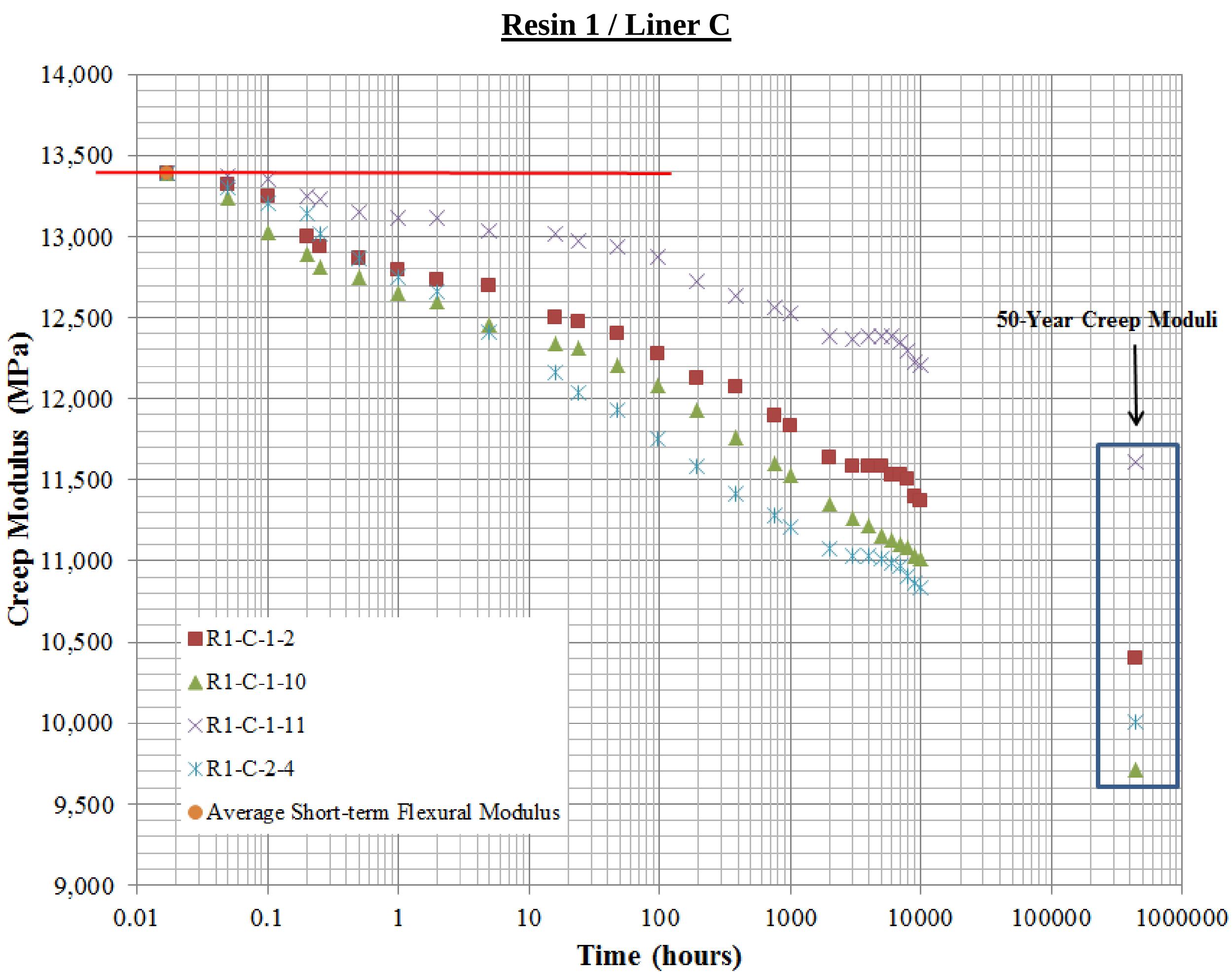


Regression Equation			
Specimen	a	b	R-Square
R2-B-1-2	-95,052	2,146,868	0.92
R2-B-1-3	-106,198	2,193,040	0.99
R2-B-2-2	-91,769	2,155,234	0.98
R2-B-2-7	-106,389	2,237,586	0.99
R2-B-2-9	-70,317	1,795,693	0.82

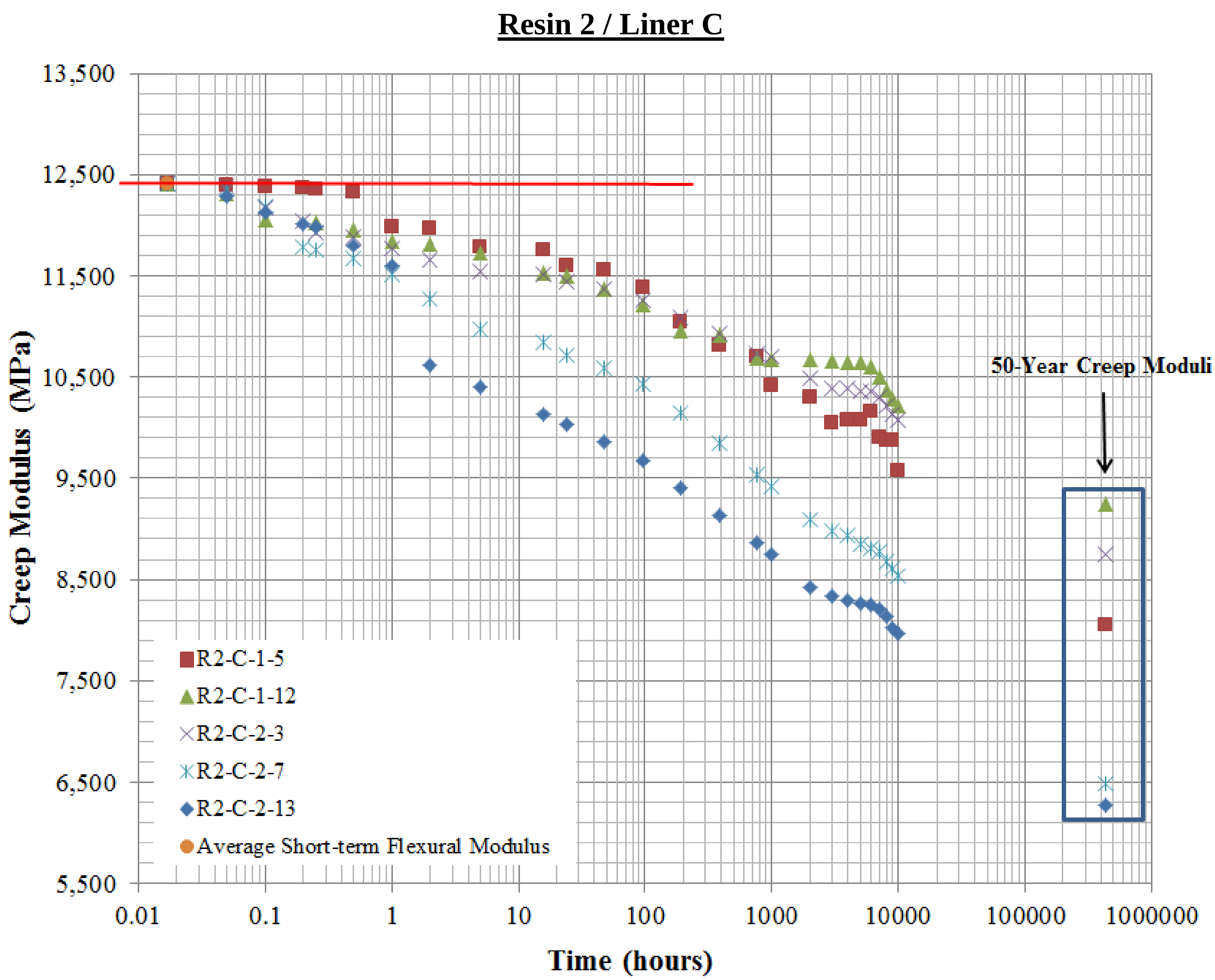
Resin 3 / Liner B



Regression Equation			
Specimen	a	b	R-Square
R3-B-1-3	-143,870	1,805,994	0.98
R3-B-1-6	-161,471	1,776,196	0.94
R3-B-2-2	-127,799	1,697,450	0.90
R3-B-2-3	-200,196	2,025,252	0.90
R3-B-2-4	-157,450	1,749,963	0.92

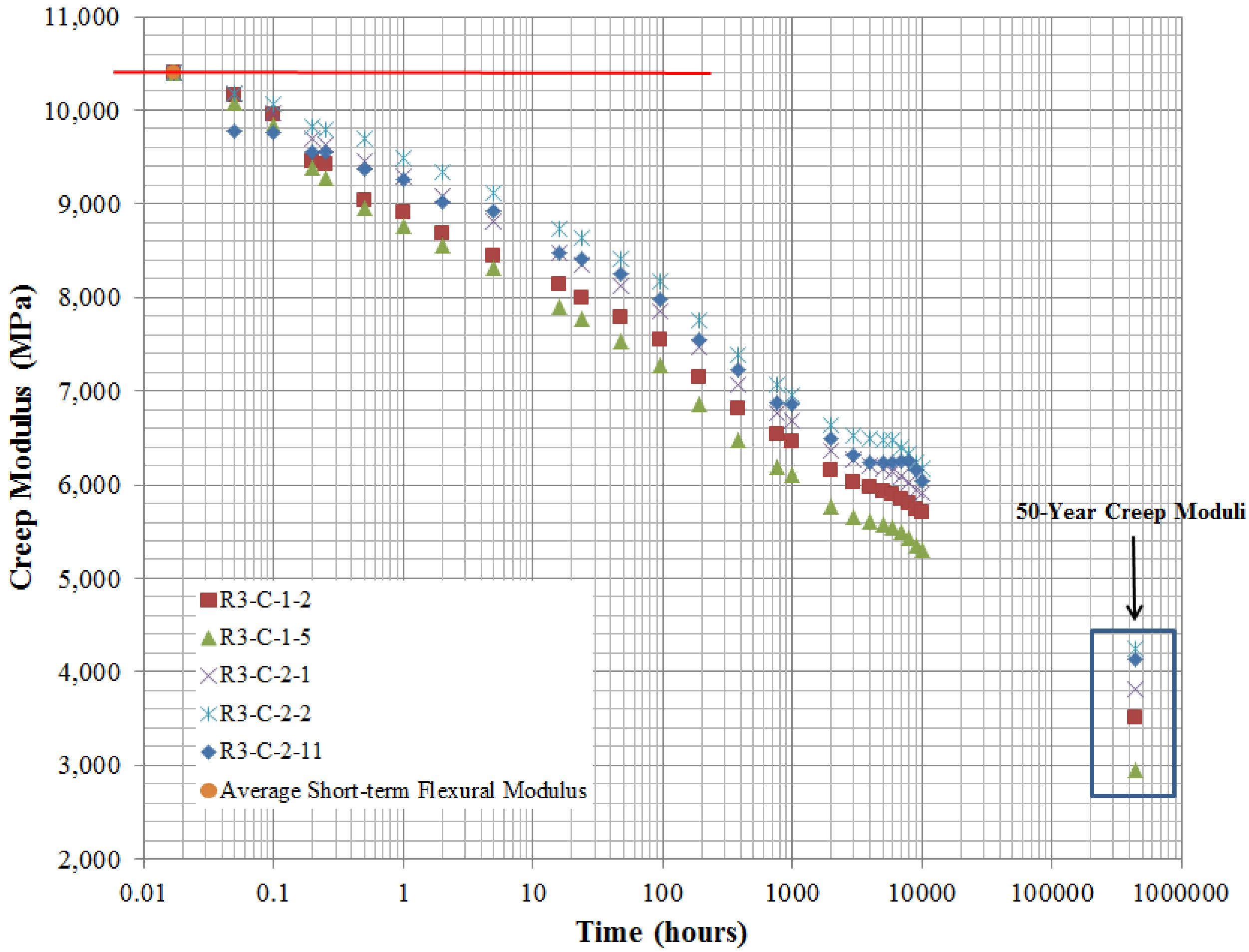


Regression Equation			
Specimen	a	b	R-Square
R1-C-1-2	-56,183	1,881,107	0.89
R1-C-1-10	-71,780	1,885,007	0.99
R1-C-1-11	-35,828	1,922,214	0.76
R1-C-2-4	-47,800	1,768,925	0.92



Regression Equation			
Specimen	a	b	R-Square
R2-C-1-5	-95,847	1,804,964	0.78
R2-C-1-12	-61,965	1,753,731	0.61
R2-C-2-3	-77,099	1,781,711	0.90
R2-C-2-7	-115,970	1,710,301	0.97
R2-C-2-13	-96,566	1,551,975	0.94

Resin 3 / Liner C



Regression Equation			
Specimen	a	b	R-Square
R3-C-1-2	-119,645	1,304,195	1.00
R3-C-1-5	-128,786	1,284,027	1.00
R3-C-2-1	-118,204	1,337,891	0.99
R3-C-2-2	-112,417	1,362,958	0.98
R3-C-2-11	-109,772	1,328,701	0.98