TESTING & DESIGN LIFE MODELING OF POLYUREA LINERS FOR POTABLE WATER PIPES

by

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ABSTRACT

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Currently, there are various renewal methods available for different applications, among which coatings and linings are most commonly used for the renewal of water pipes. Polyurea is a lining material applied to the interior surface of the deteriorated host pipe using spray technique. It is applied to structurally enhance the pipe and provide barrier coating. This thesis presents the preliminary results of an ongoing laboratory testing program designed to investigate the renewal of potable water pipes using polyurea spray lining. This research focuses on predicting the long-term behavior of polyurea composite. The goal of this test was to establish a relationship between stress, strain and time. The results obtained from these tests were used in predicting the life and strength of the polyurea material. In addition to this, based on the 1,000 hours experimental data, curve fitting and Findley Power Law models were employed to predict long-term behavior of the material Findley's power law accurately predicted the non-linear time-dependent creep deformation of this material with acceptable accuracy. Experimental results indicated that this material offers a good balance of strength and stiffness and can be utilized in structural enhancement applications in potable water pipes.

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CHAPTER 1

INTRODUCTION

1.1 Background

Pipeline systems have been in use for more than a century and most of them are deteriorated significantly and are in need for repair, renewal or replacement. Renewal of existing water pipe systems worldwide using "trenchless technology" has become popular over the past few decades. Trenchless technology is a rapidly growing industry that eliminates or reduces the need for surface excavation, often referred to as "NO-DIG" technology. Any pipe material is subjected to deterioration and subsequent failure due to many factors, such as, corrosion, age, pipe environment, climate, operational factors and so on. According to ASTM, a deteriorated pipeline is classified into partially or fully deteriorated. Partially deteriorated pipe can carry soil and surcharge load, but is unable to resist hydrostatic loads. In fully deteriorated condition, the pipe is present but is no longer considered to support the soil and the surcharge loads. This research focuses on a new trenchless renewal method, using polyurea as a lining material to extend the service life of the partially deteriorated potable water pipes. Polyurea is a lining material applied to the interior surface of the deteriorated host pipe using spray technique. It is applied to enhance the structural ability of the pipeline. For this research, commercially available polyurea composites by 3M Water Infrastructure are used under the names Scotchkote 169, Scotchkote 169HB and Scotchkote 269 are used.

Scotchkote 169, 169HB (formerly known by Copon Hycote brand) was developed by E. Wood, Ltd., in the United Kingdom. E. Woods developed this revolutionary spray on application and rapid setting polymeric product for the semi-structural renewal of potable water pipes for long-term protection and to address problems of water discoloration and odor. Scotchkote 169, 169HB and 269 are two component resins specifically designed for use in internal pipeline applications. These products can be applied to pipelines that may have been considered for replacement, due to their age or overall conditions.

1.2 Current State of Water Systems

Renewal and maintenance of buried pipes is a major challenge faced by engineers, utility owners, and decision makers due to ageing pipes and increasing gap in funding. The U.S. Environmental Protection Agency (EPA) estimates that nearly $1 trillion is needed in critical drinking water and wastewater investments over the next two decades (ASCE Report, 2009). Efficient management of these funds will require tools that managers and decision makers can employ to optimally allocate funds and prioritize infrastructure improvements (Juhl et al, 1994 & Deb, et al, 1999).

The deterioration rate of buried pipes is a function of many factors such as material, age, soil condition, and hydraulic parameters of the fluids inside these pipes. It is usually the cumulative effects of these different factors rather than each individual factor that determines the condition of the pipe (Figure 1.1).

Figure 1.1 - Effects of Tuberculation, Age and Corrosion on Water Pipes
(Source: 3M Water Infrastructure)

According to a report by the American Water Works Association (AWWA), both internal and external forces on the water main have major effects on its expected useful life (AWWA, 2001). Figure 1.2 is an example of deterioration rate over time for water pipes.

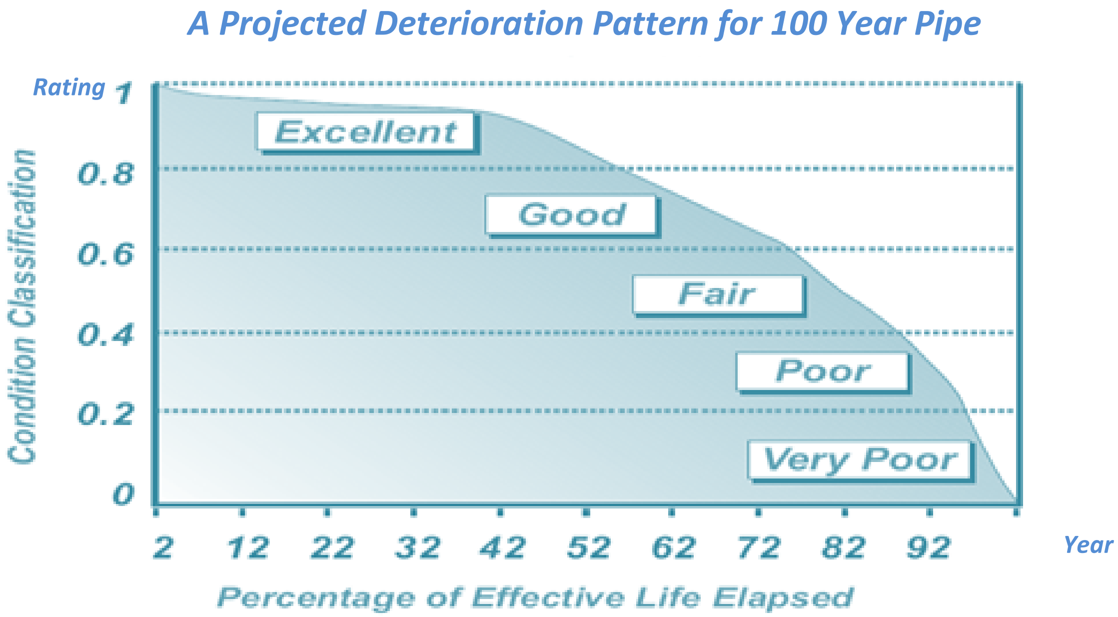
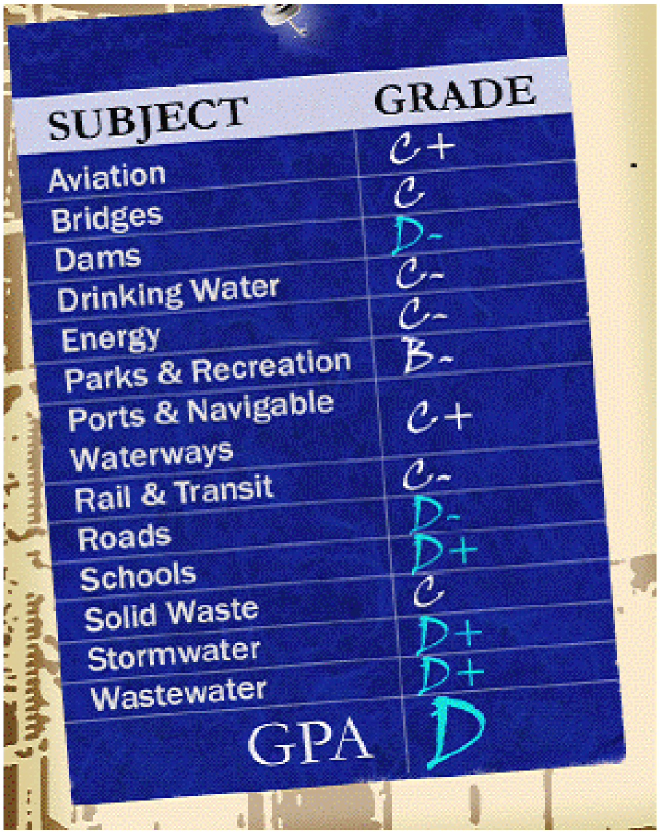


Figure 1.2 - Life Cycle Deterioration Curve for Pipes (EPA Report, 2002)

As shown in Figure 1.2, water pipes, like any other asset, decrease in performance level with time. Conversely, each pipe component is part of an integrated system, and its behavior may affect the overall service of the pipeline system. On the other hand, quality of the service is not constant, for instance, new legislations, and changes in the urban development, customers' needs and expectations. The fact that most water pipes are buried, also adds also a degree of complexity to the problem, due to the difficulty in assessing their condition. Water pipe asset management is, therefore, a complex and challenging matter, currently an important agenda item for water supply stakeholders in the industrialized countries (Alegre, et al., 2006b).

The American Society of Civil Engineers (ASCE) Report Card for the year 2009, grades the nation's infrastructure with "D" and drinking water system as "C-" as shown in Figure 1.3 (ASCE Report Card, 2009). It should be noted that pipeline deteriorating conditions together with inflation rate have increased the total cost of repair, renewal and replacement from $1.6 trillion in 2005 to $ 2.2 trillion in 2009.



SUBJECT	GRADE
Aviation	C+
Bridges	C
Dams	D-
Drinking Water	C-
Energy	C-
Parks & Recreation	B-
Ports & Navigable Waterways	C+
Rail & Transit	C-
Roads	D-
Schools	D+
Solid Waste	C
Stormwater	D+
Wastewater	D+
GPA	D

Figure 1.3 - ASCE Report Card, GPA “D” (ASCE, 2009)

The majority of water pipes installed in the United States, beginning in the late 1800’s until the late 1960’s, were manufactured from cast iron. With time, deteriorating conditions cause reduction in both structural integrity and hydraulic capacity of the pipes. The effects of pipe failure can sometimes be observed on the street due to pipe burst with consequences of traffic disruptions or pipe blockage with consequences of flooding. Therefore, managing and maintaining the performance of these buried assets is a significant task to the utility managers.

1.3 Polyurea Lining Material

1.3.1 Introduction

Polyurea is a rapid-setting and high-build renewal method for drinking water pipelines with minimum disruption of service. The spray lining requires an even internal surface to avoid discontinuities at joint areas thus ensuring optimum thickness of linings throughout the length of the application. The lining is formed using centrifugal application equipment. The end result is a high build inert and corrosion resistant lining system. The speed of application results in rapid renewal of water pipes with quick return to service.

Polyurea lining is a trenchless technology method, leading to minimum social costs and disturbances to adjacent utilities and structures, as well as minimum surface and subsurface excavations. With conventional open-cut construction methods, direct costs are greatly increased with need to restore ground surfaces such as sidewalks, pavement, landscaping, and so on (Najafi & Gokhale, 2005). Additionally, social and environmental factors related to open-cut methods include adverse impacts on the community, businesses, and commuters due to air pollution, noise and dust, safety hazards and traffic disruptions. Polyurea linings can renew and enhance water pipes with addressing the following problems as per “Scotchkote 269 Design Guide”:

1. **Pipeline Internal Corrosion Problems:**

Polyurea lining provides a highly effective and corrosion-resistant barrier coating within the pipe surface.

2. **Water Quality Problems Associated with Pipeline Internal Corrosion:**

Lining resists any tuberculation which contributes to conveyed water quality problems. In addition, the smooth surface of lining prevents the formation of other pipe deposits (Figure 1.4).

Figure 1.4 - Finished Polyurea Spray Lining

3. **Leakage from Corrosion Holes, Cracks, and Failed Pipeline Joints (Scotchkote 269, 2009):**

Polyurea lining provides a continuous pressure-tight envelope inside the existing pipeline which, can be designed to span corrosion holes and joint gaps. A Class III liner material is not a replacement of host pipe but works in conjunction with it to prevent further corrosion and leakage and maintains the integrity of the host pipe (Scotchkote 269, 2009). Table 1.1 presents the four groups of lining and their ability to address different water pipe problems.

Table 1.1 - Structural Classification of Lining Systems (AWWA M28, 2001)

System Class	*Non Structural*	*Semi-Structural (Interactive)*		*Structural (Independent)*
	I	*II*	*III*	*IV*
Corrosion Protection	YES	YES	YES	YES
Gap Spanning Capability	No	Yes	Yes	Yes
Inherent Ring Stiffness	No (Rely on Bonding)	No (Rely on Bonding)	Yes (Self Support)	Yes (Self Support)
Survives Burst Failure of Old Pipe	No	No	No	Yes

4. **Flow Capacity Problems Arising from Pipe Tuberculation and Deposits:**

Polyurea lining presents a smooth surface to the conveyed liquid, which helps maximize the flow capacity of the lined pipe. This is due to extremely low friction coefficient and thin-walled of the lining.

5. **Rapid (Same Day) Return to Service:**

Polyurea lining is a rapid setting polymeric lining which dramatically reduces shutdown periods and provides same day return to service of water lines.

6. **Volatile Organic Compound (VOCs):**

Polyurea does not contain any volatile organic compounds (VOC's) as per EPA Method 8260, which is the main source for air pollution, making polyurea lining an environmentally friendly product.

7. **Plugging Service Connections**

During installation process, polyurea lining eliminates the need for blocking of service connections. Rapid curing process thus eliminates the need for providing temporary bypass connection to the customer.

8. Structural Integrity and Design Life of Old Pipe:

Polyurea Class III lining structurally renews the old pipe with a giving a new design life.

1.4 History of Polyurea

Polyurea is a name given to a wide range of polymeric material that has extensively been used in the coating industry in solid elastomeric or rigid form. Introduced in 1989 by Texaco Chemical Company, polyurea was regarded as a product that did not fulfill the exaggerated expectations initially advertised, especially in the coating industry. Recent studies, however, have shown promising mechanical responses for polyurea that are not limited to only the coating applications but venture into critical applications such as reinforcement of metal structures against blast and impact loads (Alireza et.al, 2004).

The main components are di- or poly-isocyanate molecules exothermically reacting with amine molecules (functional group –NH2) resulting in polymers with urea bonding – (NH) (CO) (NH) – (Raghavan & Meshii, 1997) (see Figure 1.5). Urea bonding generally involves faster reaction times thus making it possible to apply polyurea as spray in coating applications. Polyurea linings offer the highest degree of chemical resistance, with new hybrids offering improved wetting and cure times (Primeaux II, 2004).

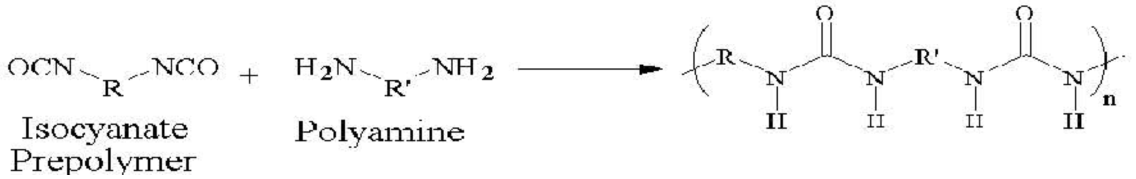


Figure 1.5 - Polyurea Formation Reaction (Primeaux II, 2004).

1.5 Comparison between 169, 169HB and 269 Specimens

Scotchkote 169, 169HB and 269 polyurea are designed as an in-situ applied rapid setting lining system for the structural enhancement renewal of drinking water mains. The rapid curing characteristics of 169, 169HB and 269 facilitate commencement of same day return to service procedures 30 minutes after completion of the lining operation. In situations where water quality issues rather than structural concerns have been the main driver, structural enhancement spray lining offers a minimum cost alternative to renewal with sliplining, close-fit, thermoformed etc. Table 1.2 shows the comparison of the three polyurea composites used for this study. Scotchkote 169 and 169HB is the preferred method for renewal of drinking water pipelines by United Kingdom's leading water utilities. Over 6213 miles (10,000 km) of distribution and trunk mains have been sprayed in the last 10 years (Copon Hycote, E Woods).

Table 1.2 – Comparison of Scotchkote 169, 169HB and 269 Polyurea Composite (Copon Hycote, E.Woods)

Properties	***Polyurea Specimen Available***		
	169	***169HB***	***269***
Mix Ratio (By volume)	2.5:1	2.5:1	1:1
Mix Ratio (By weight)	100:38.8	100:52	100:112.4
Get Time 77℉ (25℃)	60 Seconds	60 Seconds	120 Seconds
Film Set Time	2 Minutes	2 Minutes	4 Minutes
Cure Time (CCTV Inspection)	10 Minutes	10 Minutes	10 Minutes
Cure Time (Return to Service)	30 Minutes	60 Minutes	60 Minutes
Solids Content (By volume)	100%	100%	100%
V.O.C.	Nil	Nil	Nil

1.5.1 Phases of Polyurea Lining Installation

Proper installation procedures add immeasurably to the long and useful life of any lining material. Successful installation of polyurea lining depends on various factors like material transportation from shop to the site, ambient temperatures at the site, and cleanliness of the internal surface of the old pipe including its condition, geometry, alignment and defects. Figure 1.6 illustrates the phases for a successful polyurea lining installation.

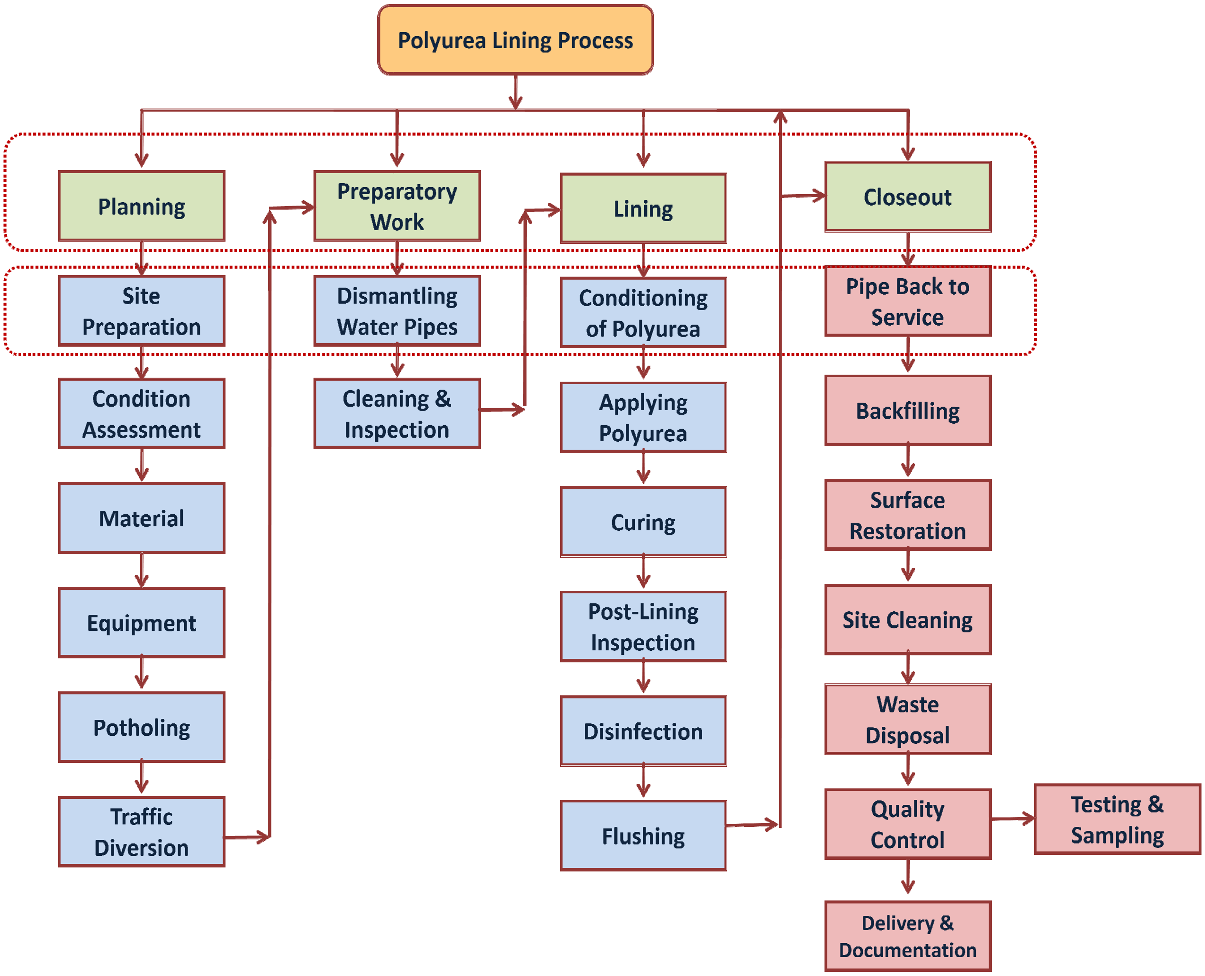


Figure 1.6 - Phases of the Polyurea Lining Installation Process

1.5.2 General Properties

Polyurea lining combine application properties such as rapid cure, at temperatures below 0°C, and high hardness along with other physical properties such as insensitivity to humidity, flexibility, tear and tensile strength and chemical and water resistance. This results in good weathering and abrasion resistance. These materials are 100% solids, making them compliant with the strictest VOC regulations. The polyurea lining are not sensitive to moisture and humidity and do not normally produce coating defects associated with moisture such as bubbles, foaming and moisture caused bubbles (Guan, 2003).

Table 1.3, shows the performance and application properties of typical 100% solid elastomeric polyurea lining, which is currently available in the market.

Table 1.3 - Physical Properties and Test Methods for Typical Polyurea Material (Copon Hycote, 2009)

Typical Physical Properties	*Description*
Tensile Strength	➢ Test Method : ASTM D-638 ➢ Range: up to 4,000 psi
100% Modulus	➢ 500 – 1,800 psi
Flexural Strength	➢ Test Method : ASTM D-790 ➢ Range: 3,200 – 3,500 psi
Flexural Modulus 'E'	➢ Test Method : ASTM D-790 ➢ 100,000 to 110,000 psi
Elongation	➢ 20 – 1,000 %
Gel Time	➢ 2 – 15 seconds
Tear Strength	➢ 250 – 600 pounds per linear inch
Application Temperature	➢ - 40^{o} F to 122^{o} F
Initial Curing Time	➢ 3 – 10 seconds ➢ Autocatalytic

According to the E. Woods Company, Copon Hycote brochure and Guan, 2003, polyurea have properties which makes it demanding in coating and trenchless industry. Some of the features of polyurea are:

1. **VOC's:** Polyurea lining does not contain any volatile organic compounds (VOC's) as per EPA Method 8260, which is the main source for air pollution, making polyurea lining an environmentally friendly product.
2. **Humidity:** Polyurea is not likely to be affected by moisture and humidity but in reality if there are excessive water puddles remaining in the pipe, some blistering may be present.
3. **Heat and Fire Resistance**: Polyurea coatings have resistance to heat distortion and sagging. Depending on the formulation, some polyurea have a low heat deflection temperature. When exposed to constant flame for 20-30 seconds, polyurea coatings will self-extinguish.

4. **Waterproof**: Seamless waterproofing system for concrete, metal, soil, and other substrates.
5. **Abrasion Resistance:** Polyurea has resistance to withstand mechanical action such as rubbing, scraping, or erosion that tends progressively to remove material from its surface.
6. **Elasticity**: Polyurea being an elastomer has a very linear structure with much less cross-linking which makes it stretchy and elastic.

Some of the other features of polyurea lining are presented in Table 1.4.

Table 1.4 - Features and Advantages of Polyurea Lining (Scotchkote 269 Coating, 2009)

Category	*Polyurea Lining*	*Polyurea Lining Advantages*
Range of Application	Applicable to all pipe diameters ranging from 4 in. (100 mm) for structural enhancement. Larger pipe diameters will benefit as a corrosion barrier coating.	Various pipe diameters can be sprayed with the same product
Rate of Application	Will allow same day return to service	Cost saving and customer satisfaction
Number of Excavations	One excavation up to 500 ft (150 m)	Cost saving and less public disruption
Utilizing Trenchless Technology	Polyurea lining is a true “No-Dig” method and does not interfere with any other utility pipe	Low Risk in comparison to other renewal method
Environmental Issues	Minimum excavation and contains no VOC’s	Environmental advantages & reduced carbon footprint
Contamination	Lining is sprayed directly into the old pipe	Less risk of contamination
Effect on Traffic Flow	Minimum excavation causing less traffic disruption	Saving on traffic management
Annular Gap/Adhesion	Polyurea lining is fully bonded to the internal face of the old pipe	No annular gap flow can develop
Service Connections	No service re-connections required. Existing corporation stops and remain open after lining	Cost saving, no secondary excavations

1.6 Need Statement

Water pipe performance reduces gradually with time, resulting in high maintenance cost, poor water quality, leakage problems and loss of pressure. Structural and leakage problems are common in old cast iron water mains, particularly in pipe larger than 30 in. (760 mm). The majority of these problems are caused by some combination of corrosion, soil movements, traffic loads, and operating pressures. About 50% of water pipes in the North American water systems are of cast iron, unlined and are installed prior to 1950s. Many of these water pipes are structurally sound, but show tuberculation, resulting in reduction in hydraulic capacity and water quality issues (Figure 1.7) (AWWA, 2006).

Figure 1.7 - Intensity of Tuberculation Present (Source: 3M Water Infrastructure)

Spray lining methods such as cement mortar, epoxy and polyurethane have been used for number years and have performed well in the water industry. Since polyurea is a new product available for the renewal of corroded underground water pipes, it is necessary to develop an appropriate design procedure for determining the strength of the lining material and to ensure that it is capable of spanning corrosion holes without failing over a minimum design life. Therefore, it is important to know the physical and mechanical properties, among which long-term tensile and flexural creep are the basic parameters which will help to decide the life expectancy of the polyurea lining material. Not much research has been done in the past in determination of long-term tensile and flexural strength of polyurea material, which is the basic requirement in the prediction of the design life of this material.

An increase in the number of pipe failures has alarmed the need for renewal of water pipes and to stop their degradation (Figure 1.8), however these deteriorated pipes when coated, will reduce the rate of deterioration. The specific cause of degradation of pipe is not fully understood. But an attempt to predict the life expectancy of polyurea lining can be studied using some long-term testing. This research was intended to clarify and understand the material properties and provide a quantitative method for predicting the performance and life expectancy of this material in potable water pipes.

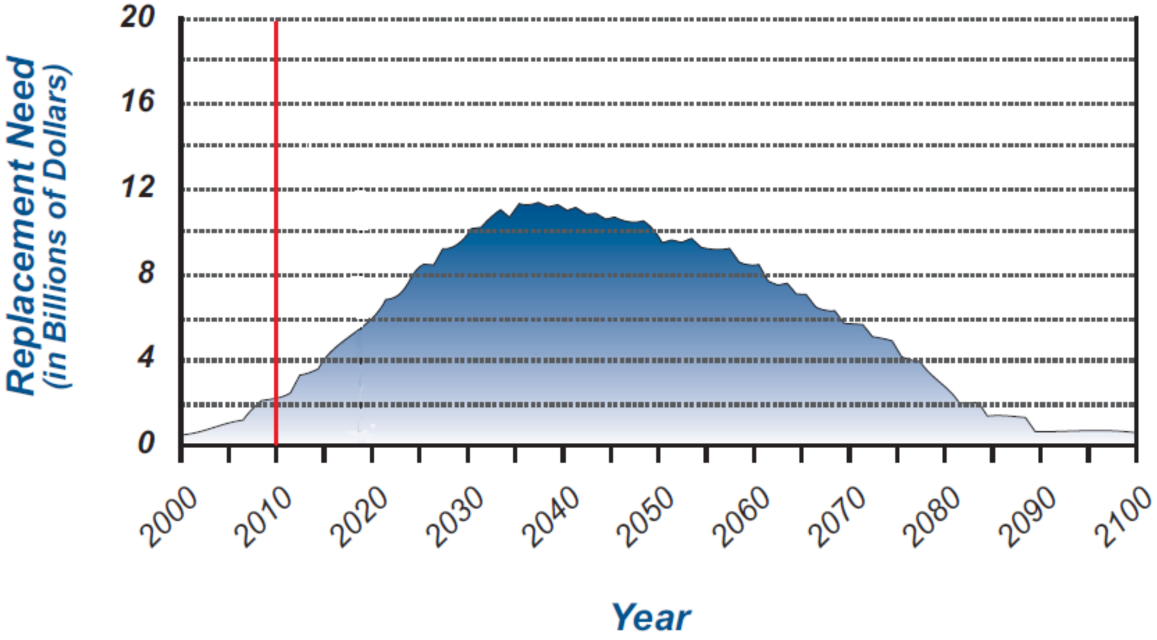


Figure 1.8 - Pipe Replacement Estimate Cost in Dollars ($) (EPA Report, 2002)

1.7 Objectives and Scope

The main goal of this thesis is to determine the long-term strength of three different polyurea composites based on the tensile and flexural creep properties. This research will systematically isolate and quantify the influence of stress parameters on short-term and long-term behavior of the liner material. This research work is comprised of following objectives:

- To evaluate the some mechanical properties at room temperature.

- Perform trial test with similar setup to determine the appropriate stress value for long-term test.
- Perform test on the liner material such as long-term tensile and flexural creep and formulate results.
- Model experimental creep strain responses using Findley's Power Law.
- Model the experimental creep strain responses using log fitting curve.
- Predict long-term properties and design life of polyurea composite.

1.8 Research Methodology

The research is based on analyzing the mechanical properties of polyurea composite such as tensile and flexural creep, its behavior and effect, when subjected to long-term continuous and constant loading. Creep takes into account the total deformation under stress after a specific time at a given temperature. This property is very useful in the design of pipe liners. To attain these mechanical properties the following tests are conducted:

1.8.1 Long-term Tests

1.8.1.1 Tensile Creep Test

The research works investigates the long-term tensile creep properties and report the following information:

- Performing test for 1,000 hours and determining stress value for long-term test.
- Applying constant load to a dumbbell shaped polyurea 169, 169HB & 269 specimens and measuring its elongation as a function of time.
- Recording strain response using strain gages attached to the specimens and measured elongation at time intervals of 1, 6, 12, 30 min; 1, 2, 5, 20, 50, 100, 200, 500, 700 and 1,000 hours.
- Carrying out the testing at room temperature.
- Testing the specimens for approximately 1,000 hours or until failure whichever comes first.

1.8.1.2 Flexural Creep Test

The research works investigates the long-term flexural creep properties and report the following information:

- Performing test for 1,000 hours and determining stress value for long-term test.
- Applying constant load to polyurea 169, 169HB & 269 specimens and measuring its flexural strength as a function of time.
- Measuring the deflection of the specimen at mid-span using accurate deflection gauges.
- Recording the deflection of the specimen at time intervals of 1, 6, 12, 30 min; 1, 2, 5, 20, 50, 100, 200, 500, 700 and 1,000 hours. Plotting the percent creep strain against time.
- Carrying out the testing at room temperature.
- Testing the specimens for approximately 1,000 hours or until failure whichever comes first (approx 2 months).

1.8.1.3 Modeling and Predicting Design Life

Time dependent deformation of a material under sustained load is referred to as creep. If the load is large and the duration is long, failure (i.e., creep-rupture) will occur. Since the duration of test is shorter, following models are used to extrapolate the results.

- Predicting the design life based on results obtained from 1,000 hour creep test and extrapolation it as described in ASTM D 2990 to ensure design of least 50-year.
- Developing a long-term design model using curve fitting method, and predicting the strain response for various specimens and comparing with other models.
- Modeling the creep strain by using Findley’s Power law to extrapolate strain to 50-year and predict the reduction in strength.
- Evaluating and comparing the percent increase in strain over 50-year using curve fitting and Findley’s law.

1.9 Structure of the Thesis

The main challenge in understanding the behavior of polyurea material in potable water pipes is the speed of degradation. The life expectancy of this material is a very slow process and testing with service conditions within the laboratory time frame requires large number of results. Hence, it is common practice in the creep testing to test more samples by varying the temperature and stress.

Chapter 1 introduces the current situation of buried pipes with statistical results showing the past, present and the future status of pipeline system. Also, it discusses the need of renewal of water pipe system, and also the cost associated with failure of these pipelines. Additionally, with some advantages, and benefits of using polyurea lining compared to other spray-on liners currently being used. It provides an overview of the objective of this thesis, the need statement and the expected outcome of this work.

Chapter 2 explains the literature review, methods of long-term performance curves generation from short-term experimental results. It also provides an overview of polyurea application in pipe lining industry. This chapter also highlights some of the past research on creep carried out with summary of results. Also, explaining some of the research carried out and method developed to determine the creep behavior of materials.

Chapter 3 discusses all the laboratory tests, test set-ups, test procedures according to ASTM and ISO standards and their significance in mechanical characterization of the polyurea composite. It also, explains the experimental setup, with figures of the setup and procedure for recording the readings.

Chapter 4 discusses experiments long-term tensile and flexure test with results, figures, tables and discussions. Additionally, the calculations for the data obtained are also shown in this chapter. It also evaluates the experimental results to predict the design life Findley's Power Law and Log-Fitting curve method. The results provide an understanding of liner behavior and will help of creep models in predicting the design life of the liner. Finally, Chapter 5 discusses the conclusions and recommendations for future work.

1.10 Expected Outcome

From the testing point of view, polyurea can prove to be an effective method in gap spanning and corrosion protection by providing some design life to the host pipe. Also this material cannot be considered to be a class IV liner (i.e. structural liner) but can provide some structural enhancement to the host pipe.

Some of the other outcomes from this thesis are highlighted below:

- A theoretical analysis of the experimental data using creep models.
- A simple comparison of the experimental and theoretical analysis data in predicting the design life.

1.11 Chapter Summary

This chapter provides an overview of current state of water system and a trenchless solution using polyurea lining renewal method. The chapter also gives a brief introduction on polyurea lining material with its material properties and advantages in trenchless applications. The most significant obstacle preventing the extensive use of polyurea lining is lack of long-term performance data, such as creep testing. The objectives, scope, need statement and expected outcome of this thesis is also highlighted in this chapter.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction to Polymers

The most basic component of elastomeric material is polymer. The word polymer is derived from the Greek term “many parts.” Polymers are large molecules of repeated units called monomers chemically bond into long chains. Elastomeric materials consist of relatively long polymeric chains having a high degree of flexibility and mobility. When subjected to external stresses, these long chains may alter their configuration rather rapidly because of the high chain mobility. Polymeric materials are available in variety of forms. They may be available in the form of solid of varying hardness, liquid or dispersed in water as latex. Some are converted into finished product and some are modified to provide desired result.

In the last few decades, polymeric materials have been widely used in many industrial applications, especially in pipe coatings (Guidetti, et al., 1996; Harris and Lorenz, 1993; Kamimura and Kishikawa, 1998; Leng, et al., 1986). Recently, the lining based on polymer such as polyurethane, epoxy and polyurea became more and more dominant in the pipe lining. They represent a durable, high performance and economical coating suitable for pipe protection. Table 2.1 presents general comparison of conventional lining materials used in industry.

Table 2.1 - Comparison of Conventional Technologies used in Coating Industry (Primeaux II, 2000)

Performance Type	*Polyurea*	*Polyurethane*	*Polyester*	*Epoxy*	*Vinyl Ester*
Physical Strength	Low-High	Low-Medium	High	High	High
Elongation	High	High	Low	Low	Low
Impact Resistance	High	Medium-High	Medium	Medium	Medium
Abrasion Resistance	High	Medium-High	Medium-High	Medium-High	Medium-High
Cure Shrinkage	Low	Low	High	Low	High
Creep	Low	High	Low-Medium	Low-Medium	Low-Medium

However, the use of polymer in a variety of aggressive environments such as corrosive environments, humidity, wide range of temperature, etc. can affect their lifetime, provoking the deterioration of their physical and mechanical properties. Study of this deterioration is time consuming; it may take several years to obtain any result. So, the comprehension of ageing mechanism and prediction of service life of polymeric coatings require convenient laboratory tests, which effectively speeds up the changes resulting from the critical weathering conditions and provides a quick indication of weather resistance (Guermazia, et.al, 1997). One of the most important aspects of long-term durability and dimensional stability of polyurea material is their long-term creep behavior. Prediction of long-term integrity of any polymeric composite structure depends on the viscoelastic properties of these materials (Raghavan & Meshii, 1997).

2.2 Creep Properties and Theories

Creep is defined as increase in strain with time at a constant stress level. When a plastic material is subjected to a sustained load, it deforms continuously. The initial strain is roughly predicted by its stress-strain modulus. The material will continue to deform slowly with time indefinitely or until rupture or yielding causes failure. The primary region is the early stage of loading when the creep rate decreases rapidly with time. Then it reaches a steady state which is called the secondary creep stage followed by a rapid increase called the tertiary stage and finally results in break. Some materials do not have secondary stage, while tertiary creep only occurs at high stresses and for ductile materials. All plastics creep to a certain extent. The degree of creep depends on several factors, such as type of plastic, magnitude of load, temperature and time (Pomeroy, 1978). In polymers, creep occurs due to a combination of elastic deformation and viscous flow of polymer molecules, commonly known as viscoelastic deformation (Park & Balatinez, 1998).

2.2.1 Effect of Temperature and Humidity on Creep

Temperature and humidity can significantly affect the deterioration process of the polymer resulting in physical and mechanical changes in material properties. Physical ageing takes place when a polymer is cooled from an elevated temperature at which the molecular mobility is high to a lower temperature at which relaxation times for molecular motions are long in comparison with the storage time at that temperature (Riande, 2000). The effect of temperature on the response of creep behavior can be quantitatively observed in Figure 2.1.

With the ageing process, there is a progressive decrease in the molecular mobility of the polymer at constant temperature. As a result, the creep deformation produced by an applied constant stress will depend upon the age of the polymer, resulting in lower creep rate in highly aged materials (ISO 899-2, 2003)· Generally, moisture absorption level is history dependent; hence the moisture absorption will be different for varying temperatures (Batra, 2009). However, the creep test time will be much shorter than the actual ageing time; thus, no significant ageing will occur during the test.

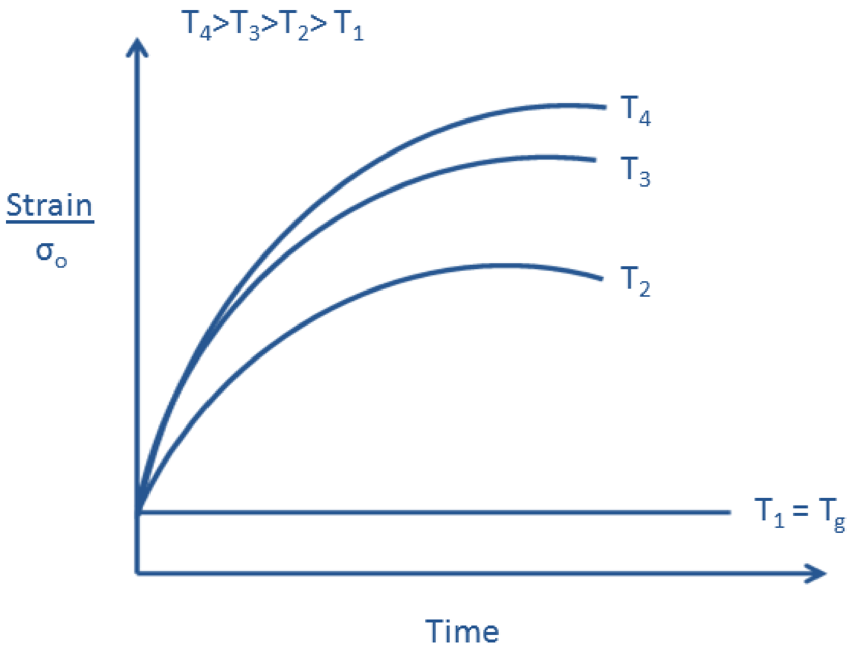


Figure 2.1 - Influence of Temperature on the Strain of Creep Experiment (Riande et.al, 2000)

In practical use, however, loading cycles are not so short, and ageing occurs during the loading cycle and temperature variations. Determination of how ageing affects the long-term response of such materials is critical to the use of polymers. Depending on the region of viscoelastic behavior, the mechanical properties of polymers differ greatly. Model stress–strain behavior for various polymer types is illustrated in Figure 2.2.

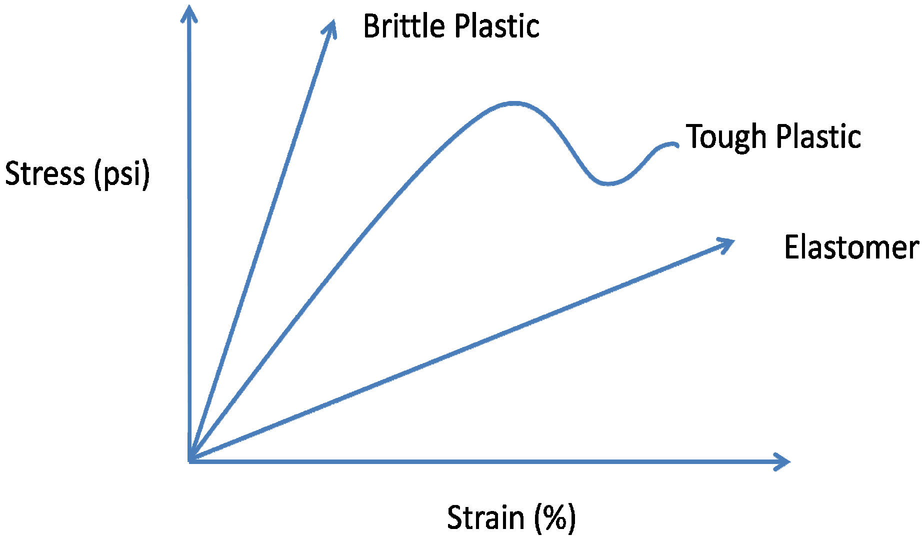


Figure 2.2 - Stress–Strain Behavior of Various Polymers (Riande, et.al, 2000)

2.2.2 Time - Temperature Superposition

There currently exist no reliable methods and techniques to predict directly the long-term ageing behavior of polymer (Ding & Wang, 2007). There are many chemical and physical changes that take place in polymer under natural ageing conditions, occurring very slowly. In order to speed up this ageing condition, high temperatures are often used to accelerate the changes. It therefore becomes necessary to demonstrate these changes that occur during accelerated ageing and compare them to the changes that occur during natural ageing at ambient conditions (Erhardt and Mecklenburg, 1995). Time-Temperature Superposition (TTS) was first noticed experimentally in the late 1930s in a study of viscoelastic behavior in polymers and polymer fluids (Vinogradov, 1980 & Tobolsky, 1967). Further studies indicated that the

TTS could be explained theoretically by some molecular structure models (Ding, et.al 1979). It has been shown experimentally that the elastic modulus (E) of a polymer is influenced by the dynamic loading and the response time.

Time-temperature superposition implies that the response time function of the elastic modulus at a certain temperature resembles the shape of the same functions of adjacent temperatures. Curves of elastic modulus (E) vs. log (response time) at one temperature can be shifted to overlap with adjacent curves. The amount of shifting along the horizontal (x-axis) in a typical TTS plot requires to align the individual experimental data points on the master curve and is generally described using one of two common theoretical models. The first of these models is the Williams-Landel-Ferry (WLF) using Equation 2.1 (Ferry, 1980):

$$Log\ A_t = \frac{-C_1\,(T - T_0)}{C_2 + (T - T_0)}$$

Equation 2.1

Where,

C_1 and C_2 = Constants,

T_0 = Reference Temperature (K),

T = Measurement Temperature (K),

A_t = Shift Factor.

The WLF equation is typically used to describe the time/temperature behavior of polymers in the glass transition region. The equation is based on the assumption that, above the glass transition temperature, the fractional free volume increases linearly with respect to temperature (Williams, et.al, 1955). The model also assumes that as the free volume of the material increases, its viscosity rapidly decreases. The other model commonly used is the Arrhenius Equation 2.2 (Li, 1999):

$$Log\ A_t = \frac{E_R}{R\,(T - T_o)}$$

Equation 2.2

Where,

E_R = Activation Energy Associated with the Relaxation

R = Gas Constant,

T = Measurement Temperature,

T_0 = Reference Temperature,

A_t = Shift Factor.

The Arrhenius equation is typically used to describe behavior outside the glass transition region, but has also been used to obtain the activation energy associated with the glass transition.

2.2.3 Maxwell and Kelvin Models

Viscoelasticity is the property of material that exhibit both viscous and elastic characteristics when undergoing deformation. In the nineteenth century, physicists such as Maxwell, Boltzmann, and Kelvin researched and experimented with creep and recovery of glasses, metals, and rubbers (McCrum, 2003). Viscoelasticity was further examined in the late 20th century when synthetic polymers were engineered and used in a variety of applications. Viscoelasticity calculations depend heavily on the viscosity variable, η as a function of temperature or as a given value (i.e. a dashpot). The Maxwell, Kelvin, Voigt model are most commonly used models to represent creep properties (Shah, 1983). The springs and dashpots can be put together to develop mathematically amenable models of viscoelastic behavior. As examples of the behavior of combinations of springs and dashpots, the Maxwell and Kelvin elements are subjected to long-term creep test. In such experiments a stress σ, is applied to the ends of the elements, and the strain ε, is recorded as a function of time. Figure 2.3 illustrates the Maxwell and Kelvin model for creep behavior.

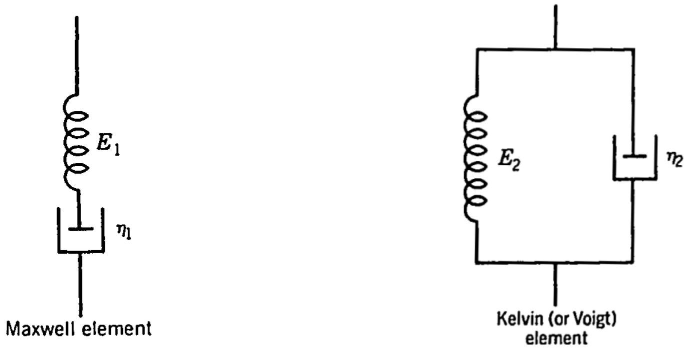


Figure 2.3 - The Maxwell & Kelvin Elements, Spring Dashpot Models (Riande et.al, 2000)

Various methods are developed explicitly to provide mathematical analysis of polymeric viscoelastic behavior. One of the methods is Maxwell's element expressing a combination of Hooke's and Newton's law (Figure 2.4). The Maxwell model for spring is expressed in Equation 2.3 (Riande et.al, 2000):

$$\sigma = E\varepsilon$$

Equation 2.3

The time dependence of the strain is expressed in Equation 2.4:

$$\frac{d\varepsilon}{dt} = \frac{1}{E}\frac{d\sigma}{dt}$$

Equation 2.4

The time dependence of the strain on the dashpot is expressed in Equation 2.5:

$$\frac{d\varepsilon}{dt} = \frac{\sigma}{\eta}$$

Equation 2.5

Since Maxwell model has a spring and dashpot in series, the model is the sum of the strains and expressed in Equation 2.6:

$$\frac{d\varepsilon}{dt} = \frac{1}{E}\frac{d\sigma}{dt} + \frac{\sigma}{\eta}$$

Equation 2.6

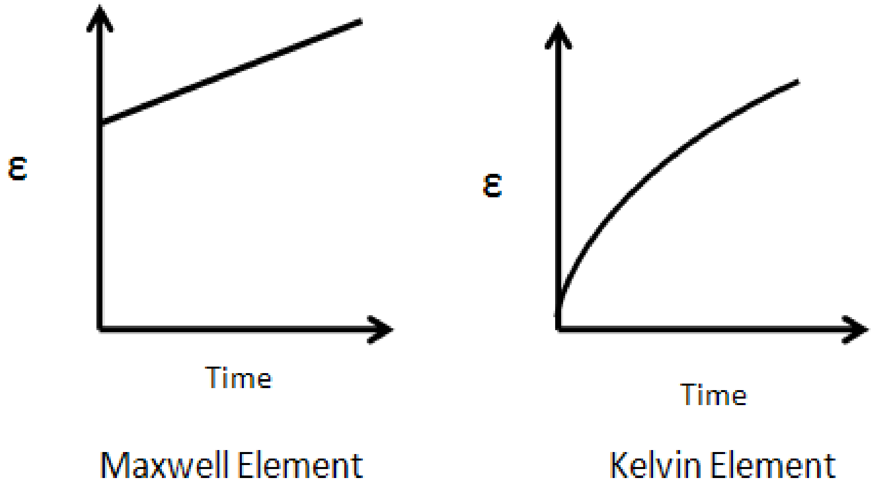


Figure 2.4 - Creep Behavior of Maxwell and Kelvin Elements (Riande et.al, 2000)

The main limitation of the Maxwell model is that it does not give a good prediction of the long-term behavior of the polymer. The creep behavior of the polymer cannot be represented accurately by only one exponential decay time. But the model gives a very good representation of the creep behavior at very short times. The Kelvin-Voigt element expresses a combination of spring and dashpot in parallel. The Kelvin-Voigt model can be represented in Equation 2.7 (Riande, et.al, 2000):

$$\sigma(t) = E\varepsilon(t) + \frac{\eta d\varepsilon(t)}{dt}$$

Equation 2.7

Where,

σ = Experimental Stress, psi

ε = Strain that Occurs under the given Stress,

E = Elastic Modulus of the Material

η = Viscosity of the Material

2.2.4 Findley model

A common experimental approach is the one proposed by Findley W.N. (1987), which was used successfully to predict the creep behavior up to 26 years. The tensile creep process is governed by several factors and number of methods, has been proposed to describe the tensile creep behavior of plastics in terms of stress (psi), strain (%) and loading time (hrs). Findley W.N (1944) has proposed a generalized discussion on the mechanisms of creep in complex linear polymer, amorphous and crystalline polymers. He also showed that creep data for a number of thermoplastic materials can be represented by Equation 2.8 (Findley, 1944).

$$\varepsilon(t) = \varepsilon_o + mt^n$$

Equation 2.8

Where,

$\varepsilon(t)$ = Sum of Elastic Strain and Time Dependent Strain (Function of Stress)

ε_o = Time-independent Strain

m = Coefficient of the Time-dependent Term (Function of Stress)

n = Constant for a Given Material Independent of Stress

t = Elapsed Time of Loading (hours).

In the structural evaluation of polymer liners, it is very important to investigate the short-term and long-term elastic modulus E_L of the material very precisely. Most polymer exhibit large creep strains at room temperature and at low stress levels. At higher temperature or large stresses, creep behavior becomes more critical. Generally, highly cross-linked thermoset polymers exhibit lower creep strains as compared to thermoplastics (Mallick, 2008). Miller and Sterrett (1988) have examined eleven analytical expressions used for creep data and reported to what extent they fitted experimental data available in literature. The material investigated were acetal, acrylonitrile butadiene styrene (ABS), Nylon 6/6, Polyethylene (PE), Polypropylene (PP), Poly Vinyl Chloride (PVC), Polyurethane (PU) and thermoplastic Polyurethane Elastomer (TPUE) (Lacroix, et. al, 2007). The data obtain from creep test are often used for the design life prediction of the material under elevated or specific temperature. They provide relationship between the rupture time (hrs), stress (psi) and temperature (^{o}C) (Aktaa & Schinke, 1996).

2.2.5 Boltzmann-Volterra Superposition Principle

The Boltzmann–Volterra linear hereditary creep theory is commonly used for characterizing the time-dependent properties of viscoelastic materials (Riande, 2000). The stress-strain relationship in the simplest loading case of creep is given by Equation 2.9 (Maksimov, et. al. 1975):

$$\varepsilon = J_o \sigma(t) + \int_0^t J_t(t-\tau) \frac{d\sigma(\tau)}{d\tau} d\tau \qquad \text{Equation 2.9}$$

Where,

J_o = Time independent Creep Compliance

J_t = Time Dependent Creep Compliance.

<u>2.3 Use of Standards on Design and Testing</u>

There are several test methods for evaluating long term properties of materials, including ASTM D 2990, ISO 899-1-03, and ASTM F1216.

2.3.1 ASTM D2990-01

ASTM D2990-01 Standard Test Methods for Tensile, Compressive and Flexural Creep and Creep Rupture of Plastics describe the measurement of creep and creep-rupture properties of plastics under specific environmental conditions, mainly temperature and humidity. The method is a good reference as it describes the test apparatus and calculations, includes the background discussion on basic concepts.
The standard outlines the test procedure for determining the long-term tensile & flexural creep modulus. While the ASTM specification governing these tests does not specifically state an amount of time that samples must remain under load.

2.3.2 ISO 899-1-03

ISO 899 Parts 1 and 2 address the same subject, but differ in technical content (and results cannot be directly compared between the two test methods). ISO 899 Part 1 addresses tensile creep and creep to rupture and ISO 899 Part 2 addresses flexural creep. Compressive creep is not addressed in ISO 899. ASTM D2990 does not specify the test load for the samples, whereas ISO specifications also do not specify the test loads for the samples. 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.

ISO 899-1-03 Plastics – Determination of Creep Behavior – Part 1: Tensile Creep is discusses method for determining the tensile creep of plastics in the form of standard test specimens under specified conditions such as those of pretreatment, temperature, and humidity. The method is suitable for use with rigid and semi-rigid non-reinforced, filled and fiber-reinforced plastics materials in the form of dumb-bell-shaped test specimens molded directly or machined from sheets or molded articles.

ISO 899-2-03 Plastics – Determination of Creep Behavior – Part 2: Flexural Creep by three-point loading specifies a method for determining the flexural creep of plastics in the form of standard test specimens under specified conditions such as those of pretreatment, temperature, and humidity.

2.3.3 ASTM F1216 Design Principle

ASTM F 1216-2009 describes the procedure for the renewal of pipelines and conduits in 4 to 108 in. (100 to 2,700 mm) diameters 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 reconstruction process can be used in a variety of gravity and pressure applications such as sanitary sewers, storm sewers, process piping, electrical conduits, and ventilation systems. F 1216 design equations are often used for evaluating the design parameters for successful renewal of pipes. Polyurea is a different material compared to CIPP; however, general design equations can still remain the same with some modifications. The appendix in the ASTM standard provides the design criteria for design partially and fully deteriorated pipe conditions considering the various load factors such as soil, water, and live load see Figure 2.5 & 2.6.

For partially deteriorated pipe condition, a polyurea installed in an existing water pipe is designed to enhance support for external hydrostatic loads due to groundwater as well as to withstand the internal pressure in spanning across certain holes in the existing pipe wall. The original pipe can support the soil and surcharge loads throughout the design life of the renewed pipe. The soil adjacent to the existing pipe must provide adequate side support. The pipe may have longitudinal cracks and up to 10.0% distortion of the diameter.

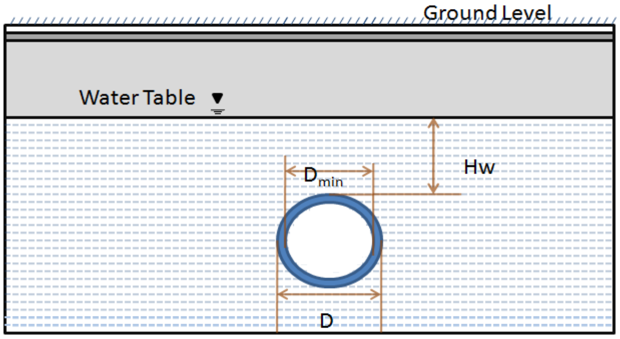


Figure 2.5 - Partially Deteriorated Design Example (Najafi & Gokhale, 2005)

For fully deteriorated condition, the original pipe is not structurally sound and cannot support soil and live loads nor is expected to reach this condition over the design life of the renewed pipe. This condition is evident when sections of the original pipe is missing, the pipe has lost its original shape, or the pipe has corroded due to the effects of the fluid, atmosphere, soil, or applied loads.

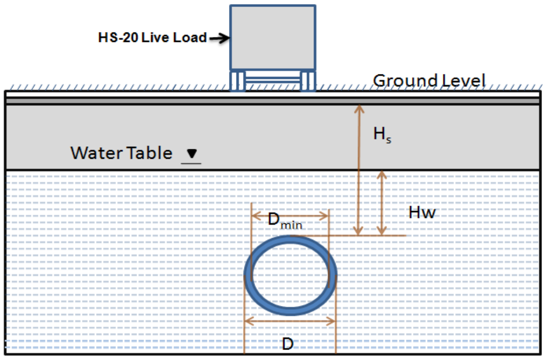


Figure 2.6- Fully Deteriorated Design Example (Najafi & Gokhale, 2005)

ASTM F1216-2009, proposed Equation 2.10 for determining the thickness of liner material for partially deteriorated pressure pipe.

$$t = \frac{D_o}{\left(\frac{2KE_LC}{P_WN(1-\upsilon^2)}\right)^{\frac{1}{3}}+1}$$

Equation 2.10

Where,

D_o = Mean Outer Lining Diameter, in.

K = Enhancement Factor, Typically K = 7

C = Ovality Correction Factor, dimensionless

P_w = External Water Pressure Measured above the Pipe Invert, psi

N = Safety Factor, Typically N = 1.5 to 2.0

t = Thickness of Polyurea, in.

υ = Poisson's Ratio, Typically υ = 0.3, dimensionless

E_L = Long-term Modulus of Elasticity (time-corrected) of Polyurea Lining

To Calculate Percent Pipe Ovality (q) using Equation 2.11 for Polyurea:

$$q = \left(\frac{\text{Mean Diameter - Minimum Diameter}}{\text{Mean Diameter}} \right) \times 100$$ Equation 2.11

To calculate Ovality Reduction Factor (C) for Polyurea using Table 2.2:

Table 2.2 - Typical Ovality Factor ‘C’ for Partially and Fully Deteriorated Conditions

Ovality q, %	***0.0***	***1.0***	***2.0***	***4.0***	***5.0***	***6.0***	***8.0***	***10.0***
Factor C	1.00	0.91	0.84	0.70	0.64	0.59	0.49	0.41

Selection of E_L, long-term modulus of elasticity for polyurea composite is one of the objectives of this study. The selection of E_L depends on the design life of the material, for example if the design life of this material is 50 years, corresponding value of E_L will be for that period of time.

2.4 Past Research on Lining

Over the past decades, many researchers have carried out a great deal of research works on the ageing of polymer materials obtaining some good results (Joachim, et.al, 1999). The behavior of liner materials encased in a host pipe is complex to analyze. To study the liner behavior under varying internal pressure and vacuum, it is important to investigate the influence of these different parameters on material behavior. Polymer materials are known to exhibit viscoelastic behavior, i.e. creep. Polymer liner performance is affected by creep behavior of the material. Creep strains in polymers its matrix are dependent upon the percent of creep rupture stress induced in a member and temperature. However, there is very little published data demonstrated especially how liner products perform over an extended period of time under actual service conditions (Thomson, et.al. 1995).

Several methods of predicting the long-time deformation properties of polymeric materials are now known (Urzhumtsev, 1971). These methods are primarily based on the mathematical modeling of the creep process with subsequent extrapolation on a series of experimentally established analogies such as superposition. Several investigations have presented different approaches to creep characterization (Findley & Gautam, 1956). Generally approaches to determine the creep behavior of polymer can be divided into theoretical and experimental methods. In the 19th century, physicists such as Maxwell, Boltzmann, and Kelvin have researched and experimented with creep and recovery of rubbers.

2.4.1 Tensile Creep Test on Filled Polychloroprene Elastomer

Tensile creep test was carried out by (Lacroix, et.al, 2007) on elastomeric polychloroprene at four different temperatures at stress level of 58, 87, 116, 145 psi respectively. The experiment was conducted over a time period of twelve hours at temperatures 20, 40, 80 and 110^{o}C. For each set of experimental conditions, at least three samples were used and data was represented. The creep data plotted on semi-log scale and was fitted by four parameter equation (Equation 2.12).

$$\frac{(\varepsilon(t)-\varepsilon_o)}{(\varepsilon_\infty-\varepsilon_o)}=\frac{1}{(1+(k_1/t^n))} \qquad \text{Equation 2.12}$$

Equation 2.12 contains ε_o, ε_∞, k_1 and n; ε (t) is value of strain at any time t. the parameters ε_o, and ε_∞ can be considered to be the limiting values of strain at zero and infinite time respectively. The values obtained for four parameters equation using Kaleida Graph Software are presented in Table 2.3.

Table 2.3 - Coefficients for Four Parameter Equations at 20^{o}C (Lacroix, et.al, 2007)

Stress, psi	ε_o	ε_∞	k_1	*n*
58	10.286	18.325	1.4796	0.30236
87	13.741	38.861	1.4796	0.30236
116	21.72	53.547	1.4796	0.30236
145	42.75	74.887	1.4796	0.30236

The test concluded that the behavior of creep of polychloroprene depends on the structure and on the molecular mobility of the chains when stress is applied. The material is hyper-elastic which enables it to cumulate large recoverable deformations at the end of relatively short times which are, at least, long according to the level of undergone deformations.

2.4.2 Creep Test of Cured-In-Place Pipe Material

Long-term tensile, compression and bending test was performed on Cured-in-Place-Pipe (CIPP) for 3,000 hrs at Louisiana Tech University, Ruston. Findley's equation, log-fit method was used as a baseline to predict the life of CIPP material. ASTM F 1216-93 Standard Practice for Rehabilitation of Existing Pipelines and Conduits by the Inversion and Curing of Resin Impregnated Tube is often used as a basis for design of CIPP liner materials. The tests were conducted based on ASTM D 2990-77 Standard Test Method for Tensile Compressive and Flexural and Creep Rupture of Plastics.

The apparatus used were bending table, lever loading and support structures for conducting the test. For the bending test four stress levels were selected 1,000 psi, 2,000 psi, 3,000 psi, 4,000 psi and for each stress two specimens were tested and summary of results are presented in Table 2.6. Similarly, for tensile test four stress levels were selected for the tests, 1,000 psi, 1,500 psi, 2,000 psi and 2,500 psi and for each stress two specimens were tested and summary of results are presented in Table 2.4 & 2.5. The results obtained from 3,000 hours testing done are as follows.

Table 2.4 - Bending Creep Modulus at Different Times (Lin, 1995)

Stress, psi	***E_o (psi)***	***E_t (psi)***	***E_t (psi)***	***E_t (psi)***
	0.0167 h	***1 h***	***1000 h***	***3000 h***
1,000	488,505	449,935	328,425	285,215
2,000	486,330	444,280	300,005	254,765
3,000	458,490	417,310	273,035	230,695
4,000	452,690	411,075	255,200	181,975

Table 2.5 - Tensile Creep Modulus at Different Times (Lin, 1995)

Stress, psi	***E_o (psi)***	***E_t (psi)***	***E_t (psi)***	***E_t (psi)***
	0.0167 h	***1 h***	***1000 h***	***3000 h***
1000	751,390	506,485	288,405	256,360
2000	510,255	393,095	258,390	243,745
3000	449,790	365,690	259,260	243,890
4000	374,970	337,270	255,635	239,685

The results obtained from the long-term testing of 3,000 hrs concluded that the flexural creep modulus is 44.2% of short-term flexural elastic modulus. Similarly average tensile creep modulus is 37.7% of short-term tensile elastic modulus.

2.4.3 AQUA-PIPE Cured-in-Place-Pipe (CIPP) Resin Project

The Centre for the Advancement of Trenchless Technology (CATT) conducted a series long-term on Cured-in-Place Pipe (CIPP) material for the City of Toronto. The long-term flexural tests were carried out to determine the creep performance and the creep retention factor. The flexural creep test was performed according to ASTM D 2990-01. The initial load selected for the test was 25% of yield stress determined using ASTM D 790. Observed test data were use to predict the design life for 50-year (Knight, 2005).

Six test specimens were water jet cut from resin plate of approximately 3.63 in. (92.1 mm) long by 0.76 in. (19.2 mm) wide by 0.181 to 0.189 in. (4.8 mm to 4.6 mm) deep. The test results for two specimens at 1,000, 3,000, 6,000 and 10,000 hrs are summarized and shown in Table 2.6 & Table 2.7. Figures 2.7 and 2.8 show the vertical deflection and the creep modulus for the 10,000 hour of load application.

Table 2.6 - Flexural Creep, Deflection & Strain for Specimen 1 (Knight, 2005)

Sample	*Time (hours)*	*Deflection (mm)*	*Strain ε (%)*	*Creep Modulus E_F (psi)*
S1-1	1,000	1.041	0.49	175,588
S1-1	3,000	1.224	0.58	149,359
S1-1	6,000	1.346	0.64	135832
S1-1	10,000	1.461	0.69	125,202

Table 2.7 - Flexural Creep, Deflection & Strain for Specimen 2 (Knight, 2005)

Sample	*Time (hours)*	*Deflection (mm)*	*Strain ε (%)*	*Creep Modulus E_F (psi)*
S1-2	1,000	1.486	0.70	128,469
S1-2	3,000	1.791	0.84	106,602
S1-2	6,000	1.918	0.90	99,542
S1-2	10,000	2.085	0.98	91,540

Three different values of creep modulus values are given in Table 2.8 for two specimens. They include modulus values based on:

- Measurements at 10,000 hours
- ASTM D 2990 50-year creep modulus
- Equal weighted 50-year creep modulus.

Table 2.8 - Creep Modulus at 10,000 hours and Estimated 50-year Modulus (Knight, 2005)

Sample	*10,000 hours Test Data (psi)*	*Regression of all 10,000 hours Test Data (psi)*	*Regression of 1,000 hours Test Data (psi)*
S1-1	175,855	118,477	69,090
S1-2	129,178	78,863	52,978

The long-term flexural results concluded that the creep modulus obtained for the 50 years design life was 50% the modulus of short-term. Industries standard creep retention factors are 0.5 for thermoplastic CIPP resins, 0.35 for polyvinyl chloride (PVC), and 0.2 for polyethylene (PE) pipe materials. Creep retention behavior for CIPP under sustained flexural loading appears to be similar to PVC and PE pipe materials (Knight, 2005).

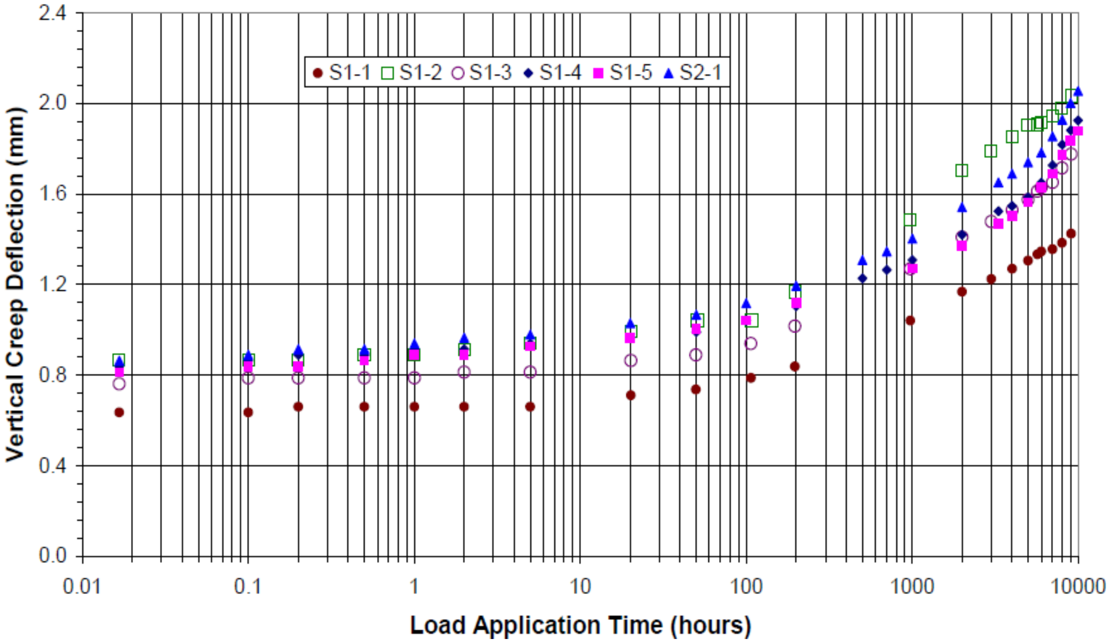


Figure 2.7 - Vertical Creep Displacement for CIPP up to 10,000 hrs of Continuous Loading (Knight, 2005)

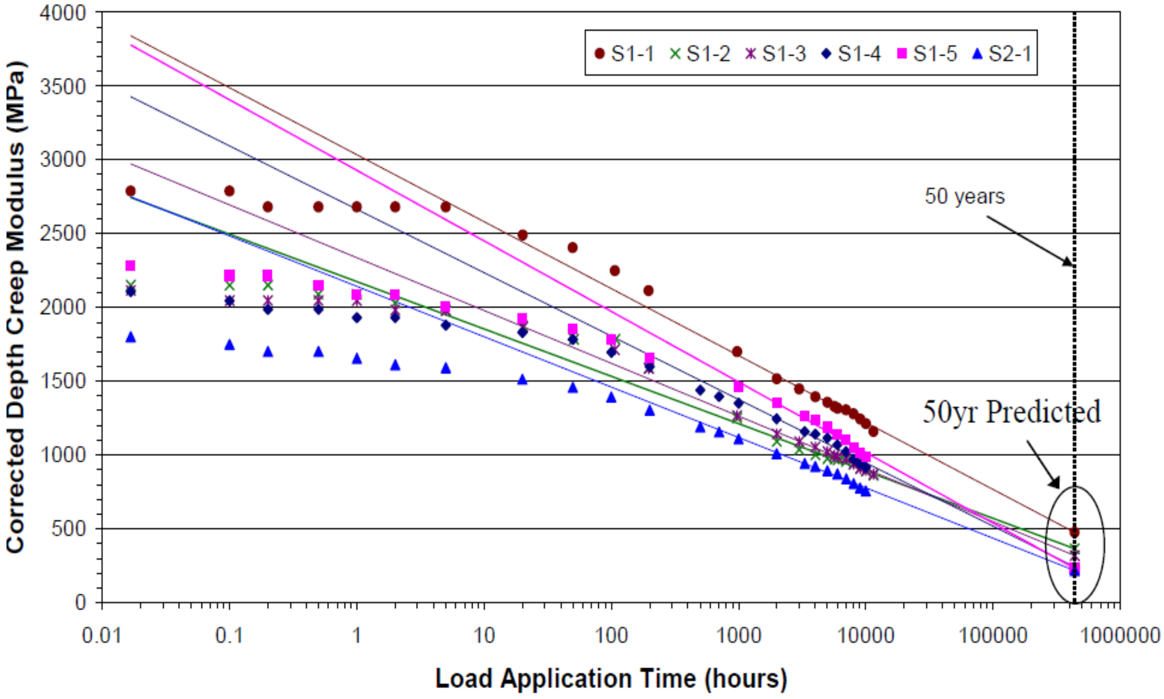


Figure 2.8 – 50-Year Creep Modulus of CIPP using Regression Analysis of 1,000 hrs (Knight, 2005)

2.5 Chapter Summary

This chapter provides an overview of several methods, models and past research carried out for predicting the long-time deformation properties of polymeric materials. Monitoring of the structural behavior of piping system is a significant issue for water company operators and managers. Design life analysis has always been interdisciplinary, because an effective analysis needs to bring together a thorough knowledge of the operating characteristics of the material, structural and mechanical behavior. The major technical barrier preventing the widespread use of polyurea composite is lack of long-term strength and performance data. One of the most important aspects of long-term durability and dimensional stability of polyurea material is their long-term creep behavior.

CHAPTER 3

EXPERIMENTATION

3.1 Introduction

This chapter illustrates the test apparatus used, test specimens and experimental procedure followed for carrying out the long-term testing. The selection of material dimensions and experiment procedure was followed using ASTM standard D2990, D638 and D790. The test apparatus designed for conducting the long-term creep test was custom fabricated and this set-up was according to the ASTM requirements. The aim here is to predict the long-term behavior of polyurea for a proposed application, using the experimental data. Most of the polymers used have desirable mechanical properties which are considered very important for various applications. Thus conducting long-term creep test on these materials gives an elementary knowledge of their mechanical behavior. Polymers have strong dependence on temperature and time on their properties as compared to other materials like metals. This strong dependence of polymer properties on temperature and how rapid the material deforms is a result of the viscoelastic nature of polymer.

The creep behavior of polymer composites, either at ambient or at higher temperatures, has become a topic of considerable interest, primarily because these materials have a high potential for use in structural applications at various temperatures. The dimensional solidity of polymers exposed to constant load for long periods of time is mainly determined by their resistance to creep. Thus, the acquisition of creep data and their quantitative analysis, prediction, and/or extrapolation remain important tasks of polymer research.

3.2 Test Specimens

The test specimen used for this particular long-term testing are three types of elastomeric polyurea composite. These test samples were provided by the manufacturing company naming it as Scotchkote 269, Scotchkote 169 and Scotchkote 169HB. All the three composites had different mechanical properties where 269 samples are medium build polyurea material and 169 and 169HB are high build materials. Figures 3.1 & 3.2 show the tensile and flexural specimen used for this testing.

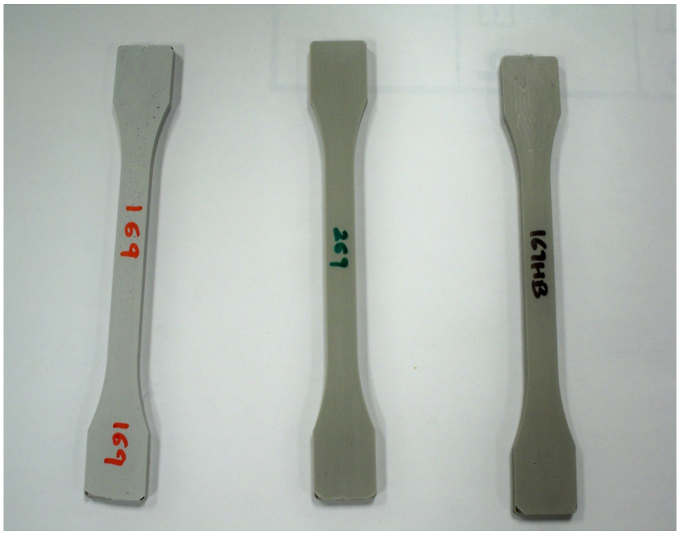


Figure 3.1 - Specimen for Tensile Creep Test

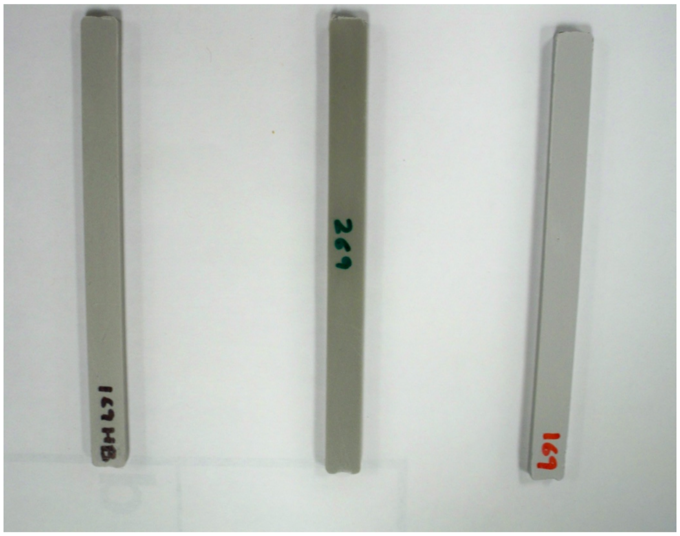


Figure 3.2 - Specimen for Flexural Creep Test

3.3 Tensile Creep

3.3.1 Introduction

All polymeric material has a tendency to deform or “creep” when subjected to loading. The time-dependence of such deformation behavior can be determined by standardization tests like tensile creep and flexural creep tests. Among the most important mechanical properties of any elastomeric polymer material, are tensile strength and tensile modulus. Tensile creep measurements are made by applying a constant load on the test specimen and measuring its elongation with time. This elongation can be carried out in several ways. The most accurate and simplest way is the use of strain gages which is capable of measuring and amplifying small changes in length with time and directly plotting them on a graph paper. The percent tensile creep strain is determined by dividing the change in length by the initial gage length and multiplying by 100. The percent tensile creep is plotted against time to obtain a tensile creep curve. The tensile strain values are determined at specified time intervals like 1, 6, 12, 30 min; 1, 5, 20, 50, 100, 500, 1,000 hours, to facilitate plotting a creep rupture curve.

3.3.2 Tensile Creep Apparatus

The apparatus designed for conducting the tensile creep test was custom fabricated and used a simple loading mechanism at constant temperature. The test frame was designed using Mild Steel (MS) angle frames of 2 in. x 2 in. (50 mm x 50 mm) machine welded. The table is designed to test 12 specimens with each sample bolted to MS square plates of 2 in. x 2 in. (50 mm x 50 mm). The plates were chamfered from inside to hold the specimen avoid slippage during the experiment. Strain gages were used to measure the strain at specific time intervals, according to ASTM D 2990 standard. The strain gage selected for the test was EA-06-250BF-350 with a strain range of +5%. GAK-2-AE-10 strain gage application kit was used to fix the strain gage to the specimen and was soldered to the terminal wire. Strain gages were mounted axially along the length of the specimen as shown in Figure 3.3.

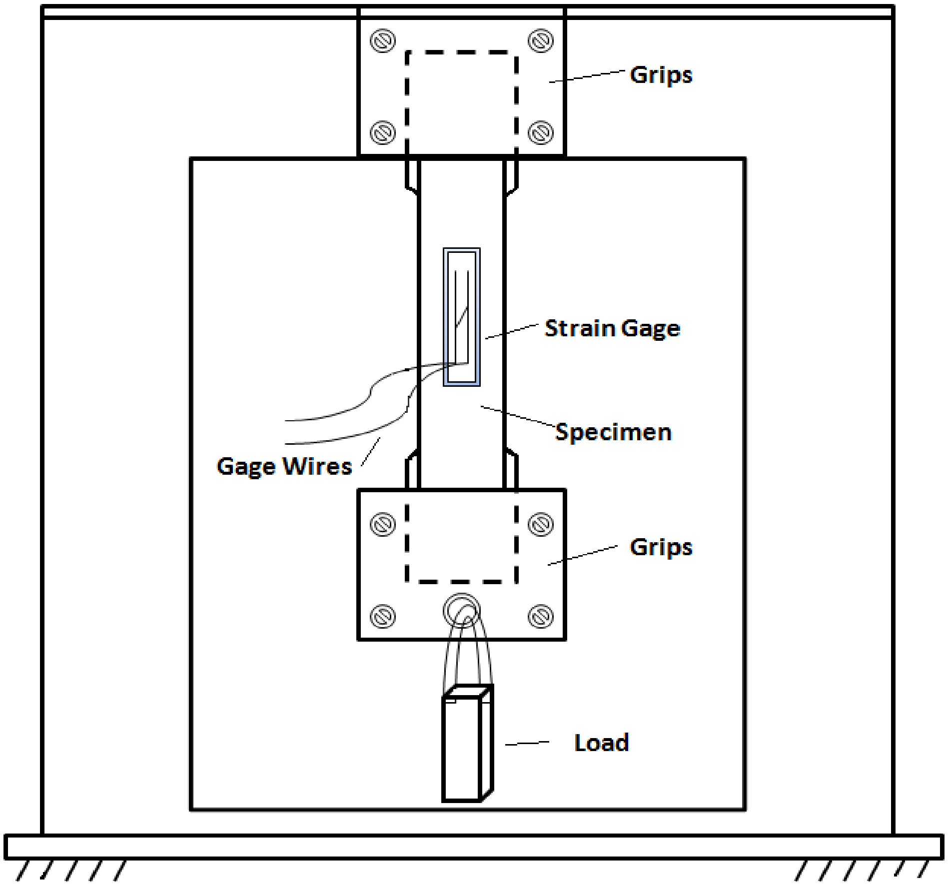


Figure 3.3 - Pictorial View of Tensile Creep Apparatus

3.3.3 Tensile Test Specimens

The specimens were prepared by the manufacturer based in on the ASTM D 638-03 specifications. Three composition of polyurea specimens were selected for conducting this test. The purpose of selection of three different specimens was to understand the behavior of polyurea based on variation in the composition. Dumbbell shaped specimens with identical dimensions for all the three compositions were selected. The load selection for the long-term tensile creep test was done on the basis of trail test carried out on the same type of specimens. The test specimen matches the dimensions as illustrated in Figure. 3.4.

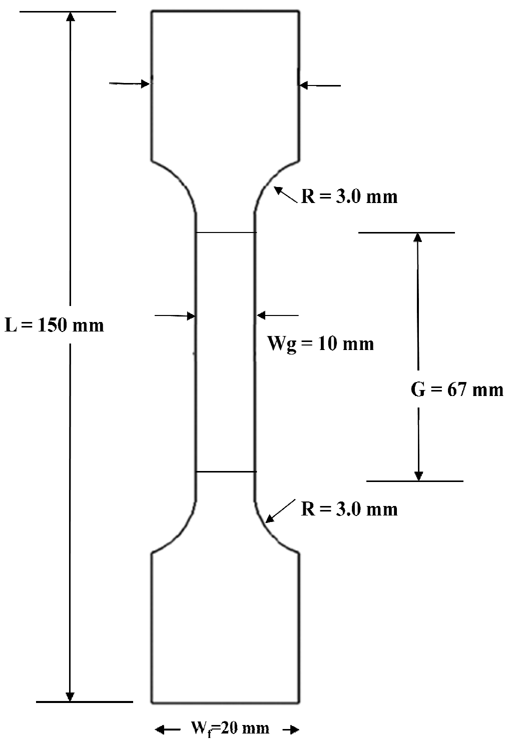


Figure 3.4 - Specimen for Tensile Creep Experiment

3.3.4 Experimental Procedure

Polyurea composite specimens were subjected to tensile and creep test to determine the mechanical properties. Comprehensive summary of testing procedure is listed below.

1. The dimensions of the specimen such as the total length, gage length, width and thickness were measured at three different locations. Cross-sectional area was calculated from average width and thickness.
2. The strain gages were mounted on the specimens using conditioner, neutralizer and degreaser. The purpose is to develop a chemically clean surface having a roughness appropriate to the gage installation requirements. For specimens tested here, strain gages were axially mounted at mid-span along the length as shown in Figure 3.5.
3. Then the specimens were centrally aligned between the steel plates of the custom built frame ensuring uniform force distribution.

4. Strain gages were connected to the strain indicator unit with connecting wires.
5. Data was recorded for strain variations during the test. Experimental values of tensile strain and modulus was calculated. This procedure was repeated for all the specimens.
6. Graphs of strain versus time for each specimen were plotted.

Figure 3.5 - Scotchkote 269 Specimen Tested for Tension

3.3.5 Tensile Creep Test Calculations

Tensile Stress (σ) - The tensile load applied per unit area of initial cross-section within the gauge length (Equation 3.1).

$$Tensile\,Stress\,(\sigma) = \frac{Force\,(P)}{Initial\,Cross\,Sectional\,\,Area\,(A)} \qquad \text{Equation 3.1}$$

Where,

F = Applied Force, lbs

A = Average initial Cross-sectional Area within the Narrow (Gauge) Section of the Specimen, in^2

Extension (ΔL) – Increase in the distance between the gauges mark (Equation 3.2).

Elongation Equation

$$Extension(\Delta L) = L_t - L_o \quad \text{Equation 3.2}$$

Where,

L_t = Gauge Length at any Given Time ‘t’ During the Test, in.

L_0 = Original Gauge Length of the Specimen Prior to Application of the Load, in.

Tensile Creep Strain (εt) - Change in the length between the gauge marks, with respect to original length, produced by the applied load at any given time ‘t’ during a creep test.

3.4 Flexural Creep

3.4.1 Introduction

Flexural loading is one of the most common types of loading experienced in practice. It is highly significant for determining bending characteristics values of polymer. Under flexural loading, the various deformation components have to be considered that are dependent on time and load. Depending on the type of polymer, linear-elastic, linear-viscoelastic, non-linear viscoelastic and plastic deformation components also occur. The ratio of deformation components to total deformation depends on the particular polymer as well as on loading conditions. The results obtained in the flexural test are the function of deformation, strain rate, load or stress, temperature and the internal state of the specimen. The result obtained in the flexural test is standardized in accordance to ASTM D 2990 appendix. The structural deficiencies in the specimens, eccentric fracture can occur under three-point loading system; as long as fracture occurs in the median of the specimen that is adequate for value. Creep flexural test using three-point bending systems are preferably performed for polymers with low flexural strain at break. According to the ASTM a three-point bending test for flexural creep is performed as per Figure 3.6.

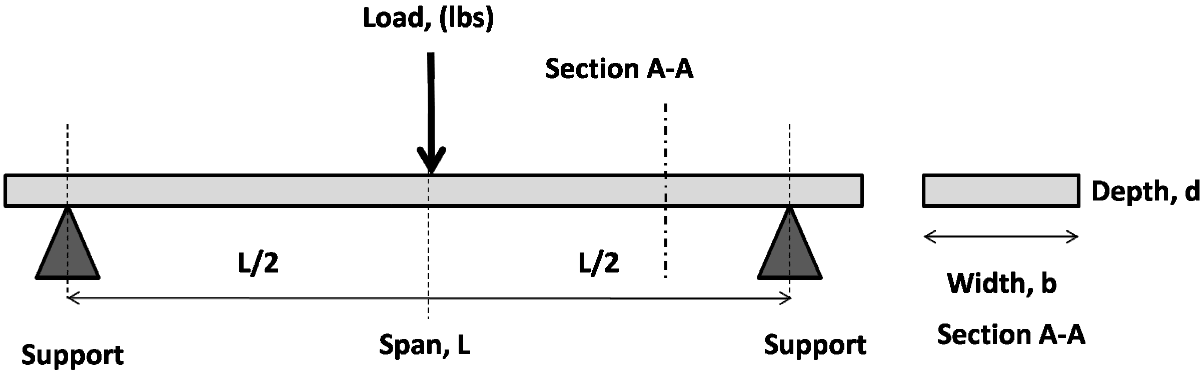


Figure 3.6 - Schematic Diagram of Flexural Creep Test

The maximum fiber stress for each specimen in lb/in^2 was calculated using Equation 3.3:

$$\sigma = \frac{3.P.L}{2.b.d^2}$$ Equation. 3.3

Where, S = Stress, psi,

P = Load, lbf,

L = Span, in.

b = Width, in.

d = Depth, in.

According to the ASTM the maximum strain in the outer fiber of the mid-span is given by Equation 3.4:

$$\varepsilon(t) = \frac{6.\Delta.d}{L^2}$$ Equation 3.4

ε (t)= Maximum strain, in./in.

Δ = Maximum deflection at mid-span, in.

d = Depth, in. and

L = Span, in.

Multiplying the strain ε(t) by 100 to obtain the percentage strain at specific time interval.

Flexural creep modulus for the specimen at any time during test is given by Equation 3.5:

$$Flexural\ Creep\ Modulus\ (E_F) = \frac{L^3 . P}{4b.d^3.\Delta} \qquad \text{Equation 3.5.}$$

Where;

L = Initial Distance between the Test Specimen Supports, in.

P = Applied Force, lbs

b = Width of the Test Specimen, in.

d = Thickness of the Specimen, in.

Δ = Deflection at Mid-span at Time ‘t’, in.

3.4.2 Flexural Creep Test Apparatus

The apparatus fabricated for conducting the flexural creep test was designed to be variable for different specimen dimensions. The test frame was machine wielded using mild steel angle frames, and steel clamps. The test frame made of Mild Steel (MS) angle of 2.0 in. x 2.0 in. (50 mm x 50 mm) wielded together to form a table of size 32.5 in. x 34.5 in. 36.5 in (813 mm L x 864 mm W x 915 mm H). The table is designed to accommodate 8 specimens with each sample resting on a pair of MS rods of diameter 0.5 in. (12.5 mm). The rods were bolted and rested on the steel frame with grooves on the top for variable specimen thickness. The clamp made of MS flat plate of 1 in. (25 mm) width with long bolts to rest the clamp on the frame and having arrangement to hold the dial gauge. The specimen was rested on the rods with at a distance of 16 times the thickness of the sample to be tested. The load selected for each sample for hanged at the center with a string with the tip of the dial indicator resting on the center of the sample and on the string. The range of the dial indicator was selected such that the sample when deflected maximum should not loose contact between the dial indicator and the specimen, as shown in Figure 3.7.

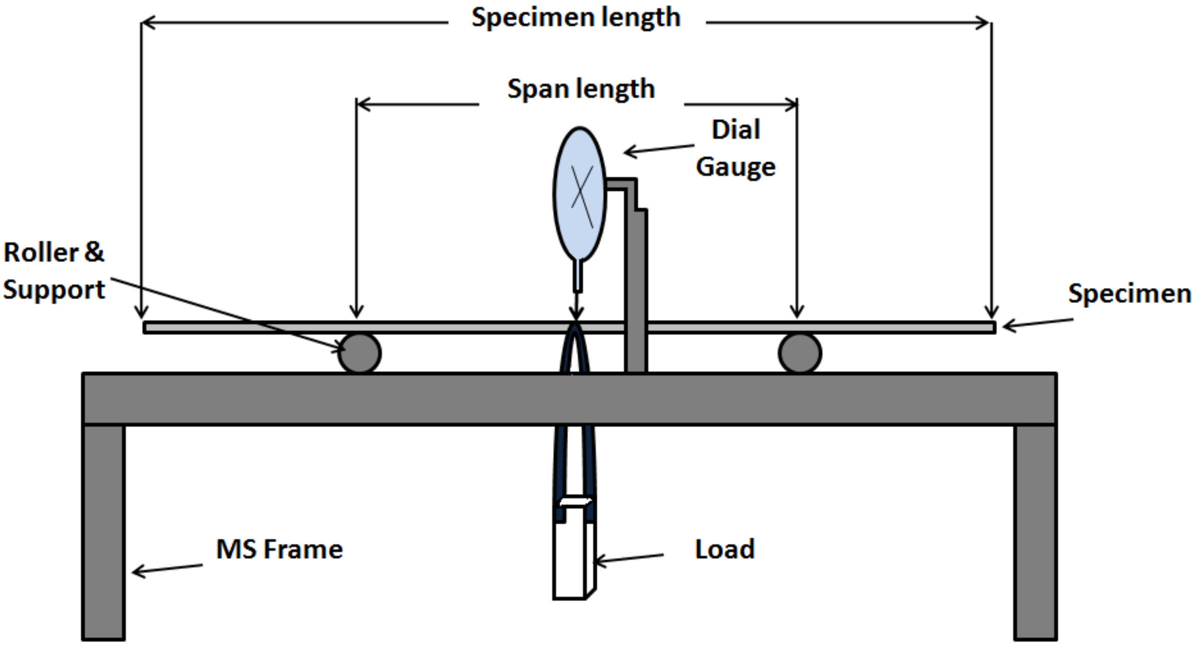


Figure 3.7 - Schematic View of Central Point Bending Setup

An accurate dial gauge (Table 3.1) was mounted on the clamp with the tip of the gauge resting on the center of the polyurea specimen.

Table 3.1 - Dial Gauge Specifications

Manufacturer	*Model Number*	*Readings in. (mm)*	*Dial Reading in. (mm)*	*Range in. (mm)*	*Ring Diameter in. (mm)*
Tresna Instrument	321-141D	0.0004 (0.01)	0 – 4 (0 - 100)	2 (50)	3.2 (80)
Tresna Instrument	321-237D	0.0004 (0.01)	0 – 4 (0 - 100)	2 (50)	2.4 (60)
Prestige Plus	21881255	0.0008 (0.02)	0 - 4 (0 - 100)	4 (100)	2.4 (60)

3.4.3 Specimen for Flexural Test

Three composite polyurea specimens were selected for conducting this test. The specimen dimensions were based in accordance to ASTM D790 specifications. The thickness of the all the specimens were 0.16 in. (4.0 mm). The dimensions of the flexural specimen are illustrated in the following

Figure 3.8. Similarly, the load selection for long-term creep test was done on the basis of trail test carried out on the same batch of specimens.

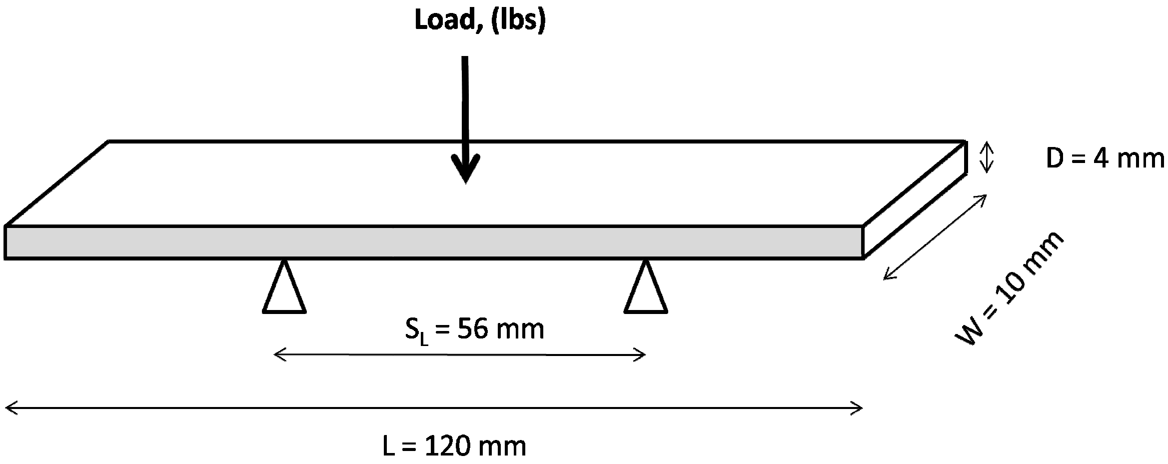


Figure 3.8 - Specimen for Flexural Creep Experiment

3.4.4 Experimental Procedure

Polyurea composite specimens were subjected to bending creep test to determine the mechanical properties. Comprehensive summary of testing procedure is listed below.

1. The flexural specimen with the thickness of 0.157 in. (4.0 mm) was placed on a three-point system, at a support at a distance of (16±1) times the thickness 2.20 in. (56 mm) of the specimen as shown in Figures 3.9 & 3.10.
2. The dimensions of the specimen were measured at three locations, at the two ends and center of the specimen to the nearest 0.00393 in. (0.01 mm).
3. The specimens were placed and tip of the dial gauge was rested on the center of the specimens.
4. The dial gauge was calibrated to zero. The dial gauge had graduations of 0.00393 in. (0.001 mm) and range of 2.0 in. (50 mm).
5. Full load was applied to the flexural specimen within 5 seconds and the corresponding deflection was recorded as per the ASTM specifications.

6. This procedure was repeated for each of the 169, 169HB and 269 specimens. Experimental values of flexural strain, and flexural modulus for each specimen were calculated and tabulated.
7. Typical load-deflection curve for these specimens were plotted.

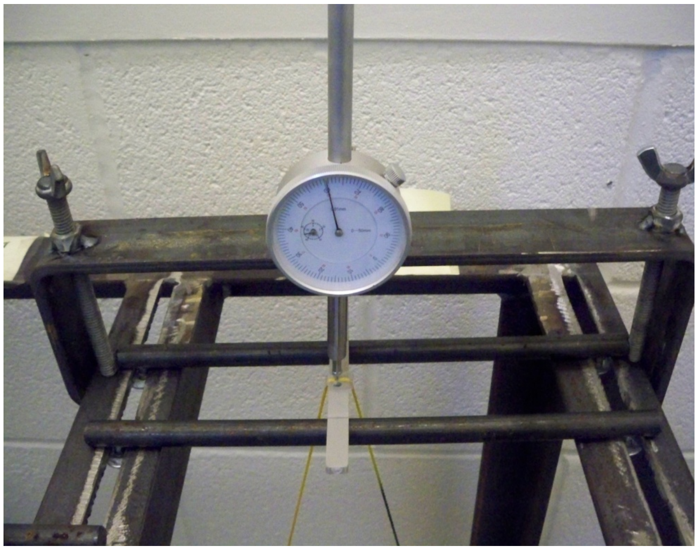


Figure 3.9 - Scotchkote 269 Specimen Tested for Bending

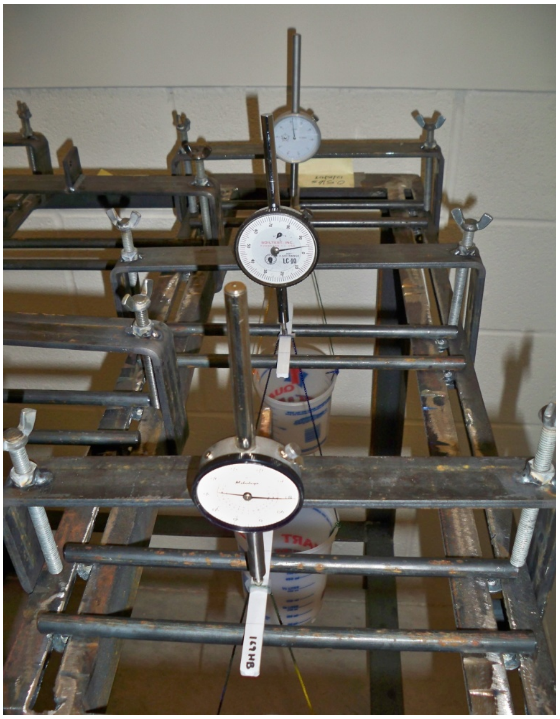


Figure 3.10 - Three-point Bending Creep Frame

3.5 Chapter Summary

This chapter provides an overview on the laboratory set-up for conducting the test and also the procedure followed for conducting the experiment. To characterize the creep behavior of polyurea, time-dependent material parameters and calculation guidelines were determined based on the standardized test specifications. In order to design long-term loaded component parts and products from polymers for reliability; information is required as to their material behavior under long acting static loading. An attempt to investigate these properties using long-term tensile and flexural test methodology is explained in the chapter.

CHAPTER 4

ANALYSIS OF EXPERIMENTAL DATA

4.1 Introduction

This chapter covers the various ways to analyze the experimental test results and using them to study the creep behavior of the polyurea lining material. Results and analysis of experimental data are presented in the form of tables and graphs. The most common method of displaying the interdependency of stress, strain and time is by means of creep curves. The relationship between creep strain and time indicates an important creep behavior of polymer materials. It can control the design strength and service life of any polymer.

The data collected through testing as shown in this chapter were used to life prediction of these composites; and also change in modulus with time was determined using the creep data which is useful for design purposes. The models were used for carrying out these studies are also described in this chapter.

4.2 Analysis of Tensile Creep Data

When a pipe is subjected to an internal pressure, tensile stress can occur in the pipe. Therefore, tensile creep is also a basic consideration in pipe design. Ten dumbbell shaped specimens of polyurea lining material were tested for tensile to determine the tensile properties of the material. Out of the 10 specimens used, 3 Scotchkote 169, 4 Scotchkote 169HB and 3 Scotchkote 269 were tested. The test was conducted in accordance to the procedure explained in Section 3.3.4. The data from the tests were used to obtain the tensile modulus and tensile creep strain. The tensile creep data were recorded for a period up to 1,000 hrs. The different polyurea specimens were loaded at different stress levels for the test.

The maximum strain in the fibers due to elongation of the tensile creep test can be expressed in terms of change in length by the original length of the specimen. Polyurea being a viscoelastic material can attain high elongation levels before rupture occurs. Ultimate elongation is the property that defines elastomeric materials. However, ultimate elongation still does not provide a precise indication of serviceability because service conditions do not require the polyurea material to stretch to any significant fraction of its ultimate elongation.

ASTM standard D2990 section 10.3 recommends the tensile stress should be such that it produces 1% strain in 1,000 hours. In tensile tests, it is recommended that the strain be limited to 5% (i.e. 0.1319 in. (3.35 mm) elongation) if the specimen does not fail before reaching this strain level. Table 4.1 lists the various loads selected for the different polyurea composite specimens based on the trail test carried out for 700 hours.

Table 4.1 - Load Selection for Various Polyurea Specimens

Polyurea Type	***Number of Specimens***	***Loads (lbs)***			
169	3	1.5	1.5	1.75	-
169 HB	4	2	2.5	3	3.5
269	3	2	2	3	-

The following table summarizes the ratio of applied constant stress by corresponding strain. Table 4.2 presents the stress values of various polyurea specimens along with their corresponding tensile strain at various time intervals.

The creep test results are presented in Figures 4.1, 4.2 and 4.3 highlighting the effect of stress on the response characteristic with time. The different graphs for creep strain data (%) versus time (hours) for 169, 169HB and 269 specimens tested can be obtained using constitutive relationship. It can be seen clearly that at higher stresses the failure is faster for all specimens.

Table 4.2 - Summary of Measured Tensile Strain at Various Time Intervals

Specimen	*Stress (psi)*	*Strain ε (%)*			
		100 hrs	*300 hrs*	*500 hrs*	*1000 hrs*
LF-1-169	24.194	0.0611	0.1114	0.1451	0.1717
LF-2-169	24.194	0.0391	0.0993	0.1262	0.2178
LF-3-169	28.226	0.0160	0.0639	0.1258	0.1737
LF-1-169HB	32.258	0.0369	0.0590	0.0944	0.1374
LF-2-169HB	48.387	0.1134	0.1319	0.1431	0.1837
LF-3-169HB	56.452	0.0547	0.0659	0.1017	0.1258
LF-4-169HB	40.323	0.0547	0.1403	0.1439	0.1805
LF-1-269	32.258	0.0752	0.1966	0.2577	0.2904
LF-2-269	32.258	0.0694	0.1664	0.2251	0.2947
LF-3-269	48.387	0.0570	0.1840	0.2570	0.3430

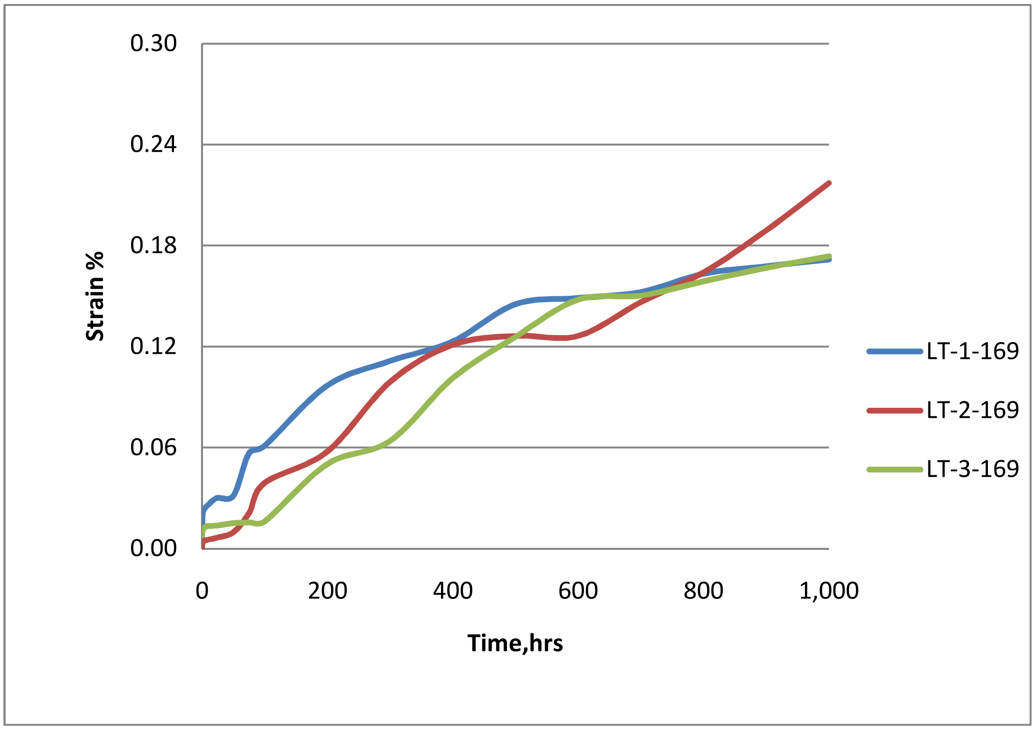


Figure 4.1 - Tensile Creep Strain ε in 169 Polyurea Specimens

Based on Figures 4.1 & 4.2 all test specimens demonstrated a similar tensile behavior except for specimen 269 in Figure 4.3. Specimen 269 showed significantly elongation and thus low creep modulus than the other specimens.

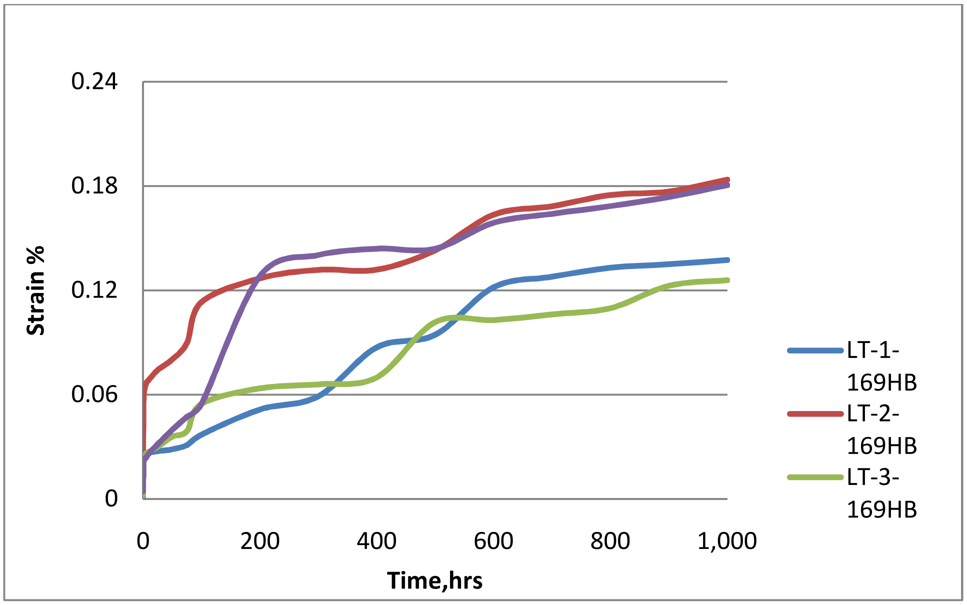


Figure 4.2 - Tensile Creep Strain ε in 169HB Polyurea Specimens

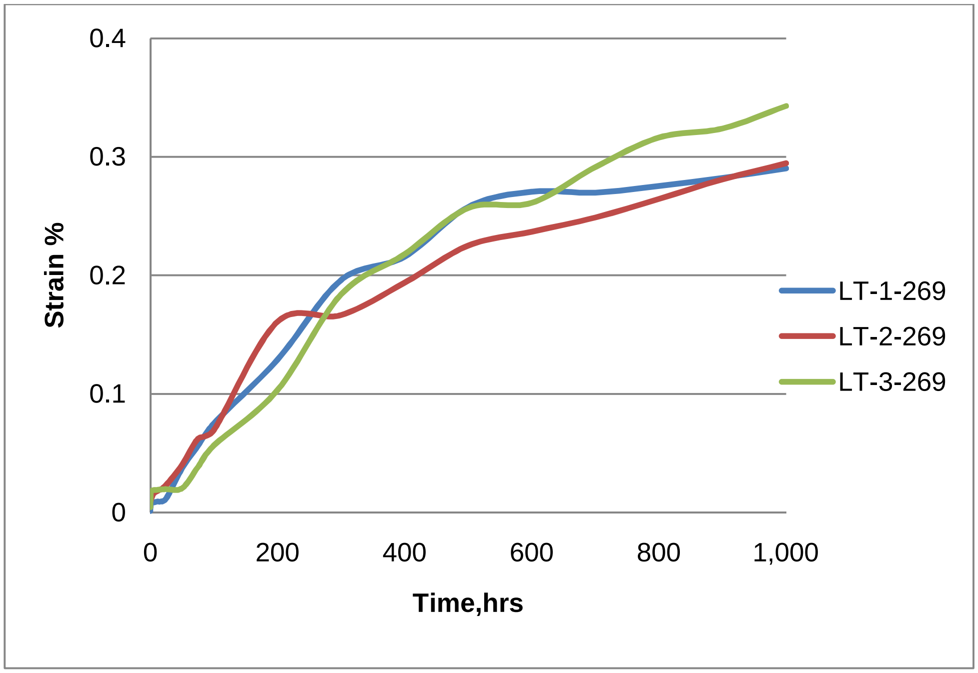


Figure 4.3 - Tensile Creep Strain ε in 269 Polyurea Specimens

The average short-term tensile modulus for the specimens tested is shown in Table 4.3. The following test results are provided by the manufacturer for the test carried out on same batch of specimens.

Table 4.3 - Summary of Short-term Tensile Modulus for the Polyurea Composite

Specimen	*Tensile Modulus 'E' (psi)*
Scotchkote 169	87,000
Scotchkote 169HB	87,000
Scotchkote 269	73,500

The following table summarizes the ratio of applied constant stress by corresponding strain. From the long-term testing the tensile modulus (E_T) for the specimen are presented in Table 4.4. Polymer composite specimen experienced large elongation under sustained load due to its creep characteristics and temperature sensitivity. Figures 4.4, 4.5 and 4.6 show the graphical variation of the flexural creep modulus data (psi) versus time (hours) for 169, 169HB and 269 specimens tested.

Table 4.4 - Summary of Measured Tensile Modulus E_T at Various Time Intervals

Specimen	*Stress (psi)*	*Tensile Creep Modulus E_T (psi)*			
		100 hrs	*300 hrs*	*500 hrs*	*1000 hrs*
LT-1-169	24.194	39,594	21,727	16,671	14,094
LT-2-169	24.194	61,877	24,364	19,167	11,144
LT-3-169	28.226	175,533	44,159	22,432	16,253
LT-1-169HB	32.258	87,222	54,588	34,146	23,463
LT-2-169HB	48.387	42,683	36,697	33,811	26,338
LT-3-169HB	56.452	103,255	85,626	55,505	44,865
LT-4-169HB	40.323	73,754	28,741	28,018	22,339
LT-1-269	32.258	42,896	16,407	12,519	11,114
LT-2-269	32.258	62,372	27,929	14,329	10,947
LT-3-269	48.387	84,889	26,297	18,837	14,107

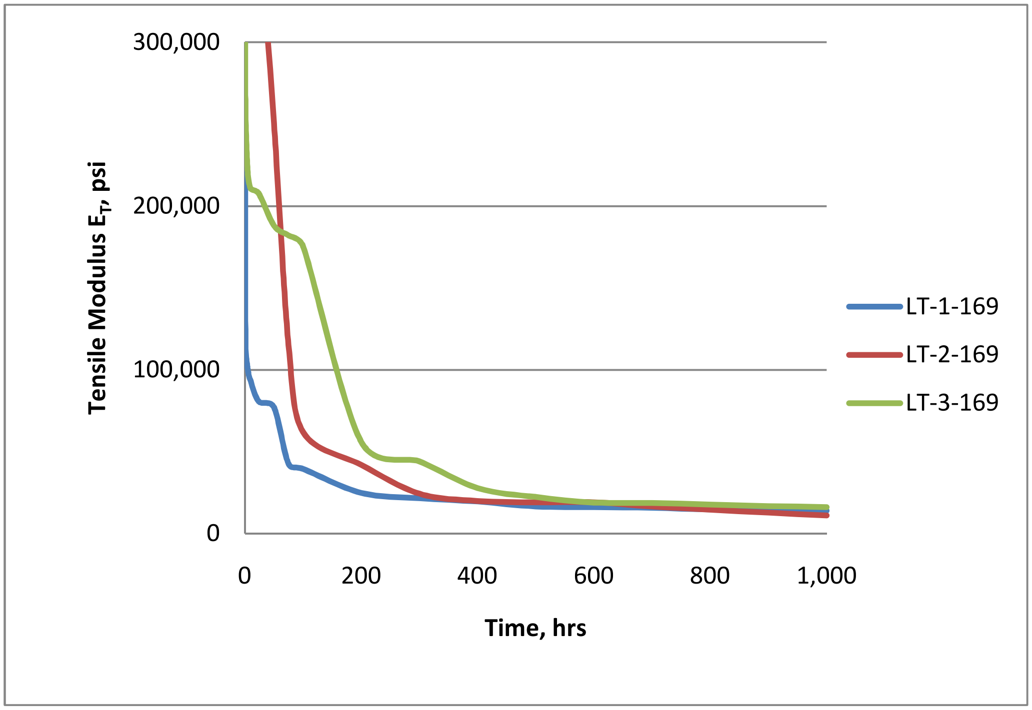


Figure 4.4 - Tensile Creep Modulus E_T versus Time at Various Stress for 169 Specimens

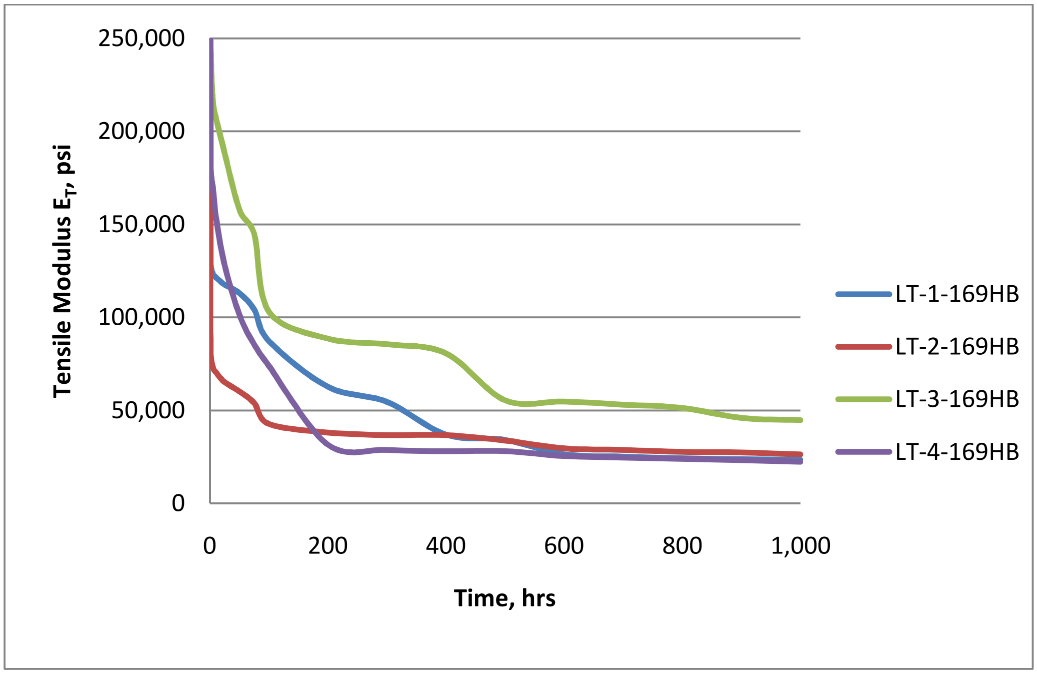


Figure 4.5 - Tensile Creep Modulus E_T versus Time at Various Stress for 169HB Specimens

The creep rate (creep modulus vs. load application time) was found to be linear from the application of the load to the first 500 hours. Following 500 hours the creep rate was observed to increase at a constant rate. Thus, in accordance with Figures 4.4, 4.5 and 4.6 secondary creep (Stage II) occurred up to approximately 150 hours of load application.

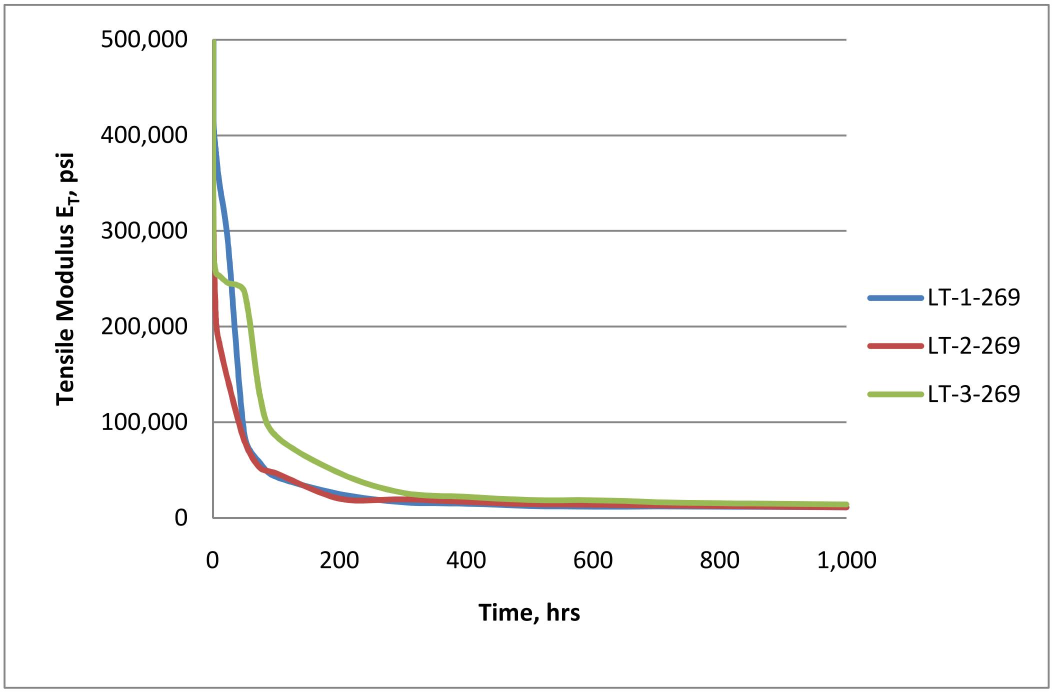


Figure 4.6 - Tensile Creep Modulus E_T versus Time at Various Stress for 269 Specimens

The level of stress had an effect on the change in creep modulus. At lower stress levels, the tensile elongation was higher for some of the specimen compared to same batch of the specimens with higher stress levels. The response of polyurea under typical stress levels depends on the rate of loading.

4.2.1 Summary of Tensile Creep Test Results

Pipe subjected to internal pressure, is under the influence of tensile stress. Therefore, tensile creep is a basic consideration in pipe design. In this study, tensile creep test was conducted as per Section 3.2. Different stress levels were selected for various polyurea composites. Experimental strain percent versus time were plotted as shown in Figures 4.1, 4.2 and 4.3.

The average tensile strain for Polyurea 169 specimens after 1,000 hrs was found to be approximately 0.002, for 169HB was 0.0015, whereas for 269 was 0.003. Similarly the tensile modulus after 1,000 hours for 169 specimens was 13,830 psi, for 169HB was 29,250 psi and for 269 was 12,056 psi. In the linear creep range, the average tensile creep modulus for 169 specimens is about 34% of short-term tensile modulus (87,000 psi), for 169HB is about 14% of short-term tensile modulus (87,000 psi) and for 269 specimens it is approximately 16 % of short-term tensile modulus (73,500 psi).

With reference to the above results, the creep strain rates decrease very rapidly at the initial stage and further deforms slowly after 500 hours of loading during the tests. It can be concluded that there is very little elongation for all the three composites and load needs to be increased to get appropriate strain and elongation. Also the elongation needs to be monitored for more number of hours to study their behavior.

4.3 Analysis of Flexural Creep Data

When a pipe begins to buckle, the pipe no longer keeps its shape in a circle, so the bending moment which exists in the pipe increases. Therefore, bending is one of the typical factors which could affect creep behavior of the pipe. Hence, it is necessary to investigate the viscoelastic behavior of the pipe material under flexure.

Eight specimens of polyurea lining material were tested for flexural in longitudinal directions to determine the flexural properties of the material. Three different composite of polyurea flexural specimens 169, 169HB and 269 were used for the test period up to 1,000 hrs. The different polyurea composite specimens were loaded at different stress levels. The specimens 269 and 169 were tested for three different loads, while the specimen 169HB was tested for two different loading conditions. The respective strains and flexural modulus for these specimens were calculated and tabulated based on the equations explained in Chapter 3.

Tests results were analyzed as per the ASTM D790 and ASTM D2990 specifications. The test was conducted in accordance with the procedure explained in section 3.4.4. The data from the tests were used to obtain the flexural modulus and flexural strength. Table 4.5 lists the various loads selected for the different polyurea specimens based on the trail test carried out for 700 hours. For the flexural measurements, Equations 3.3, 3.4 and 3.5 were just to determine the values of strain and modulus for different specimens. The maximum strain in the extreme fibers at the mid-span locations of the flexural creep test can be expressed in terms of mid-span deflection.

According to the ASTM the maximum strain in the outer fiber at the mid-span is evaluated using Equation 3.4. It is based on the assumption in the elementary theory of bending, namely plane section perpendicular to the longitudinal axis of the beam remain plane subsequent to bending. The flexural modulus of the material for the strain determine at time (t) is calculated using the Equation 3.5.

Table 4.5- Load Selection for Various Polyurea Specimens

Polyurea Type	***Number of Specimens***	***Loads (lbs)***	***Loads (lbs)***	***Loads (lbs)***
169	3	0.1	0.08	0.12
169 HB	2	0.1	0.12	-
269	3	0.1	0.08	0.06

Data obtained from the creep tests provided important information on the time-dependent response characteristics of the material. Traditionally, in the creep tests, the creep strain under a sustained load is recorded as a function of time. Using the above loads the test is performed for a period of 1,000 hrs. The creep test data are summarized in Table 4.6. Polyurea being a viscoelastic material can attain high strain levels before rupture occurs. ASTM standard D 2990 section 10.3 recommends that the basis for comparing the flexural creep material should be stress which produces 1% strain in 1,000 hours. In flexural tests, it is recommended that the strain to be limited to 5% if the specimen does not fail before reaching this strain level.

The creep test results are presented in Figures 4.7, 4.8 and 4.9 highlighting the effect of stress on the response characteristic with time. The different graphs for creep strain data (percent) versus time (hours) for 169, 169HB and 269 specimens tested can be obtained using constitutive relationship. It can be seen clearly that at higher stresses the failure is faster for all specimens.

Table 4.6 - Summary of Measured Flexural Strain at Various Time Intervals

Specimen	*Stress (psi)*	*Strain ε (%)*			
		100 hrs	*300 hrs*	*500 hrs*	*1000 hrs*
LF-1-169	33.871	0.070	0.100	0.130	0.160
LF-2-169	27.097	0.069	0.111	0.136	0.148
LF-3-169	40.645	0.088	0.145	0.176	0.193
LF-1-169HB	33.871	0.263	0.428	0.685	0.996
LF-2-169HB	40.645	0.201	0.400	0.534	0.652
LF-1-269	33.871	1.240	2.790	4.210	5.625
LF-2-269	27.097	1.350	1.588	2.258	3.444
LF-3-269	20.323	0.819	1.852	2.890	3.980

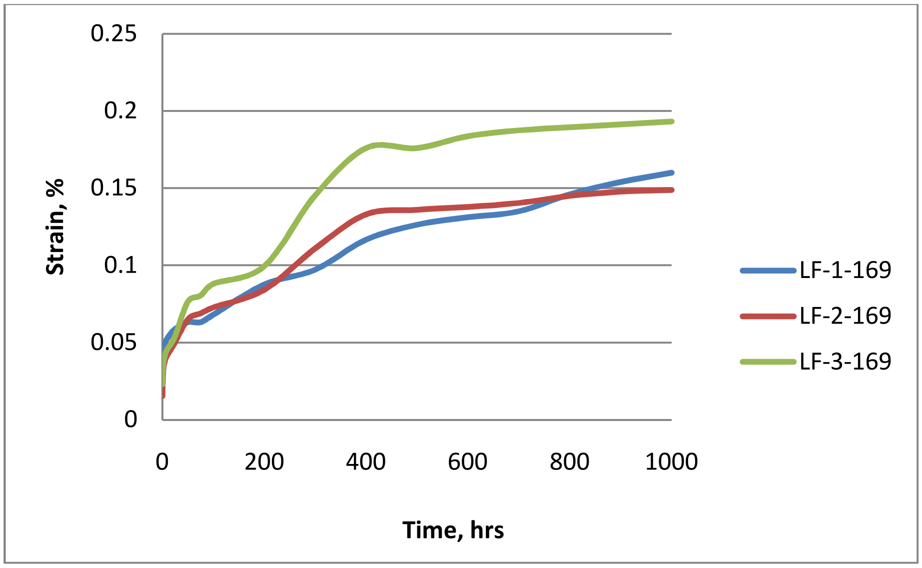


Figure 4.7 – Flexural Creep Strain ε in 169 Polyurea Specimens

Using Equation 3.4, the maximum strain in the extreme fibers at the mid-span location of the flexural tests specimens was calculated based on the deflection obtained. The directly proportional relationship implies that the conclusions drawn earlier for deflection are also applicable for strain. However, it is important to take a look at the strain values in this case because they are used to define the flexural modulus of the polyurea composite. From the Figures 4.7 and 4.8 it is concluded that the strain is within the limit of 1% in 1, 000 hours of the test. However, the stress in 169 specimens can be increased to obtain the more specific results as per the ASTM.

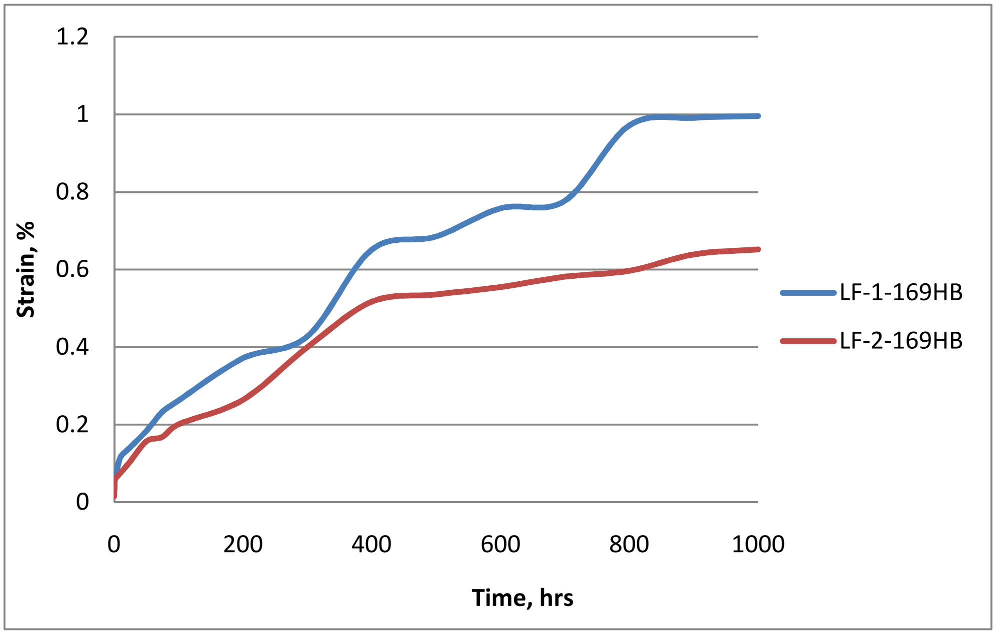


Figure 4.8 - Flexural Creep Strain ε in 169HB Polyurea Specimens

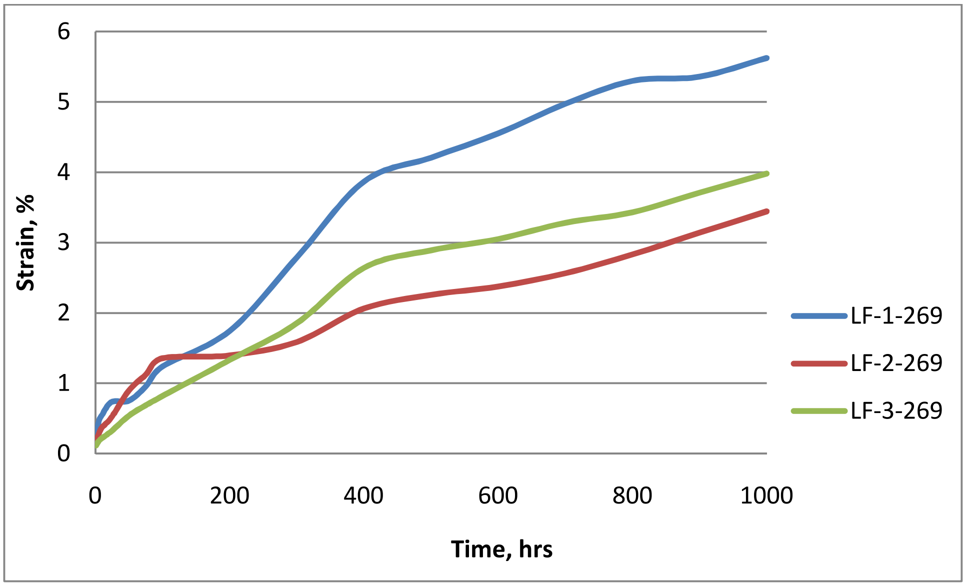


Figure 4.9 - Flexural Creep Strain ε in 269 Polyurea Specimens

Similarly, 269 specimens, tested for 1,000 hours showed higher strain rate and deflection. The strain limit of 1% was achieved in 100 hours of testing and 5% strain was reached for one of the specimen in 1,000 hour. As per the ASTM recommendations, the 269 specimen was detached from the load frame after 1,000 hour and reloaded with lower loads.

4.3.1 Long-Term Flexural Modulus E_F

The formula for computing flexural modulus as per ASTM D790 and D6272 is based on that equation, which implicitly assumes that all the deformation is contributed by bending and any shear deflection is ignored. The flexural creep modulus is defined as the ratio of applied stress to corresponding strain obtained including instantaneous, transient and steady state strain. In the linear creep range, the average short-term flexural modulus for the specimens tested is shown in Table 4.7.

The modulus changes with time and is referred to as the creep modulus of polyurea composite. In the creep phenomenon the stress is constant while the strain is increasing. According to Equation 3.5, if the strain increases then the creep modulus decreases with time in order for the stress to remain constant. This relationship is applied to obtain the time dependent creep modulus of polymers (Williams, 1980) and is used by the ASTM standard D 2990 “Tensile, Compressive, and Flexural Creep and Creep-Rupture of Plastics”.

Table 4.7 - Summary of Short-term Flexural Modulus for the Polyurea Composite

Specimen	***Flexural Modulus ‘E’ (psi)***
Scotchkote 169	116,000
Scotchkote 169HB	116,000
Scotchkote 269	104,000

From the long-term testing the flexural modulus for the specimen are presented in Table 4.8. The low modulus of polyurea material limits its potential for structural applications. This situation further aggravated by the reduction in this modulus with increase in time of loading. It is for these reasons that the design of polyurea material is controlled by stiffness rather than by strength.

Table 4.8 - Summary of Measured Flexural Modulus E_F at Various Time Intervals

Specimen	*Stress (psi)*	*Flexural Creep Modulus E_F (psi)*			
		1 hr	*100 hrs*	*500 hrs*	*1000 hrs*
LF-1-169	33.871	116,163	49,784	26,807	26,881
LF-2-169	27.097	88,516	37,270	19,924	18,203
LF-3-169	40.645	118,021	46,182	23,091	21,033
LF-1-169HB	33.871	58,081	12,907	4,943	3,400
LF-2-169HB	40.645	70,813	20,232	7,587	6,233
LF-1-269	33.871	21,075	2,732	805	602
LF-2-269	27.097	15,563	1,998	1,200	786
LF-3-269	20.323	17,703	2,482	704	510

269 Polymer composite specimen experienced large deflection under sustained load due to its creep characteristics and temperature sensitivity as compared to 169 and 169HB specimen. Figures 4.10, 4.11 and 4.12 show the graphical variation of the flexural creep modulus E_F data (psi) versus time (hours) for 169, 169HB and 269 specimens tested.

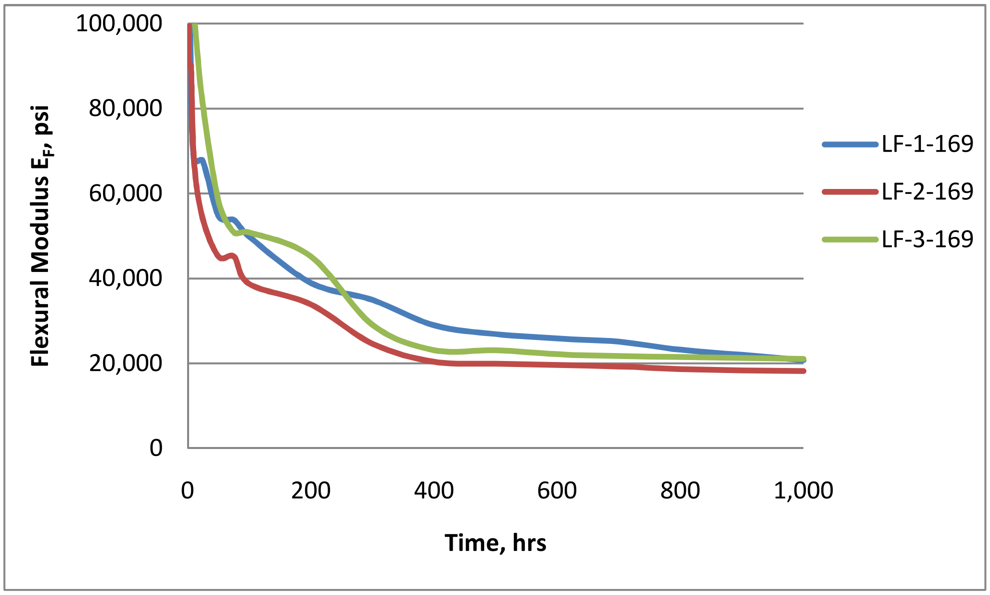


Figure 4.10 – Flexural Creep Modulus E_F versus Time at Various Stress for 169 Specimens

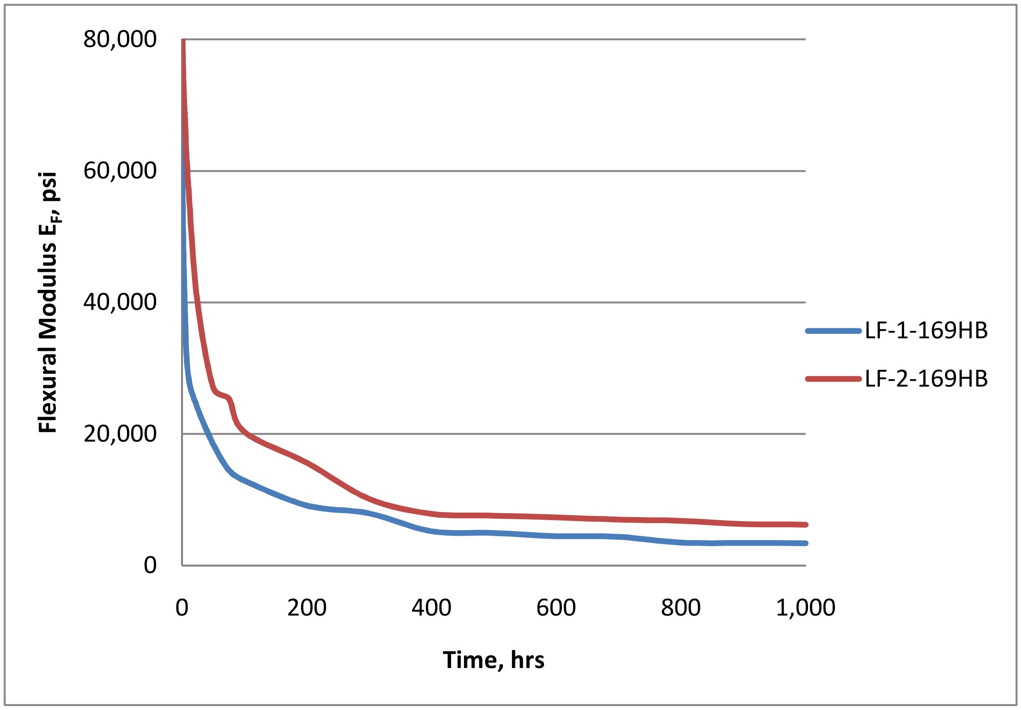


Figure 4.11 - Flexural Creep Modulus E_F versus Time at Various Stress for 169HB Specimens

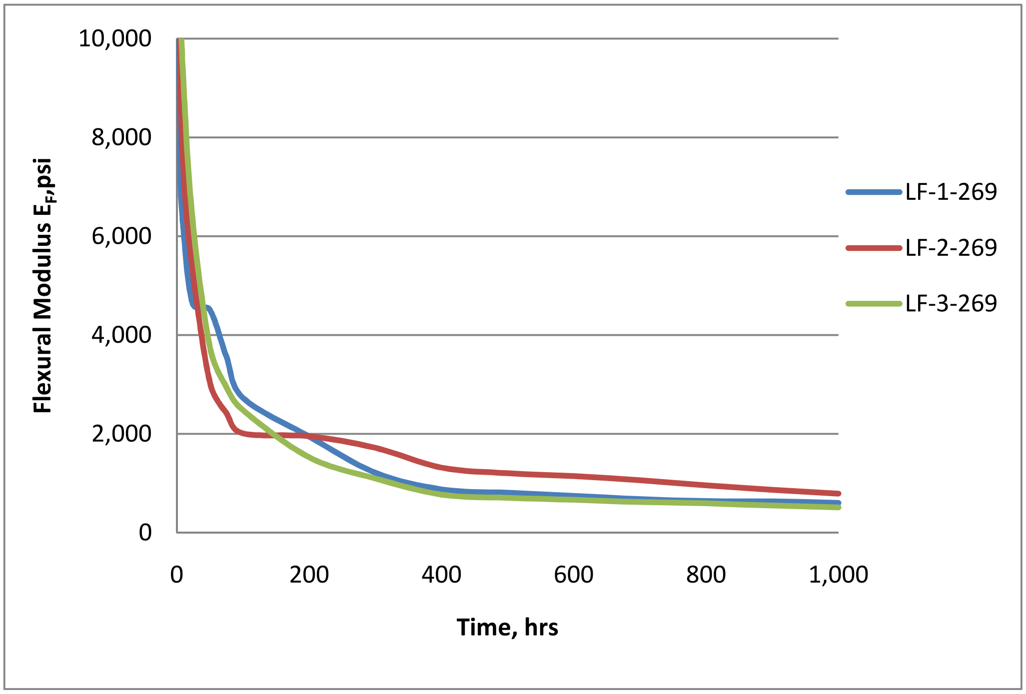


Figure 4.12 - Flexural Creep Modulus E_F versus Time at Various Stress for 269 Specimens

The stress level has a very small effect on the change in creep modulus. At low stress levels, the creep modulus is slightly higher than at high stress level but the difference is not significant. The response of polyurea under typical service stress levels will always be linear viscoelastic.

4.3.2 Summary of Flexural Creep Test Results

When a pipe starts to buckle under influence of load and internal pressure it no longer keeps its circular shape. With the rise in buckle there is an increase in bending moment in the pipe and liner material. Therefore, bending is one of the typical factors which will affect the creep behavior of the pipe. To study, this effect of bending on the liner material, the proposed flexural creep test was carried out.

During the 1,000 hours of flexural creep test, the creep strain increased exponentially with time for first 600 hours. After 600 hours, the strain varied approximately linearly with time.

The average strain for polyurea 169 specimens after 1,000 hrs was found to be approximately 0.0017, for 169HB was 0.008, whereas for 269 was 0.0044. Similarly the flexural modulus after 1,000 hours for 169 specimens was 22,039 psi, for 169HB was 4817 psi and for 269 was 633 psi. In the linear creep range, the average flexural creep modulus for 169 specimens is about 19% of short-term flexural modulus (116,000 psi), for 169HB is about 4% of short-term flexural modulus (116,000 psi) and for 269 specimens it is approximately 1 % of short-term flexural modulus (104,000 psi).

With reference to the above results, reducing the stress levels acts to increase the flexural creep modulus; that is, to make the material more resistant to deformation. These results indicate that the 269 specimen samples are very flexible compared to 169 and 169HB specimens and further testing is required with reduced stress level. Similarly, for 169 and 169HB which is more rigid material can be tested with higher stress level. For further analysis, this test needs to be monitored for more number of hours.

4.4 Log Curve Fitting Analysis

Curve fitting method is used to analyze and extrapolate the values. Equation 4.5 represents all conic curves including an ellipse, circle, straight line, parabola and hyperbola (Lin, 1995).

$$y^2 = Ax^2 + Bx + C$$ Equation 4.5

For most of the polymer materials, the long-term performance the design life can be quite long period. The log-log method is used to predict the design life of the material which will tend to display linearly on the log-log coordinate. Considering x and y coordinates as log.

Therefore, y = Log ε

and x = Log t

Hence, Equation 4.5 becomes

$$\left[Log(\varepsilon)\right]^2 = A\left[Log(t)\right]^2 + B\log(t) + C$$ Equation 4.6

Where,

ε = Creep Strain at a Constant Stress

t = Time, in Hours,

A, B, C = Coefficient (Stress, Material, loading condition related)

Since ε, is less than 1, a negative solution of the Equation 4.6 is selected (Lin, 1995).

$$Log(\varepsilon) = -\sqrt{A\left[Log(t)\right]^2 + B\log(t) + C}$$ Equation 4.7

The coefficient of the equation is determined using the following procedure. Three points of test are selected for each stress, choosing the beginning of the test as t1, t2 =1.0 hr and end of the test t3. In this study t1 = 0.0167 hr, t2 = 1 hr and t3 = 500 hrs. Since analysis is based on 1000 hrs, which is insufficient to predict 50-year design life of this material.

When t = 1 hr Equation 4.6 becomes;

$$C = (\log(\varepsilon_{t=1}))^2$$ Equation 4.8

Substituting the value of t_1, t_3 and ε_{t1} and ε_{t3} into Equation 4.6, we get.

$$\left[Log(\varepsilon_{t1})\right]^2 = A\left[Log(t_1)\right]^2 + B\log(t_1) + C$$ Equation 4.9

$$\left[Log(\varepsilon_{t3})\right]^2 = A\left[Log(t_3)\right]^2 + B\log(t_3) + C$$ Equation 4.10

Where,

ε_{t1}, ε_{t3} = Creep strain at time t_1 and t_3, respectively.

4.4.1 Log Curve Fitting Analysis for Flexural Specimens

Coefficients of Equation 4.6 for Flexural Creep experiment were obtained using the above method. Table 4.9 shows the coefficient for the flexural experiment using the curve fitting method.

Table 4.9 – Coefficients for Flexural Creep using Log-Curve Fitting Method

Specimen	***Stress, psi***	***Coefficient***		
		A	***B***	***C***
LF-1-169	33.871	-0.45027	-0.80026	13.8476
LF-2-169	27.097	-0.04829	-1.38653	12.3105
LF-3-169	40.645	-0.21616	-1.06295	12.0306
LF-1-269	33.871	0.24689	-2.86141	7.81694
LF-1-169HB	33.871	-0.22302	-1.54376	10.4754
LF-2-169HB	40.645	0.07080	-2.17988	10.5243
LF-2-269	27.097	0.07018	-2.00654	7.61456
LF-3-269	20.323	-0.17155	-1.85949	8.63949

Because of the limited time for observation, the coefficients in equation 4.6 were obtained based on only 500 hours of data. The equation should not be used to predict the creep behavior for more than single decade at the end of the experimental data. Table 4.10 lists the measured bending creep strain by curve fitting method at various times comparing it with the long-term flexural experimental values.

Table 4.10 – Comparison of Experimental and Theoretical Flexural Strain %

Specimen	Stress, psi	Experimental ε (%)				Theoretical ε (%) (Log Curve Fitting Method)			
		500 hrs	1000 hrs	3000 hrs	10000 hrs	500 hrs	1000 hrs	3000 hrs	10000 hrs
LF-1-169	33.871	0.126	0.160	-	-	0.126	0.190	0.425	1.395
LF-2-169	27.097	0.136	0.148	-	-	0.136	0.166	0.235	0.356
LF-3-169	40.645	0.176	0.193	-	-	0.176	0.236	0.405	0.834
LF-1-169HB	33.871	0.685	0.996	-	-	0.685	1.099	1.800	2.945
LF-2-169HB	40.645	0.536	0.652	-	-	0.536	0.708	1.123	1.932
LF-1-269	33.871	4.210	5.625	-	-	4.210	6.220	11.930	27.091*
LF-2-269	27.097	2.258	3.444	-	-	2.258	3.219	6.0385	14.341*
LF-3-269	20.323	2.890	3.980	-	-	2.885	5.865	48.329	-

Note: * Data extrapolated is beyond the limit of the test results. As per ASTM requirements the maximum strain generated in the specimen should not be more than 5%.

4.4.2 Log Curve Fitting Analysis for Tensile Specimens

Similarly, coefficients of Equation 4.6 for tensile creep experiment were obtained using the above method. Table 4.11 shows the coefficient for the tensile experiment using log curve fitting method.

Table 4.11 - Coefficients for Tensile Creep using Log Curve Fitting Method

Specimen	Stress, psi	Coefficient		
		A	B	C
LT-1-169	24.194	0.0329475	-2.1216924	13.54132
LT-2-169	24.194	-0.06723859	-3.8643536	19.32283
LT-3-169	28.226	-0.4500371	-1.4925315	15.71778
LT-2-169HB	48.387	0.25724330	-1.5584223	10.42312
LT-4-169HB	40.323	0.26643243	-2.6775276	13.63203
LT-1-269	32.258	0.06068314	-3.9601995	16.94892
LT-2-269	32.258	-0.66137137	-1.6180853	15.84744
LT-3-269	48.387	0.02424393	-2.8446675	14.15419

Also for the tensile test because of the limited time for observation, the coefficients in equation 4.9 were obtained based on only 500 hours of data. Table 4.12 lists the measured bending creep strain by curve fitting method at various times comparing it with the long-term flexural experimental values.

Table 4.12 - Comparison of Experimental and Theoretical Tensile Strain %

Specimen	***Stress, psi***	***Experimental ε (%)***				***Theoretical ε (%) (Log Curve Fitting Method)***			
		500 hrs	***1000 hrs***	***3000 hrs***	***10000 hrs***	***500 hrs***	***1000 hrs***	***3000 hrs***	***10000 hrs***
LT-1-169	24.194	0.1451	0.1717	-	-	0.1451	0.1846	0.2743	0.4339
LT-2-169	24.194	0.1262	0.2173	-	-	0.1262	0.2141	0.5593	2.1369
LT-3-169	28.226	0.1258	0.1736	-	-	0.1258	0.2082	0.5553	2.5354
LT-2-169HB	48.387	0.1431	0.1837	-	-	0.1430	0.1446	0.1417	0.1612
LT-4-169HB	40.323	0.1439	0.1805			0.1291	0.1486	0.1792	0.2087
LT-1-269	32.258	0.2578	0.2902	-	-	0.2576	0.4270	1.0519	3.6149
LT-2-269	32.258	0.2251	0.2947	-	-	0.2623	0.6861	3.2238	-
LT-3-269	48.387	0.2568	0.3430	-	-	0.2634	0.3834	0.7336	1.6649

Comparing the strain values obtained from curve fitting method with that of the experimental data, it was found that both the results were close. Using curve fitting method is not suitable for predicting the strain value for more than a decade. Since 1,000 hours is just a small part of the service life, so the real slope of the creep cannot be determined with very short-term data. Therefore, Equation 4.6 will not accurately predict the creep behavior of material more than 10,000 hours if the data observed is not adequate.

4.5 Findley's Power Law Model

One of the ways of describing the time-dependent behavior of polymer in linear and moderately non-linear regions is use of Findley's constants. Findley's employed equation of the type (Findley, 1989):

$$\varepsilon(t) = \varepsilon_o \sinh\frac{\sigma}{\sigma_o} + \varepsilon_t t^n \sinh\frac{\sigma}{\sigma_o} \qquad \text{Equation 4.11}$$

The equation has a time-dependent part, and involves five material constants. It is hard to find the Findley's constant, so for small stresses, the sinh (σ/σ_o) term becomes (σ/σ_o) and Findley's equation reduces to (Findley, 1989):

$$\varepsilon(t) \approx \sigma\left[\frac{1}{E_o} + \frac{t^n}{E_t}\right] \quad \text{Equation 4.12}$$

This section attempts to determine the time dependent behavior of polyurea composites of 169, 169HB, 269 under constant loads. The time dependent behavior was evaluated using Findley's Power Law model and was studied on the polyurea specimens. The creep deformations with time were collected for the specimens. Test procedure and specimen description is given in Chapter 3 and results are provided in the Appendix. Since the experimental data is only available for 1,000 hrs the predicted strain for 50-year design life is highly variable. In order to extrapolate for 400,000 hrs more data is required. However, an attempt is made to predict the 50-year strain based on 1,000 hrs results.

The Findley's power law is given as (Findley, 1989):

$$\varepsilon(t) = \varepsilon_o + mt^n \quad \text{Equation 4.13}$$

Where,

$\varepsilon(t)$ = Total Time-Dependent Creep Strain,

ε_o = Stress-Dependent and Temperature-Dependent Initial Elastic Strain;

m = Stress-Dependent and Temperature Dependent Coefficient;

n = Stress-Independent Material Constant;

t = Time after Loading (hrs).

Constants m and n are needed to formulate the power law were evaluated using the experimental creep data obtained and plotting logarithmic graph. Using Equation 4.13 and taking log on both sides we get:

$$\log(\varepsilon(t)-(\varepsilon_o)=\log(m)+n\log(t)$$

Equation 4.14

To obtain the m and n constants plotting the Equation 4.14 on log-log graph which will yield a straight line. Plotting the creep strain data on a log-log scale for log(ε- ε_o) on the y-axis and time log(t) on the x-axis. The vertical intercept at time t = 1 hr will give m and the slope of the line will give the material constant n. constant m and n for the tensile and bending specimens are shown in section 4.5.1 and 4.5.2.

4.5.1 Tensile Specimens

As discussed in the section 3.5 tensile specimens were subjected to creep with different stress levels. The entire tests were conducted for 1,000 hours under room temperature. The strain versus time data for different stress levels are shown in Appendix. Since the tests were conducted for short duration, changes in strain with time were determined using Findley's equation. Figures 4.13, 4.14 and 4.15 show the log-log graph for specimen 169, 169HB and 269 where intercept t = 1 hour gives constant 'm' and slope of the line gives the constant 'n'.

The constant 'm' and 'n' are for different specimens of 169; 169HB and 269 are shown in Table 4.13. It can be seen that the value of m increases with increase in stress, verifying the fact that 'm' is a stress dependent constant. Also, 'n' remains closer to all specimens of composite proving that it depends on material property and does not vary with stress.

The Findley's model generated by these constants was plotted along with the experimental creep data as shown in Figure 4.16. Findley's coefficient 'n' and 'm' for 169 specimens was 0.515 and 44.054 respectively. Similarly, Findley's coefficient 'n' and 'm' for 169HB and 269 specimens were 0.284, 190.614 and 0.5905 and 51.004.

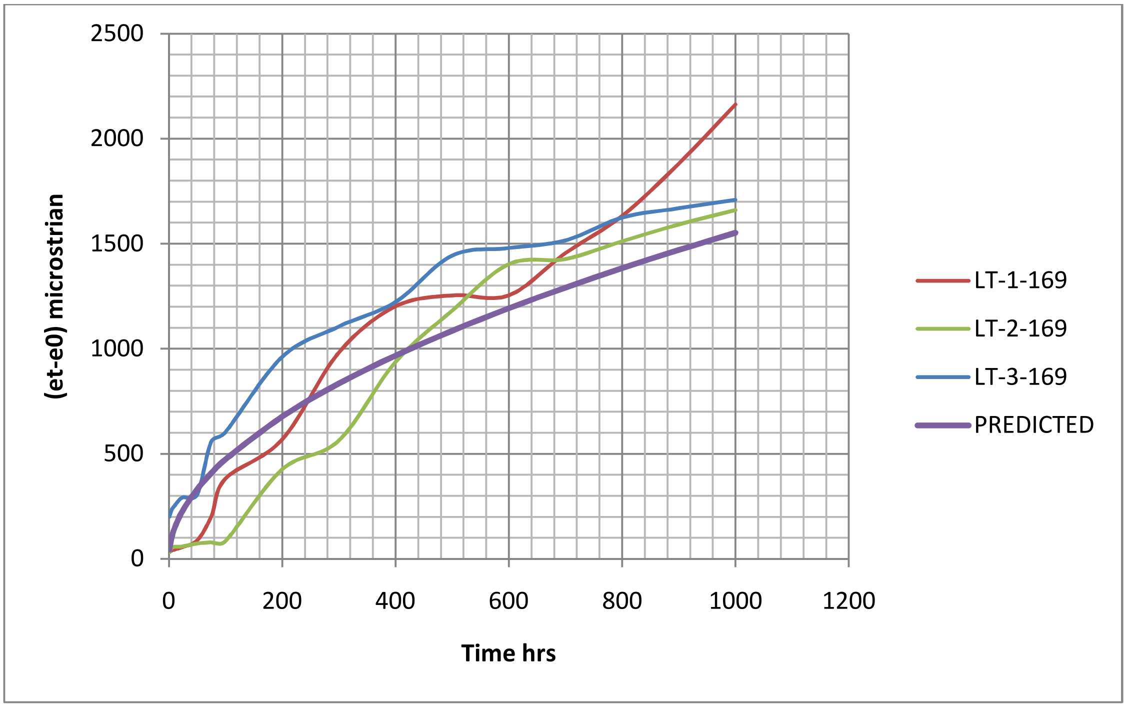


Figure 4.13 - Log-Log Plot of Specimen 169 to Evaluate Findley's Constant

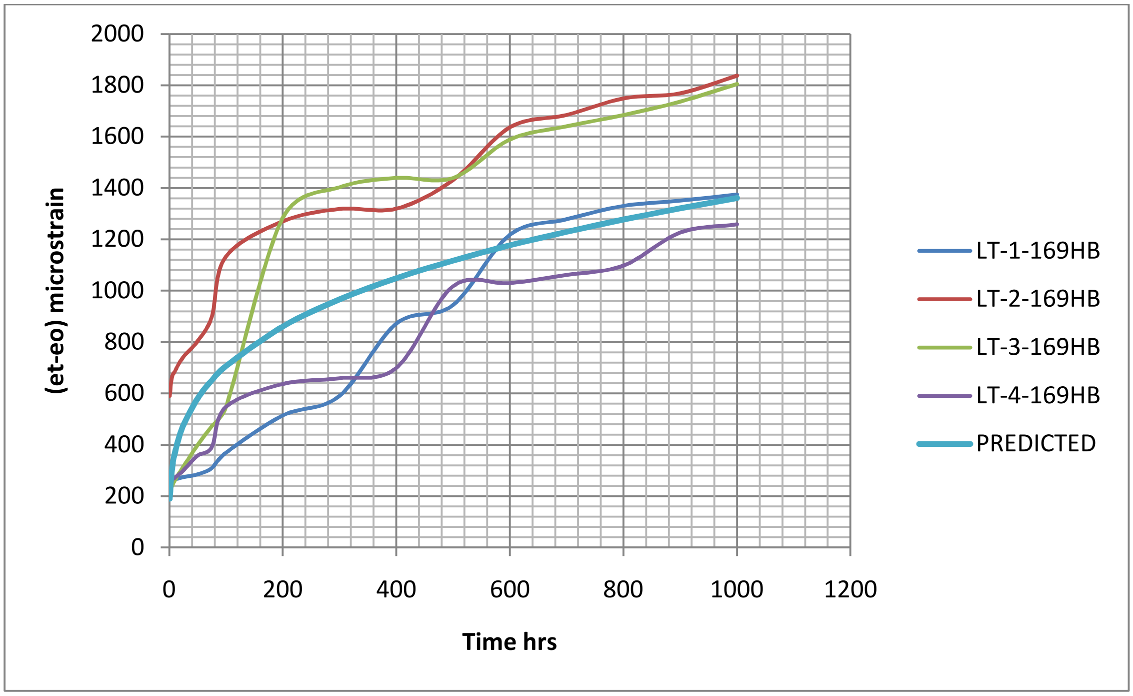


Figure 4.14 - Log-Log Plot of Specimen 169HB to Evaluate Findley's Constant

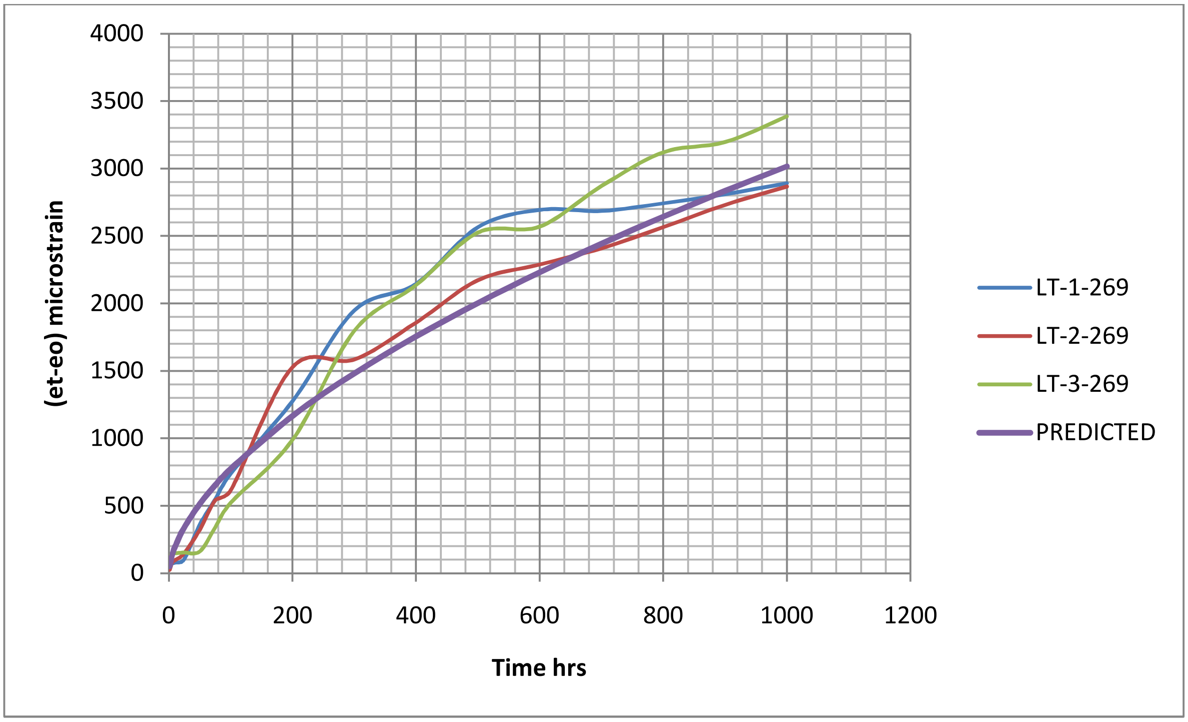


Figure 4.15 - Log-Log Plot of Specimen 269 to Evaluate Findley's Constant

Table 4.13 - Findley's Coefficient 'm' & 'n' for Tensile Creep Test

Specimen	*Stress psi*	*Findley's Coefficient*	
		m	*n*
169	24.194	44.054	0.515
	24.194		
	28.226		
169HB	32.258	190.614	0.284
	48.387		
	56.452		
	40.323		
269	32.258	51.004	0.5905
	32.258		
	48.387		

The Findlay's constant generated above where used to determine the strain values for the corresponding time. Table 4.14 shows the comparison of experimental tensile creep strain (%) for various specimens and strain (%) obtain from Findley's equation. Table 4.15 shows the increase in the strain in the material over a service life of 50 years using the Findley's model. Figure 4.16, 4.17 and 4.18 shows the creep strain extrapolated data over a service life of 50 years.

As mentioned above the data extrapolated for 269 specimens is above the limit of strain that it can carry. Since the 269 specimen being very flexible and the load being on the higher side, the sample will not be able to sustain the load for larger duration.

Table 4.14 - Comparison of Tensile Creep Strain Theoretical and Experimental

Specimen	***Stress psi***	***Experimental ε (%)***				***Theoretical ε (%)***				
		500 hrs	***1000 hrs***	***3000 hrs***	***10000 hrs***	***500 hrs***	***1000 hrs***	***3000 hrs***	***10000 hrs***	***438000 hrs***
LT-1-169	24.19	0.15	0.17	-	-	0.11	0.16	0.27	0.51	3.57
LT-2-169	24.19	0.13	0.22	-	-					
LT-3-169	28.23	0.13	0.17	-	-					
LT-1-169HB	32.26	0.09	0.14	-	-	0.11	0.14	0.19	0.26	0.77
LT-2-169HB	48.39	0.14	0.18	-	-					
LT-3-169HB	56.45	0.10	0.13	-	-					
LT-4-169HB	40.32	0.14	0.18	-	-					
LT-1-269	32.26	0.26	0.29	-	-	0.20	0.30	0.58	1.17	10.9
LT-2-269	32.26	0.23	0.29	-	-					
LT-3-269	48.39	0.26	0.34	-	-					

Note: * Data extrapolated is beyond the limit of the test results. As per ASTM requirements the maximum strain generated in the specimen should not be more than 5%.

The Findley's model generated by these constants was plotted with the experimental creep data are shown in Figures. From Figure 4.16 it can be concluded the 50-year strain for 169, 169HB and 269 the tensile specimen of polyurea 169HB behaved better with lower strain rate and high modulus.

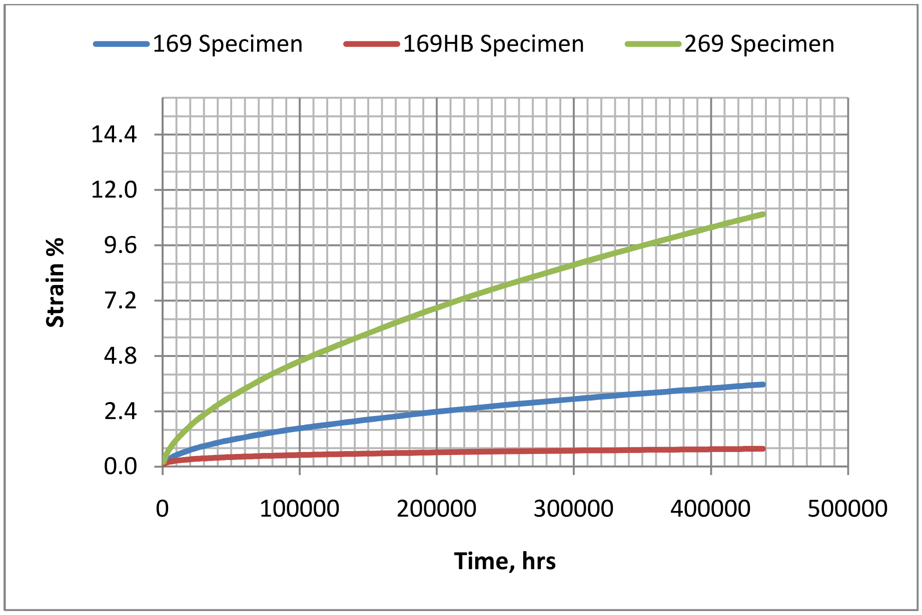


Figure 4.16 - Tensile Strain Prediction for 169, 169HB & 269 Specimens over 50-Year (Findley's Law)

4.5.2 Flexural Specimens

As discussed in the section 3.4 flexural specimens were subjected to creep with different stress levels. The entire tests were conducted for 1,000 hours under room temperature. The strain versus time data for different stress levels are shown in Appendix. Since the tests were conducted for short duration, changes in creep strain response for 50 years were extrapolated using Findley's Power Law model. Figures 4.17, 4.18 and 4.19 show the log-log graph for specimen 169, 169HB and 269 where intercept t = 1 hour gives constant m and slope of the line gives the constant 'n.

The constant m and n are for different specimens of 169, 169HB and 269 are shown in Table 4.15. It can be seen that the value of 'm' increases with increase in stress, verifying the fact that 'm' is a stress dependent constant. Also, an 'n' remains closer to all specimens of composite proving that 'n' depends on material property and does not vary with stress.

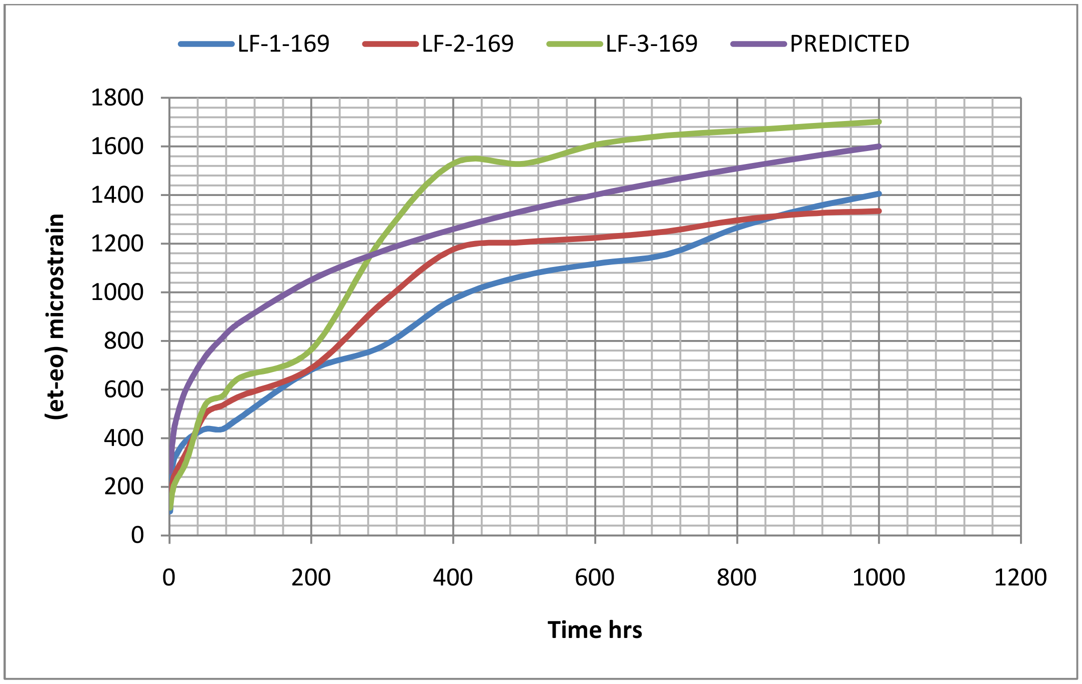


Figure 4.17 - Log-Log Plot of Specimen 169 to Evaluate Findley's Constant

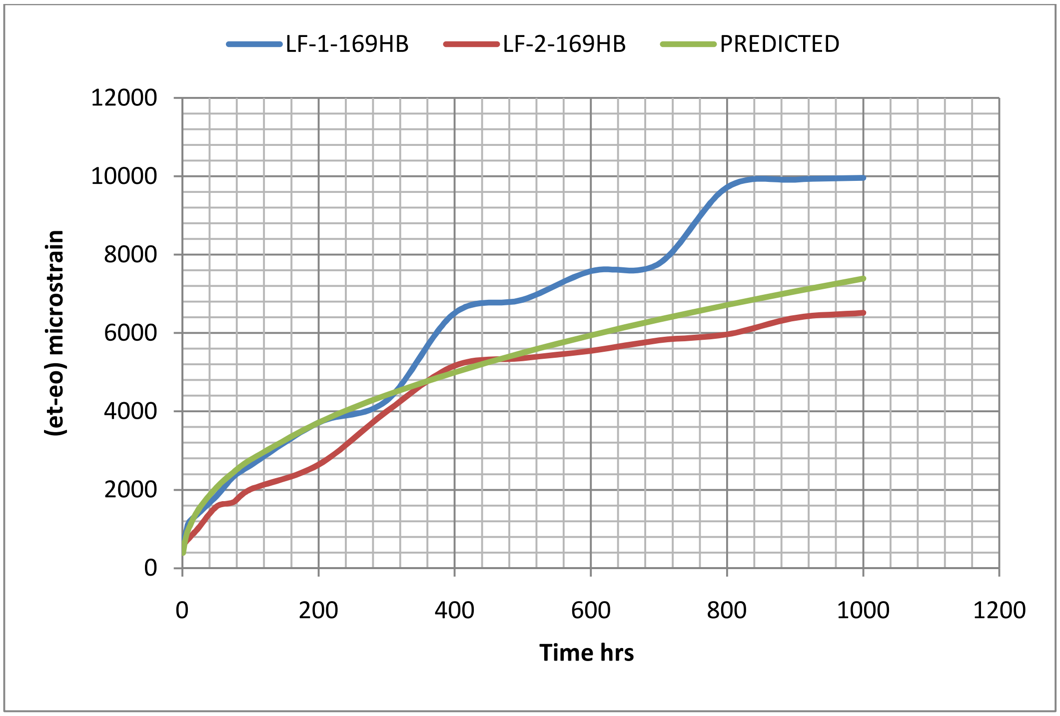


Figure 4.18 - Log-Log Plot of Specimen 169HB to Evaluate Findley's Constant

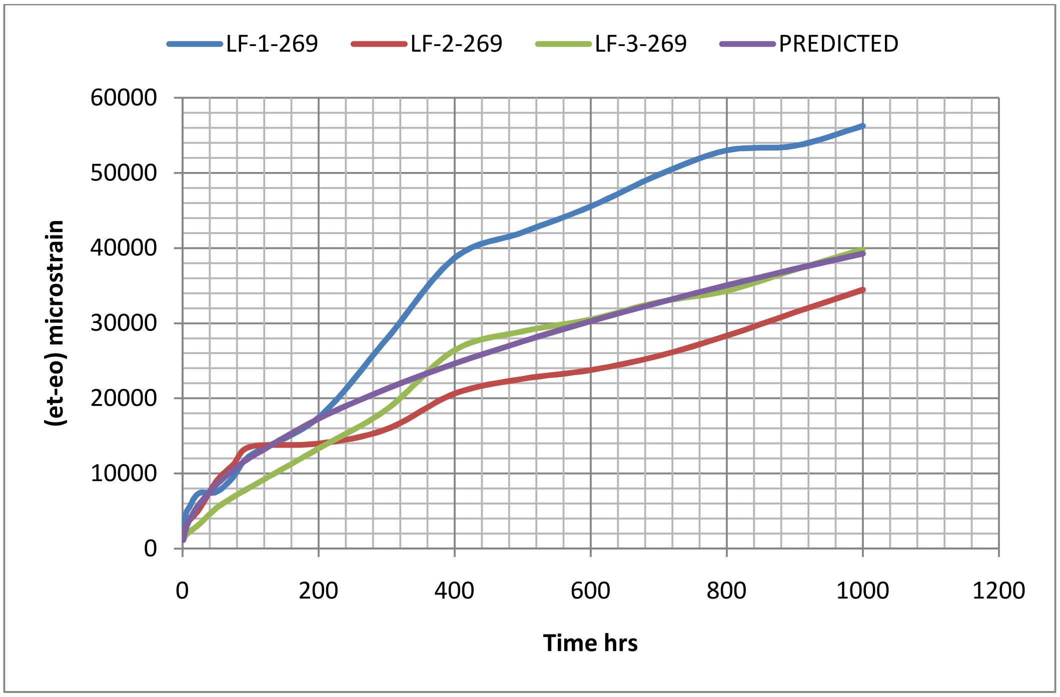


Figure 4.19 - Log-Log Plot of Specimen 269 to Evaluate Findley's Constant

Table 4.15 - Findley's Coefficient 'm' & 'n' for Tensile Creep Test

Specimen	***Stress psi***	***Findley's Coefficient***	
		m	***n***
169	24.194	44.054	0.515
	24.194		
	28.226		
169HB	32.258	386.459	0.427
	48.387		
	56.452		
	40.323		
269	32.258	1164.045	0.509
	32.258		
	48.387		

The Findlay's constant generated above where used to determine the strain values for the corresponding time. Table 4.16 shows the comparison of experimental flexural creep strain (%) for various specimens and strain (%) obtain from Findley's equation. The Findley's model generated by these constant were plotted with the experimental data. Findley's power law model proved to be a good approximation of linear creep behavior of polyurea composite. Hence, Findley's power law can be successfully used to model creep for lower stress levels, since the tertiary creep stage approaches in case of high stress levels.

Findley's law does not predict the tertiary creep region, i.e. the time to failure that will occur in the region. However, the law predicts the secondary creep region well. Figures 4.20 shows the creep strain extrapolated data for 169, 169HB and 269 using Findley's Power Law model for a service life of 50 years. The data extrapolated for 269 specimens is above the limit of strain that it can carry. Since the 269 specimen being very flexible and the load being on the higher side, the sample will not be able to sustain the load for larger duration.

Table 4.16 - Comparison of Flexural Creep Strain Theoretical and Experimental

Specimen	***Stress psi***	***Experimental ε (%)***				***Theoretical ε (%)***				
		500 hrs	***1000 hrs***	***3000 hrs***	***10000 hrs***	***500 hrs***	***1000 hrs***	***3000 hrs***	***10000 hrs***	***438000 hrs***
LF-1-169	33.87	0.13	0.16	-	-	0.13	0.16	0.21	0.29	0.78
LF-2-169	27.08	0.14	0.15	-	-					
LF-3-169	40.65	0.18	0.19	-	-					
LF-1-169HB	33.87	0.69	0.99	-	-	0.55	0.74	1.18	1.98	9.94
LF-2-169HB	40.65	0.54	0.65	-	-					
LF-1-269	33.87	4.21	5.63	-	-	2.76	3.93	6.87	12.69	-
LF-2-269	27.08	2.26	3.44	-	-					
LF-3-269	20.32	2.89	3.98	-	-					

Note: * Data extrapolated is beyond the limit of the test results. As per ASTM requirements the maximum strain generated in the specimen should not be more than 5%.

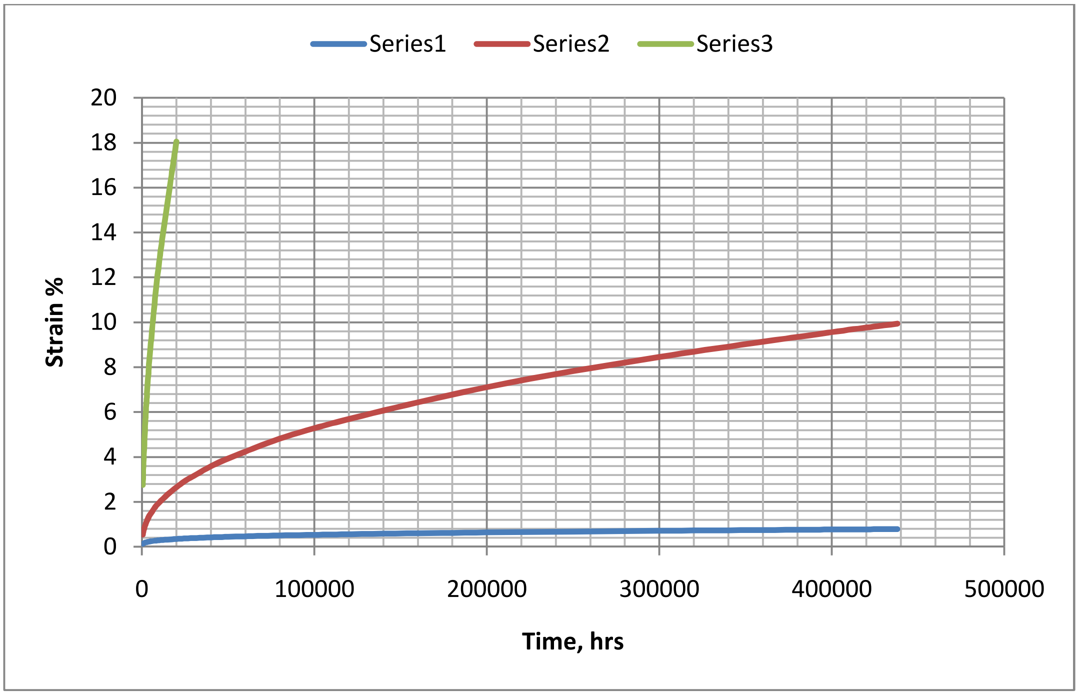


Figure 4.22 - Flexural Strain Prediction for 169,169HB & 269 Specimens over 50-Year (Findley's Law)

From the flexural strain prediction using Findley's Power Law model it can be concluded that the 169 specimen will behave well in deflection compared 169HB and 269 polyurea composite. The 269 specimen is not extrapolated beyond 10,000 hours since it was decided to take out the specimen after 1,000 hours of testing and reload with low loads. These predictions proved valid for this particular material and to study other composites further research is needed.

4.6 Chapter Summary

The experimental and theoretical creep curves are presented in this chapter for tensile and flexure, respectively. The long-term behavior of creep is very important for a number of applications. Predictions presented in the figures are formulated using both the general form of Findley's Power Law as well as the log curve fitting method. This chapter involves prediction of long-term properties of polyurea composites and extrapolating the results to 50-year. The experimental results presented here help in establishing material properties and stress-strain relationships for polyurea composites.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This study developed an understanding of long-term test behavior of polyurea pipe lining used for renewal of deteriorated potable water pipes. The liner materials used for testing are commercially available composites of polyurea i.e. Scotchkote 169, 169HB and 269 used in pipe lining applications.

For this study, it was necessary to adopt an iterative approach to determine the loads that will best represent the creep response over 10,000 hours of testing. In general, the creep testing provided valuable information about the durability of the Scotchkote 169, 169HB and 269 lining. The long-term tests conducted in this thesis, showed that the obtained creep data were in good agreement with Findley's Power law and log-fit method. These methods were used to analyze and extrapolate the creep behavior and strain response of polyurea composite. It was observed that polyurea samples, loaded for same period under similar loading conditions and stress, did not perform identical results. There were differences observed both in strain, magnitude of deflection and elongation. This can be attributed to material composition and stress distribution.

The results of creep behavior under different loading conditions for both tensile and flexure are presented in the appendices. Based on the experimental results and theoretical studies, the following conclusions are made:

Flexural Creep

Based on the 1,000 hours on polyurea composite specimens at room temperature, we can conclude that 169 and 169HB polyurea specimens performed better in bending when compared to 269 specimens. This is due to more rigidity in case of 169 & 169HB specimen which provided a better stress distribution. There was a 90% reduction in strength for 269 specimens, unlike the other two composites.

This concludes 269 polyurea to be more flexible material and 169 and 169HB more rigid. The value of elastic modulus of the materials obtained from long-term test was compared with the values obtained from the short-term tests results.

Tensile Creep

Polyurea composite specimens of dumbbell shape were used for evaluating the tensile and creep properties. The 169, 169HB and 269 specimens, all performed well in tensile under constant stress and at a constant room temperature. The average tensile modulus E_T was very low compared to the short-term modulus of the specimen.

Log-Curve Fitting

The log curve fitting method was in excellent conformity with the experimental data. Log curve fitting also proved to be good practice to extrapolate the data up to 10,000 hours. Since the available experimental data were for short duration, data extrapolation was not done for more than 10,000 hours.

Findley's Power Law

The equation of Findley was used to predict the creep strain under tensile and flexure. The results of the experiments were in agreement with the predicted values by this method. Using Findley's method to predict the 50-year data was also useful in determining the specimen that reached the 5% strain limit. Using Findley's Power Law model, stress-independent model, time-dependent strain was predicted with accuracies that were acceptable. An important restriction to this model is that it cannot describe non-linear tertiary creep; therefore stress levels must be kept sufficiently low to avoid this stage of creep.

5.2 Limitations

Some of the limitations of this research are:

1. These tests are carried out in room temperature, but generally creep tests are usually conducted at constant and lower temperatures.
2. The humidity was not maintained constant, where in actual cases the humidity is as low as 25%.
3. The loads selected for some of the specimens were too high which resulted in high strain rate.
4. Analysis is based on 1000 hrs, which is insufficient to predict 50-year design life of this material.

5.2 Recommendations for Future Research

Based on this study, the following recommendations for future research are being made:

1. Investigating the creep response at various temperatures such as below 70^{o}F (21^{o}C) and above 100^{o}F (37^{o}C). This will be useful in understanding the material behavior at extreme temperatures and site conditions present in certain regions of the country
2. Investigating the creep behavior of the same specimen for longer duration of time
3. Conducting test by lowering and rising stress levels, than the ones used in this research to obtain better creep curves
4. Comparing the creep response of polyurea composites under effect of temperature and moisture
5. Conducting other tests like stress relaxation and hydrostatic these specimens for further understanding of the material properties
6. Developing standard short-term testing procedures with same samples and predicting the long-term behavior using the results of the short-term tests.

APPENDIX A

TENSILE CREEP STRAIN DATA

A.1 Tensile Creep Strain Data – Polyurea 169 Specimen, @ Stress 24.19 psi

Creep of Polyurea 169 Tensile Loading at Room Temperature Specimen = LT-1-169 Load, lbs = 1.50 Stress, psi = 24.19 Duration = 1000 hrs					
Date	**Time (hrs)**	**Temperature ^{o}F**	**Elongation (mm)**	**Strain**	**% Strain**
20-Jan-10	0.0167	71	0.004	0.0000671	0.0067
20-Jan-10	1	71	0.014	0.0002090	0.0209
20-Jan-10	5	71	0.016	0.0002412	0.0241
20-Jan-10	10	71	0.017	0.0002599	0.0260
21-Jan-10	24	71	0.020	0.0003000	0.0300
22-Jan-10	50	70	0.021	0.0003136	0.0314
24-Jan-10	75	70	0.038	0.0005668	0.0567
25-Jan-10	100	70	0.041	0.0006110	0.0611
29-Jan-10	200	72	0.065	0.0009688	0.0969
02-Feb-10	300	73	0.075	0.0011135	0.1114
06-Feb-10	400	71	0.082	0.0012301	0.1230
10-Feb-10	500	72	0.097	0.0014512	0.1451
14-Feb-10	600	69	0.100	0.0014874	0.1487
18-Feb-10	700	69	0.102	0.0015236	0.1524
22-Feb-10	800	70	0.109	0.0016321	0.1632
26-Feb-10	900	72	0.112	0.0016763	0.1676
02-Mar-10	1000	71	0.115	0.0017165	0.1717

A.2 Tensile Creep Strain Data – Polyurea 169 Specimen, @ Stress 24.19 psi

Creep of Polyurea 169 Tensile Loading at Room Temperature

Specimen = LT-2-169

Load, lbs = 1.5

Stress, psi = 24.19

Duration = 1000 hrs

Date	Time (hrs)	Temperature °F	Elongation (mm)	Strain	% Strain
20-Jan-10	0.0167	71	0.001	0.000008	0.0008
20-Jan-10	1	71	0.003	0.0000402	0.0040
20-Jan-10	5	71	0.003	0.0000482	0.0048
20-Jan-10	10	71	0.004	0.0000524	0.0052
21-Jan-10	24	71	0.004	0.0000643	0.0064
22-Jan-10	50	70	0.006	0.0000965	0.0096
24-Jan-10	75	70	0.014	0.0002100	0.0210
25-Jan-10	100	70	0.026	0.0003900	0.0390
29-Jan-10	200	72	0.039	0.0005760	0.0576
02-Feb-10	300	73	0.066	0.0009900	0.0990
06-Feb-10	400	71	0.081	0.0012100	0.1210
10-Feb-10	500	72	0.085	0.0012623	0.1262
14-Feb-10	600	69	0.085	0.0012623	0.1262
18-Feb-10	700	69	0.098	0.00146328	0.1463
22-Feb-10	800	70	0.110	0.00164016	0.1640
26-Feb-10	900	72	0.127	0.0018894	0.1889
02-Mar-10	1000	71	0.145	0.0021708	0.2170

A.3 Tensile Creep Strain Data – Polyurea 169 Specimen, @ Stress 28.22 psi

Creep of Polyurea 169 Tensile Loading at Room Temperature

Specimen = LT-3-169

Load, lbs = 1.75

Stress, psi = 28.22

Duration = 1000 hrs

Date	Time (hrs)	Temperature ^{o}F	Elongation (mm)	Strain	% Strain
20-Jan-10	0.0167	71	0.005	0.000076	0.0076
20-Jan-10	1	71	0.007	0.000109	0.0109
20-Jan-10	5	71	0.009	0.000129	0.0129
20-Jan-10	10	71	0.009	0.000134	0.0134
21-Jan-10	24	71	0.009	0.000136	0.0136
22-Jan-10	50	70	0.010	0.000150	0.0150
24-Jan-10	75	70	0.010	0.000155	0.0155
25-Jan-10	100	70	0.011	0.000161	0.0161
29-Jan-10	200	72	0.034	0.000503	0.0503
02-Feb-10	300	73	0.043	0.000639	0.0639
06-Feb-10	400	71	0.068	0.001013	0.1013
10-Feb-10	500	72	0.084	0.001258	0.1258
14-Feb-10	600	69	0.099	0.001479	0.1479
18-Feb-10	700	69	0.101	0.001503	0.1503
22-Feb-10	800	70	0.106	0.001588	0.1588
26-Feb-10	900	72	0.112	0.001668	0.1668
02-Mar-10	1000	71	0.116	0.001737	0.1737

A.4 Tensile Creep Strain Data – Polyurea 169HB Specimen, @ Stress 32.25 psi

Creep of Polyurea 169HB Tensile Loading at Room Temperature

Specimen = LT-4-169HB

Load, lbs = 2

Stress, psi = 32.25

Duration = 1000 hrs

Date	Time (hrs)	Temperature ^{o}F	Elongation (mm)	Strain	% Strain
20-Jan-10	0.0167	71	0.001	0.000012	0.0012
20-Jan-10	1	71	0.017	0.000249	0.0249
20-Jan-10	5	71	0.018	0.000261	0.0261
20-Jan-10	10	71	0.018	0.000265	0.0265
21-Jan-10	24	71	0.018	0.000274	0.0273
22-Jan-10	50	70	0.019	0.000285	0.0285
24-Jan-10	75	70	0.021	0.000310	0.0309
25-Jan-10	100	70	0.025	0.000370	0.0369
29-Jan-10	200	72	0.034	0.000515	0.0514
02-Feb-10	300	73	0.040	0.000591	0.0590
06-Feb-10	400	71	0.058	0.000872	0.0872
10-Feb-10	500	72	0.063	0.000945	0.0944
14-Feb-10	600	69	0.082	0.001218	0.1218
18-Feb-10	700	69	0.086	0.001278	0.1278
22-Feb-10	800	70	0.089	0.001331	0.1330
26-Feb-10	900	72	0.090	0.001351	0.1350
02-Mar-10	1000	71	0.092	0.001375	0.1374

A.5 Tensile Creep Strain Data – Polyurea 169HB Specimen, @ Stress 48.38 psi

Creep of Polyurea 169HB Tensile Loading at Room Temperature

Specimen = LT-5-169HB

Load, lbs = 3.0

Stress, psi = 48.38

Duration = 1000 hrs

Date	Time (hrs)	Temperature °F	Elongation (mm)	Strain	% Strain
22-Jan-10	0.0167	70	0.012	0.000181	0.0181
22-Jan-10	1	70	0.040	0.000591	0.0591
22-Jan-10	5	70	0.044	0.000663	0.0663
22-Jan-10	10	70	0.046	0.000686	0.0686
23-Jan-10	24	73	0.050	0.000740	0.0740
24-Jan-10	50	71	0.054	0.000804	0.0804
27-Jan-10	75	72	0.060	0.000898	0.0898
28-Jan-10	100	69	0.076	0.001134	0.1134
01-Feb-10	200	69	0.085	0.001270	0.1270
05-Feb-10	300	70	0.088	0.001319	0.1319
09-Feb-10	400	72	0.088	0.001319	0.1319
13-Feb-10	500	71	0.096	0.001431	0.1431
17-Feb-10	600	70	0.110	0.001636	0.1636
21-Feb-10	700	70	0.113	0.001684	0.1684
25-Feb-10	800	70	0.117	0.001749	0.1749
01-Mar-10	900	72	0.119	0.001769	0.1769
05-Mar-10	1000	73	0.123	0.001837	0.1837

A.6 Tensile Creep Strain Data – Polyurea 169HB Specimen, @ Stress 56.45 psi

Creep of Polyurea 169HB Tensile Loading at Room Temperature

Specimen = LT-6-169HB

Load, lbs = 3.5

Stress, psi = 56.45

Duration = 1000 hrs

Date	Time (hrs)	Temperature ^{o}F	Elongation (mm)	Strain	% Strain
22-Jan-10	0.0167	70	0.001	0.000020	0.0020
22-Jan-10	1	70	0.015	0.000225	0.0225
22-Jan-10	5	70	0.018	0.000261	0.0261
22-Jan-10	10	70	0.018	0.000272	0.0272
23-Jan-10	24	73	0.020	0.000298	0.0298
24-Jan-10	50	71	0.024	0.000358	0.0358
27-Jan-10	75	72	0.026	0.000390	0.0390
28-Jan-10	100	69	0.037	0.000548	0.0548
01-Feb-10	200	69	0.043	0.000637	0.0637
05-Feb-10	300	70	0.044	0.000659	0.0659
09-Feb-10	400	72	0.047	0.000700	0.0700
13-Feb-10	500	71	0.068	0.001017	0.1017
17-Feb-10	600	70	0.069	0.001029	0.1029
21-Feb-10	700	70	0.071	0.001061	0.1061
25-Feb-10	800	70	0.074	0.001098	0.1098
01-Mar-10	900	72	0.082	0.001226	0.1226
05-Mar-10	1000	73	0.084	0.001258	0.1258

A.7 Tensile Creep Strain Data – Polyurea 169HB Specimen, @ Stress 40.32 psi

Creep of Polyurea 169HB Tensile Loading at Room Temperature

Specimen = LT-7-169HB

Load, lbs = 2.5

Stress, psi = 40.32

Duration = 1000 hrs

Date	**Time (hrs)**	**Temperature °F**	**Elongation (mm)**	**Strain**	**% Strain**
22-Jan-10	0.0167	70	0.003	0.000044	0.0044
22-Jan-10	1	70	0.015	0.000221	0.0221
22-Jan-10	5	70	0.016	0.000237	0.0237
22-Jan-10	10	70	0.018	0.000261	0.0261
23-Jan-10	24	73	0.021	0.000312	0.0312
24-Jan-10	50	71	0.027	0.000398	0.0398
27-Jan-10	75	72	0.032	0.000473	0.0473
28-Jan-10	100	69	0.037	0.000547	0.0547
01-Feb-10	200	69	0.086	0.001282	0.1282
05-Feb-10	300	70	0.094	0.001403	0.1403
09-Feb-10	400	72	0.096	0.001439	0.1439
13-Feb-10	500	71	0.096	0.001439	0.1439
17-Feb-10	600	70	0.106	0.001589	0.1589
21-Feb-10	700	70	0.110	0.001640	0.1640
25-Feb-10	800	70	0.113	0.001684	0.1684
01-Mar-10	900	72	0.116	0.001737	0.1737
05-Mar-10	1000	73	0.121	0.001805	0.1805

A.8 Tensile Creep Strain Data – Polyurea 269 Specimen, @ Stress 32.25 psi

Creep of Polyurea 269 Tensile Loading at Room Temperature

Specimen = LT-8-269

Load, lbs = 2

Stress, psi = 32.25

Duration = 1000 hrs

Date	Time (hrs)	Temperature ^{o}F	Elongation (mm)	Strain	% Strain
24-Jan-10	0.0167	71	0.001	0.000012	0.0012
24-Jan-10	1	72	0.005	0.000076	0.0076
24-Jan-10	5	69	0.006	0.000084	0.0084
24-Jan-10	10	69	0.006	0.000092	0.0091
25-Jan-10	24	70	0.008	0.000113	0.0112
27-Jan-10	50	72	0.025	0.000374	0.0373
29-Jan-10	75	71	0.038	0.000563	0.0562
31-Jan-10	100	70	0.050	0.000752	0.0751
03-Feb-10	200	70	0.086	0.001289	0.1289
07-Feb-10	300	70	0.131	0.001960	0.1960
11-Feb-10	400	72	0.145	0.002158	0.2157
15-Feb-10	500	73	0.173	0.002577	0.2576
19-Feb-10	600	71	0.181	0.002706	0.2705
23-Feb-10	700	72	0.181	0.002697	0.2697
27-Feb-10	800	69	0.184	0.002754	0.275
03-Mar-10	900	69	0.189	0.002822	0.2822
07-Mar-10	1000	70	0.194	0.002902	0.2902

A.9 Tensile Creep Strain Data – Polyurea 269 Specimen, @ Stress 32.25 psi

Creep of Polyurea 269 Tensile Loading at Room Temperature

Specimen = LT-9-269

Load, lbs = 2

Stress, psi = 32.25

Duration = 1000 hrs

Date	Time (hrs)	Temperature ^{o}F	Elongation (mm)	Strain	% Strain
24-Jan-10	0.0167	71	0.005	0.000080	0.0080
24-Jan-10	1	71	0.007	0.000105	0.0105
24-Jan-10	5	71	0.011	0.000157	0.0157
24-Jan-10	10	71	0.012	0.000176	0.0176
25-Jan-10	24	70	0.015	0.000225	0.0225
27-Jan-10	50	72	0.027	0.000402	0.0402
29-Jan-10	75	71	0.042	0.000621	0.0621
31-Jan-10	100	70	0.046	0.000694	0.0694
03-Feb-10	200	70	0.108	0.001608	0.1608
07-Feb-10	300	70	0.111	0.001664	0.1664
11-Feb-10	400	72	0.130	0.001938	0.1938
15-Feb-10	500	73	0.151	0.002251	0.2251
19-Feb-10	600	71	0.159	0.002368	0.2368
23-Feb-10	700	72	0.167	0.002488	0.2488
27-Feb-10	800	69	0.177	0.002645	0.2645
03-Mar-10	900	69	0.188	0.002810	0.2810
07-Mar-10	1000	70	0.197	0.002947	0.2947

A.10 Tensile Creep Strain Data – Polyurea 269 Specimen, @ Stress 48.38 psi

Creep of Polyurea 269 Tensile Loading at Room Temperature

Specimen = LT-10-269

Load, lbs = 3.0

Stress, psi = 48.38

Duration = 1000 hrs

Date	Time (hrs)	Temperature ^{o}F	Elongation (mm)	Strain	% Strain
24-Jan-10	0.0167	71	0.0030	0.00004	0.0040
24-Jan-10	1	71	0.0116	0.00017	0.0170
24-Jan-10	5	71	0.0127	0.00019	0.0190
24-Jan-10	10	71	0.0128	0.00019	0.0190
25-Jan-10	24	70	0.0132	0.00020	0.0200
27-Jan-10	50	72	0.0137	0.00021	0.0210
29-Jan-10	75	71	0.0258	0.00039	0.0390
31-Jan-10	100	70	0.0379	0.00057	0.0570
03-Feb-10	200	70	0.0692	0.00103	0.1030
07-Feb-10	300	70	0.1233	0.00184	0.1840
11-Feb-10	400	72	0.1461	0.00218	0.2180
15-Feb-10	500	73	0.1721	0.00257	0.2570
19-Feb-10	600	71	0.1751	0.00261	0.2610
23-Feb-10	700	72	0.1953	0.00291	0.2910
27-Feb-10	800	69	0.2120	0.00316	0.3160
03-Mar-10	900	69	0.2171	0.00324	0.3240
07-Mar-10	1000	70	0.2298	0.00343	0.3430

APPENDIX B

TENSILE CREEP STRAIN GRAPHS

B.1 Tensile Creep Strain Graph – Polyurea169 Specimen, @ Stress 24.19 psi

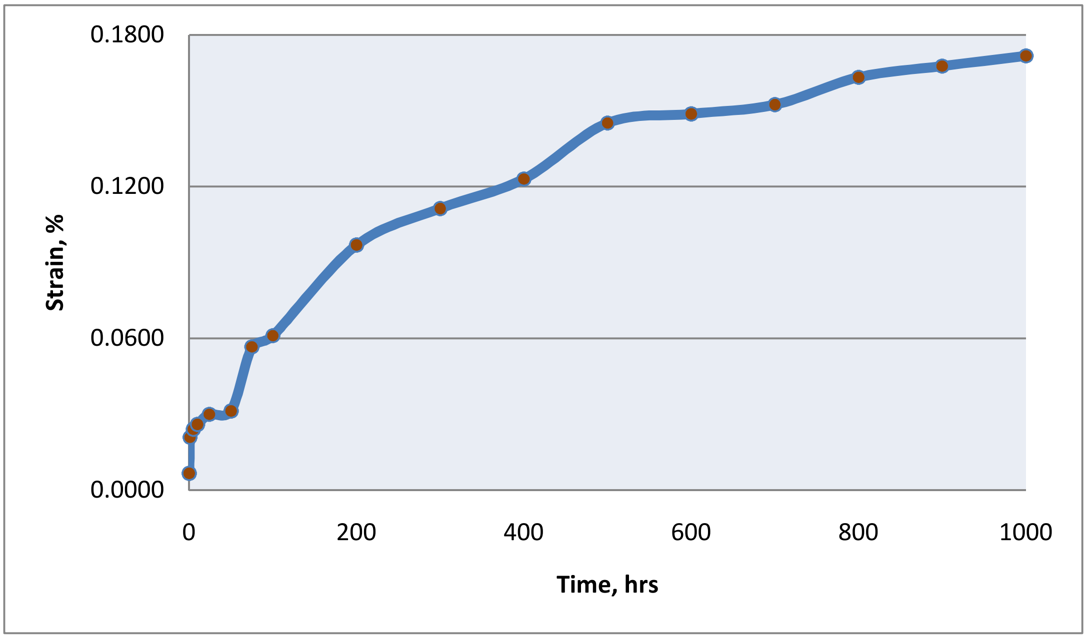


Figure B.1 – Strain (%) vs. Time (hours) for Polyurea 169

B.2 Tensile Creep Strain Graph – Polyurea 169 Specimen, @ Stress 24.19 psi

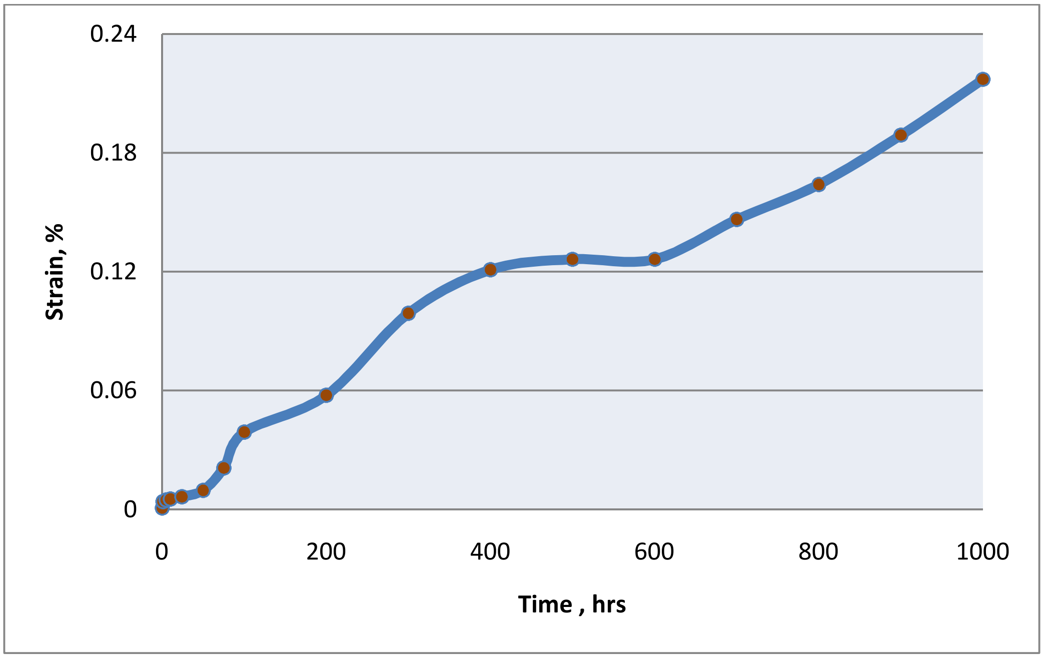


Figure B.2 – Strain (%) vs. Time (hours) for Polyurea 169

B.3 Tensile Creep Strain Graph – Polyurea 169 Specimen, @ Stress 28.22 psi

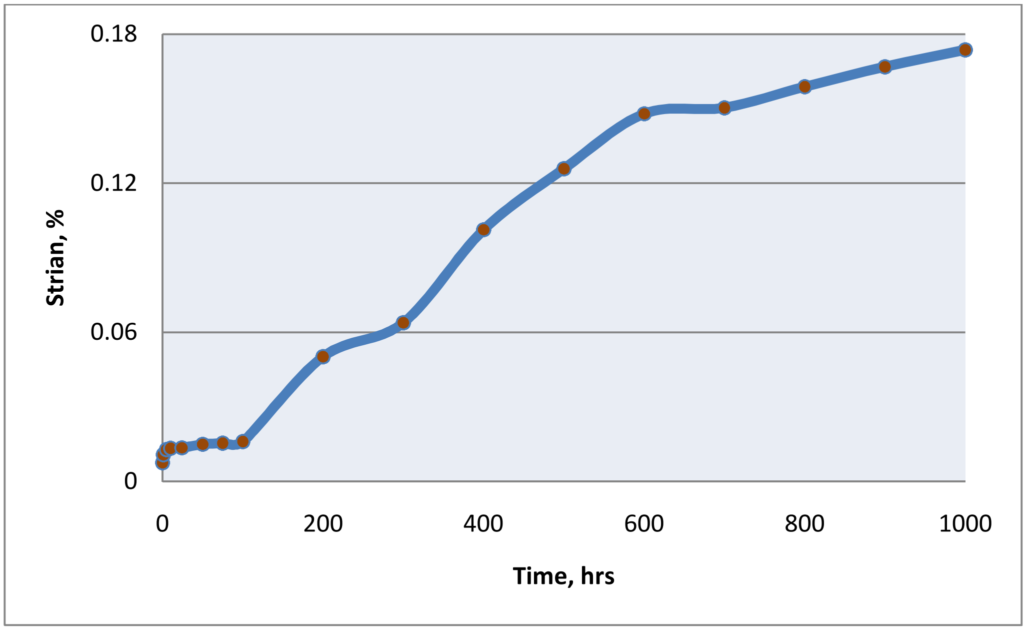


Figure B.3 – Strain (%) vs. Time (hours) for Polyurea 169

B.4 Tensile Creep Strain Graph – Polyurea 169HB Specimen, @ Stress 32.25 psi

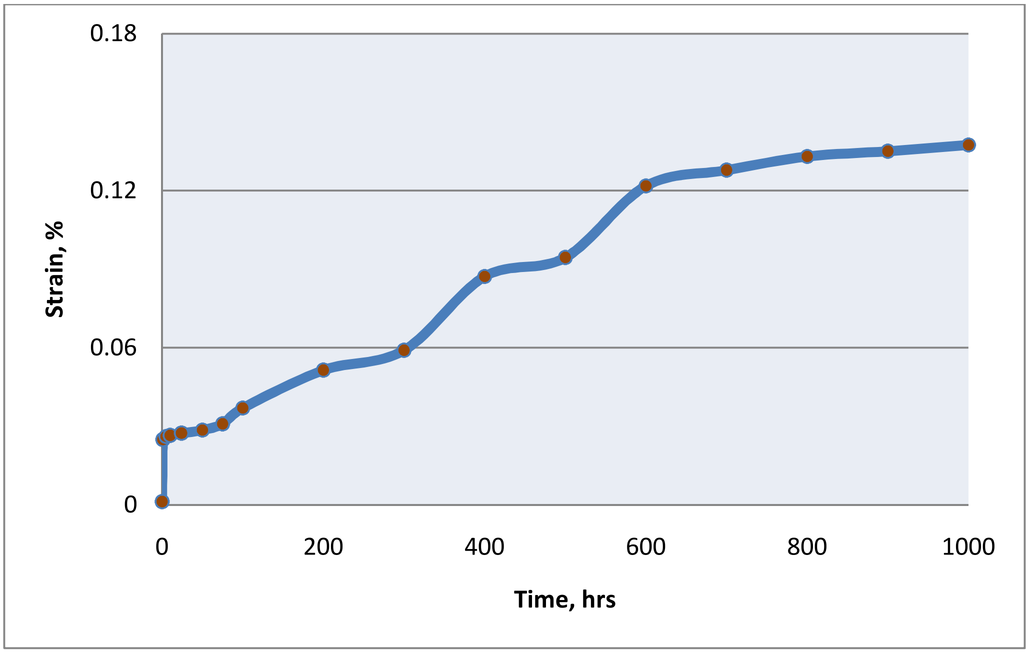


Figure B.4 – Strain (%) vs. Time (hours) for Polyurea 169HB

B.5 Tensile Creep Strain Graph – Polyurea 169HB Specimen, @ Stress 48.38 psi

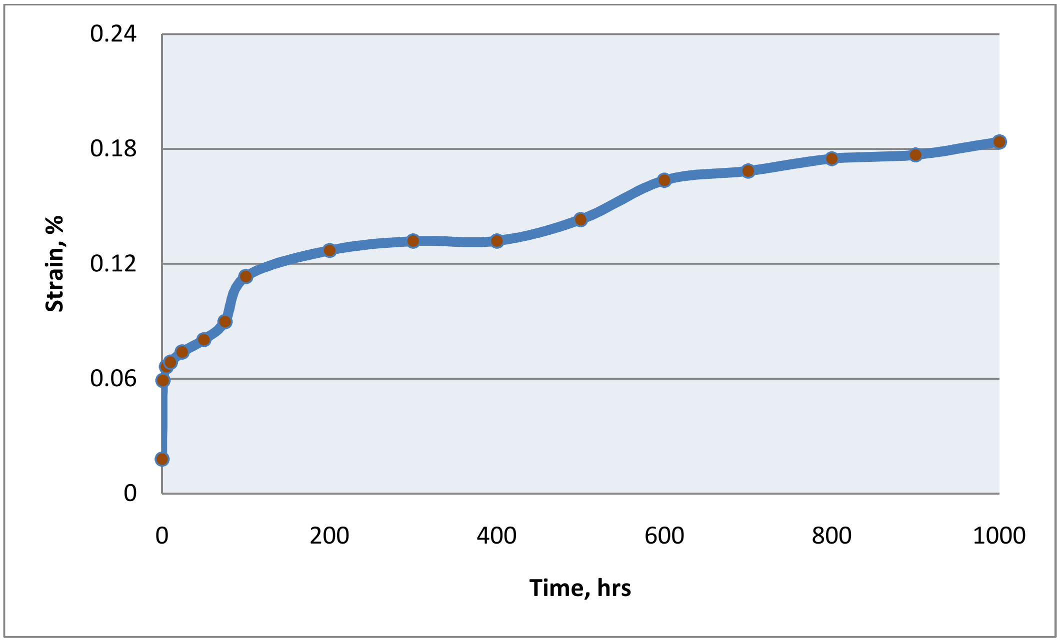


Figure B.5 – Strain (%) vs. Time (hours) for Polyurea 169HB

B.6 Tensile Creep Strain Graph – Polyurea 169HB Specimen, @ Stress 56.45 psi

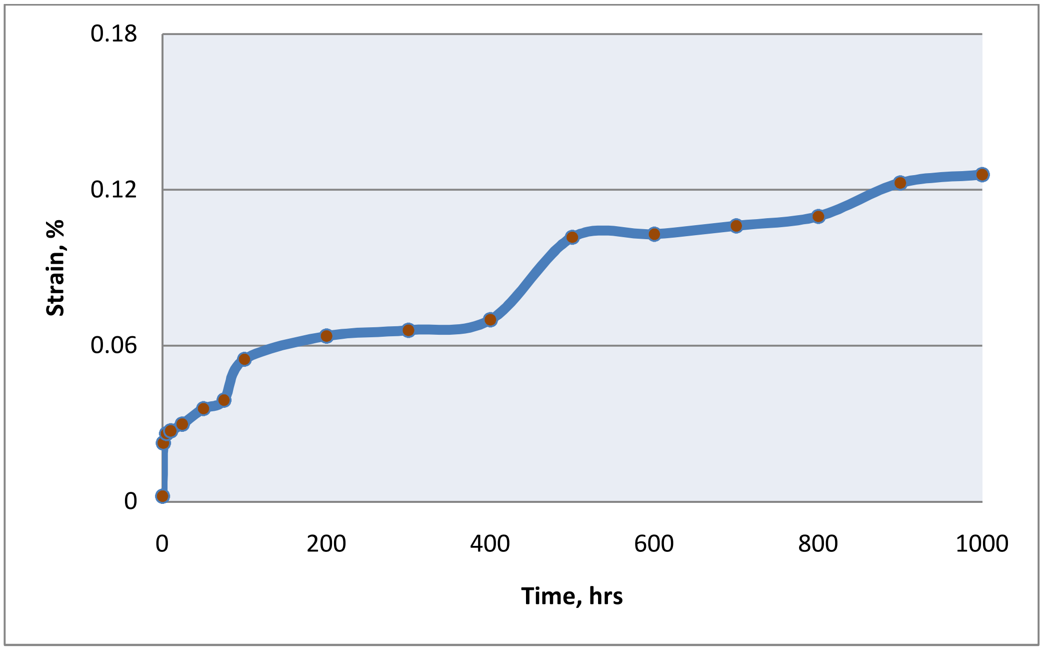


Figure B.6 – Strain (%) vs. Time (hours) for Polyurea 169HB

B.7 Tensile Creep Strain Graph – Polyurea 169HB Specimen, @ Stress 40.32 psi

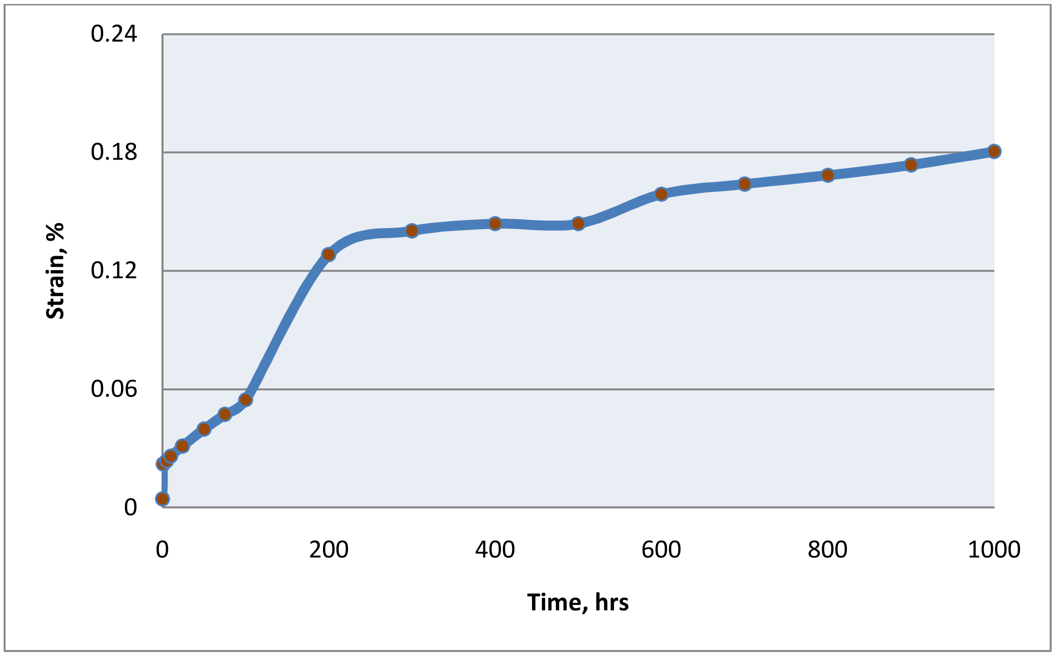


Figure B.7 – Strain (%) vs. Time (hours) for Polyurea 169HB

B.8 Tensile Creep Strain Graph – Polyurea 269 Specimen, @ Stress 32.25 psi

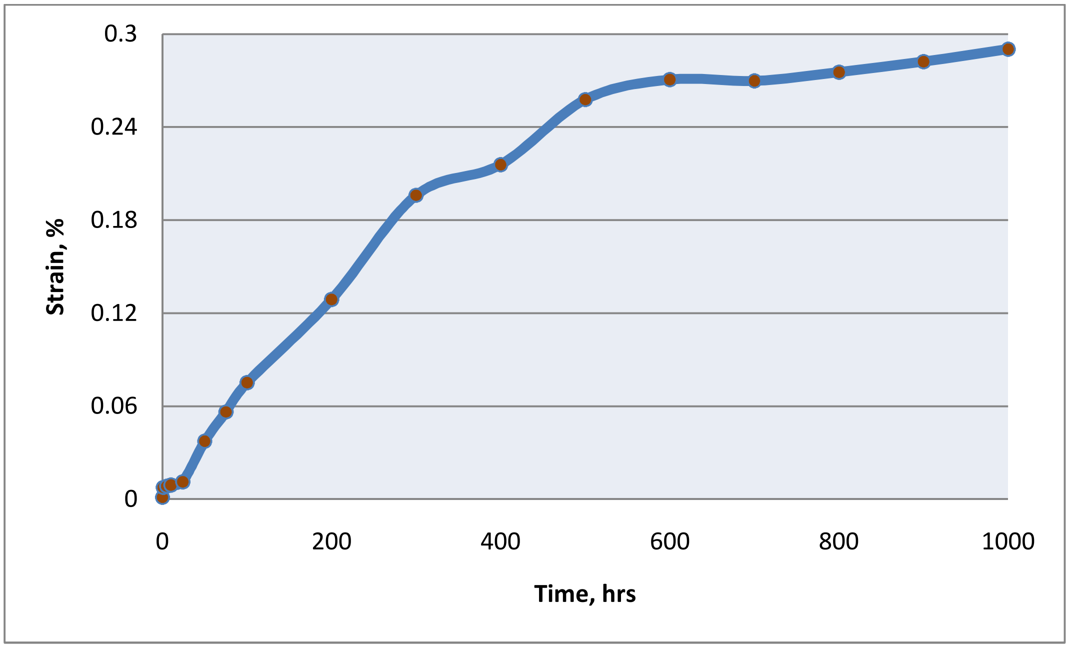


Figure B.8 – Strain (%) vs. Time (hours) for Polyurea 269

B.9 Tensile Creep Strain Graph – Polyurea 269 Specimen, @ Stress 32.25 psi

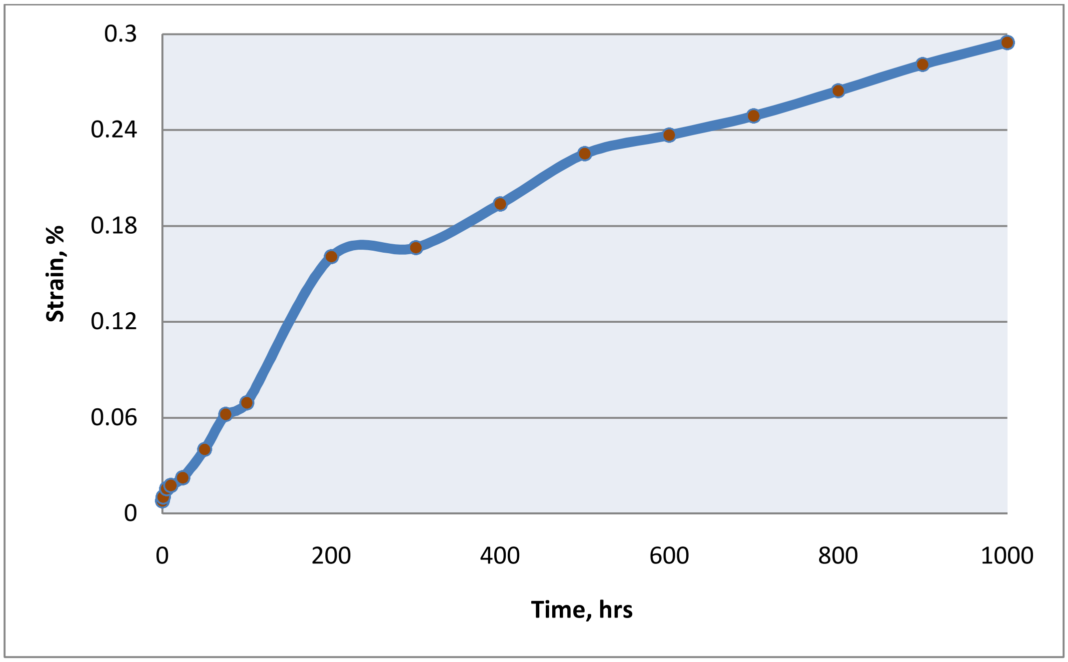


Figure B.9 – Strain (%) vs. Time (hours) for Polyurea 269

B.10 Tensile Creep Strain Graph – Polyurea 269 Specimen, @ Stress 48.38 psi

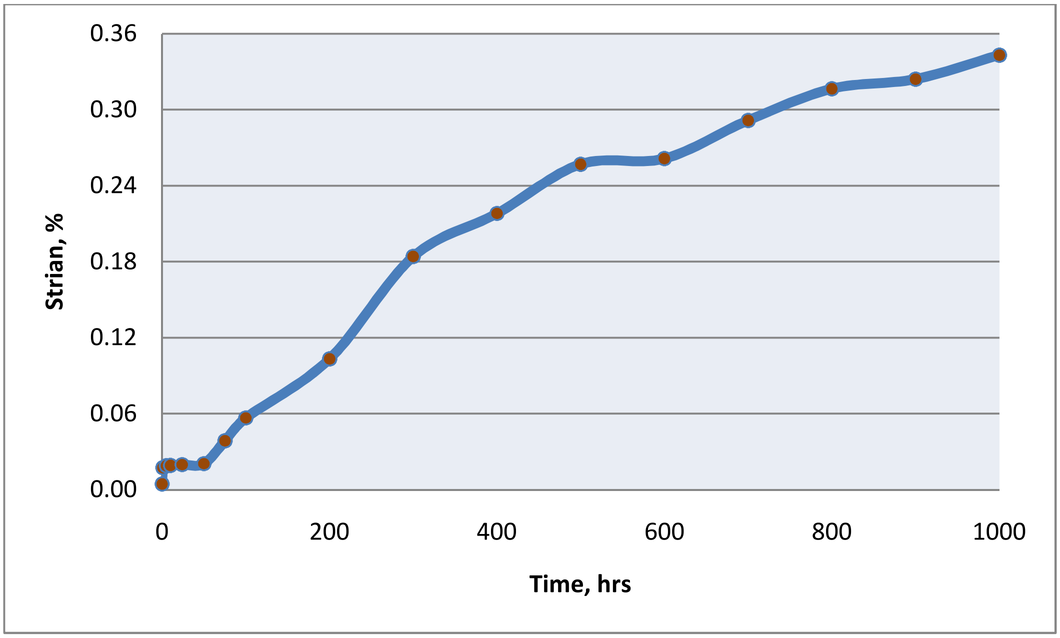


Figure B.10 – Strain (%) vs. Time (hours) for Polyurea 269

APPENDIX C

TENSILE CREEP MODULUS GRAPHS

C.1 Tensile Creep Modulus E_T Graph – Polyurea 169 Specimen, @ Stress 24.19 psi.

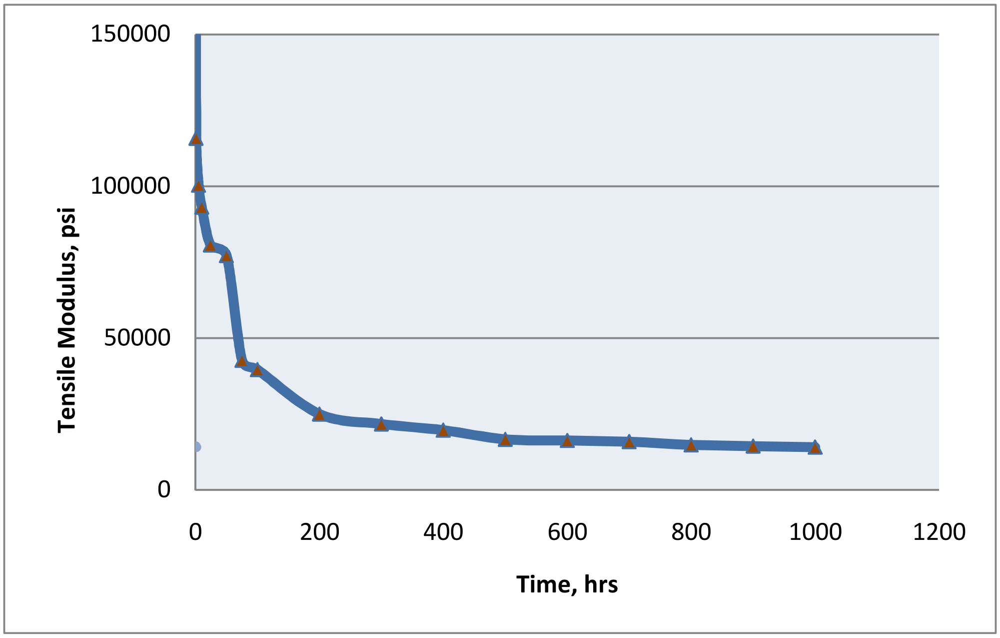


Figure C.1 – Tensile Modulus E_T (psi) vs. Time (hours) for Polyurea 169

C.2 Tensile Creep Modulus E_T Graph – Polyurea 169 Specimen, @ Stress 24.19 psi

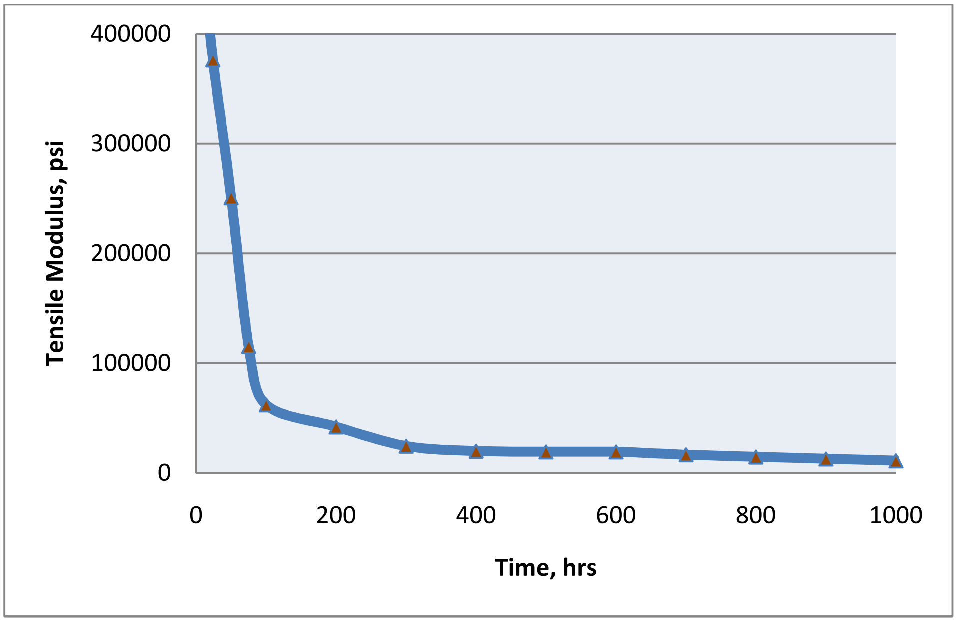


Figure C.2 – Tensile Modulus E_T (psi) vs. Time (hours) for Polyurea 169

C.3 Tensile Creep Modulus E_T Graph – Polyurea 169 Specimen, @ Stress 28.22 psi

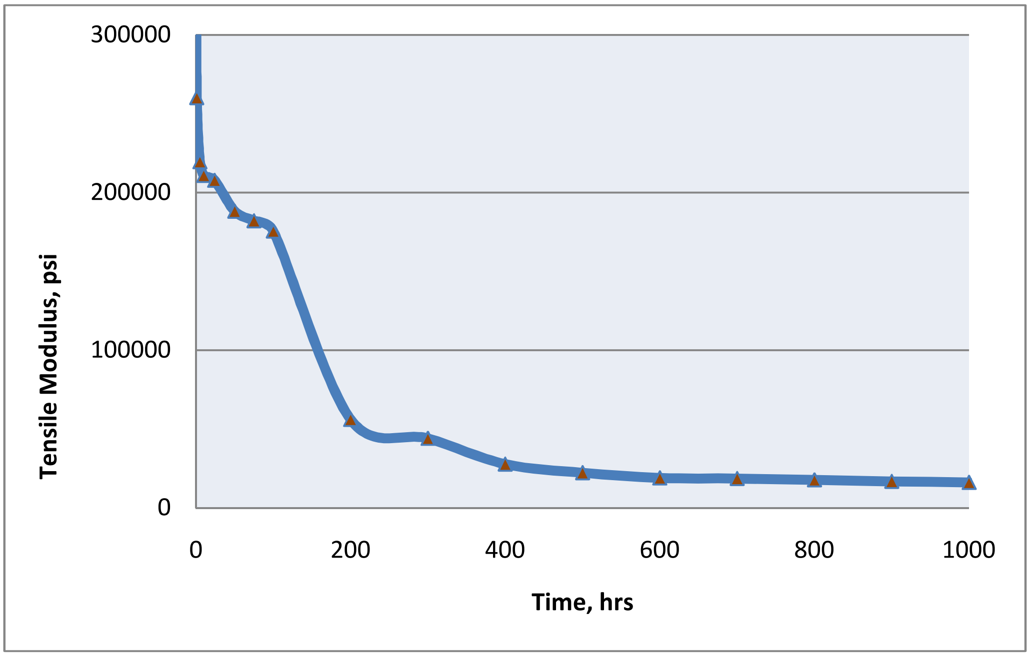


Figure C.3 – Tensile Modulus E_T (psi) vs. Time (hours) for Polyurea 169

C.4 Tensile Creep Modulus E_T Graph – Polyurea 169HB Specimen, @ Stress 32.25 psi

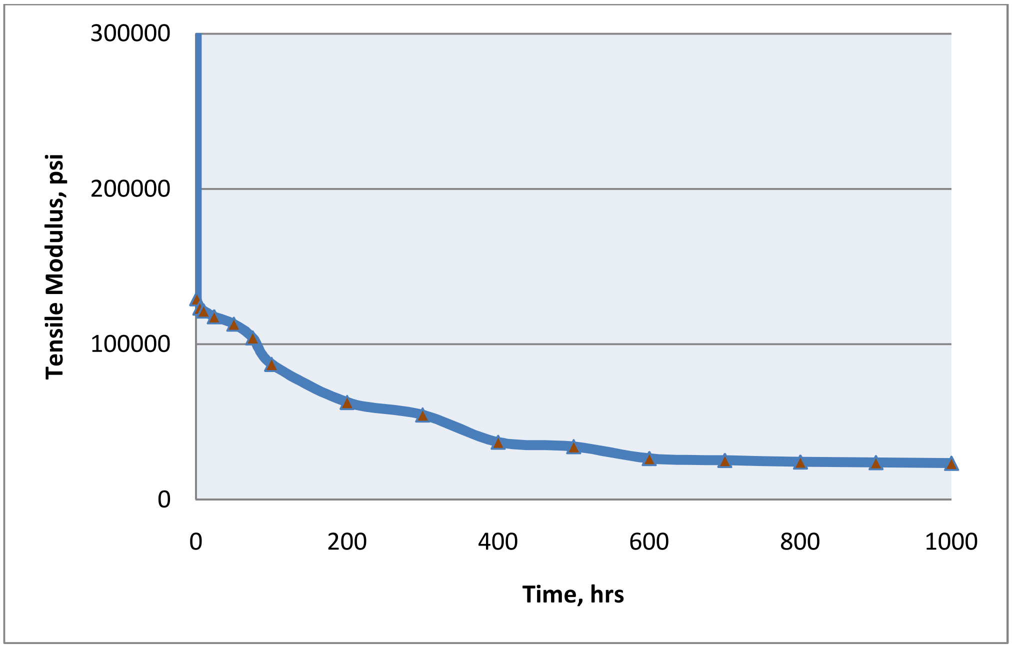


Figure C.4 – Tensile Modulus E_T (psi) vs. Time (hours) for Polyurea 169HB

C.5 Tensile Creep Modulus E_T Graph – Polyurea 169HB Specimen, @ Stress 48.38 psi

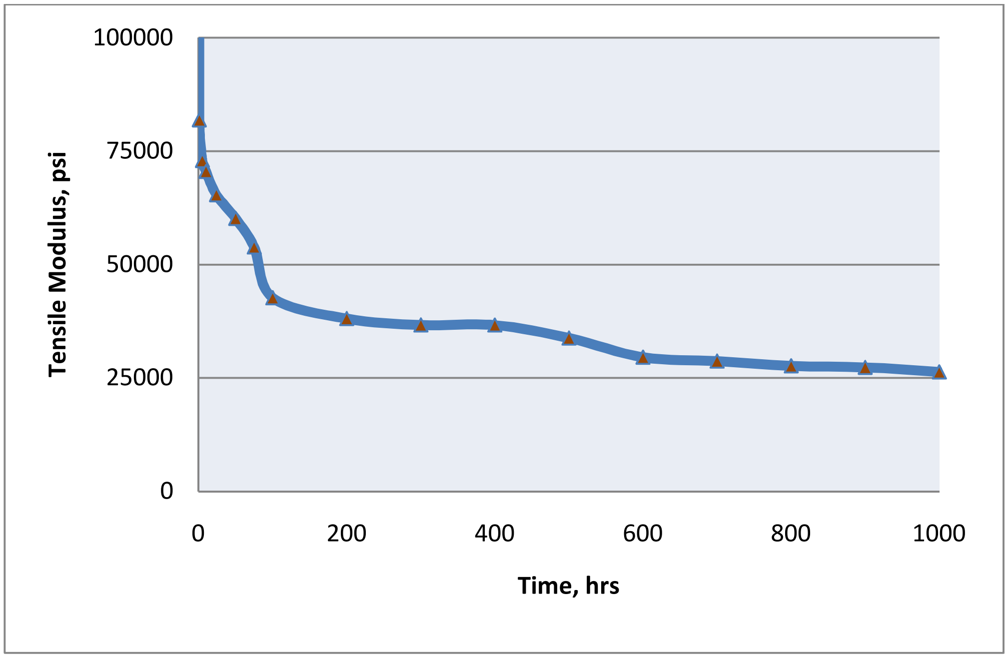


Figure C.5 – Tensile Modulus E_T (psi) vs. Time (hours) for Polyurea 169HB

C.6 Tensile Creep Modulus E_T Graph – Polyurea 169HB Specimen, @ Stress 56.45 psi

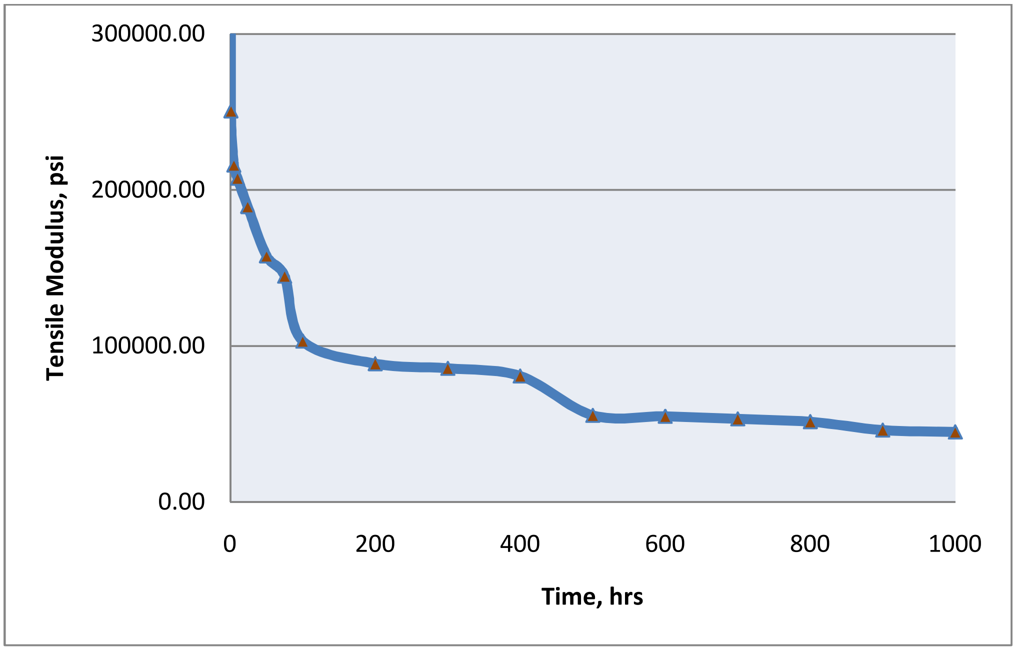


Figure C.6 – Tensile Modulus E_T (psi) vs. Time (hours) for Polyurea 169HB

C.7 Tensile Creep Modulus E_T Graph – Polyurea 169HB Specimen, @ Stress 40.32 psi

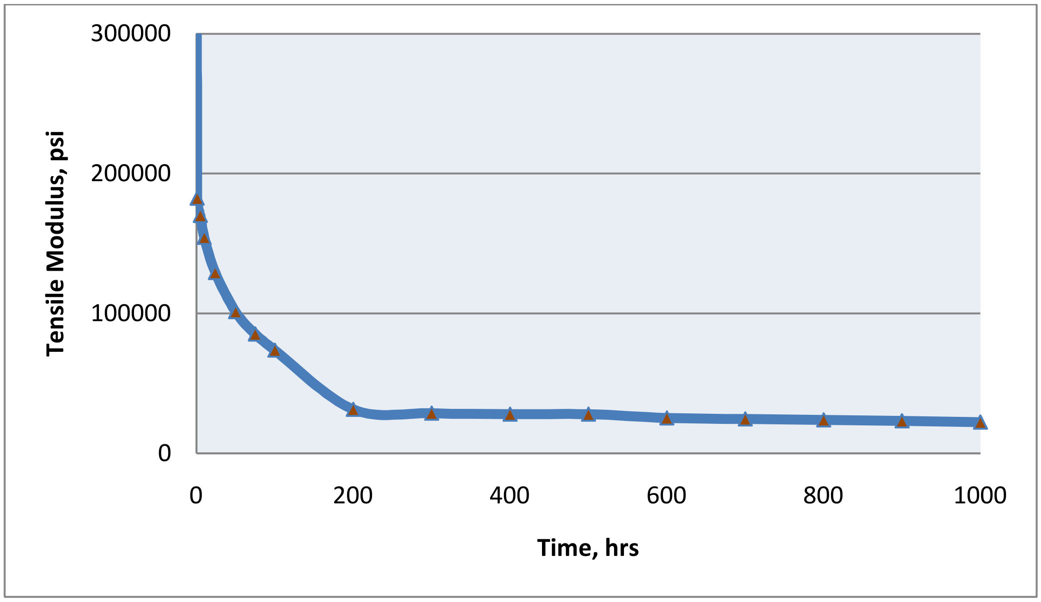


Figure C.7 – Tensile Modulus E_T (psi) vs. Time (hours) for Polyurea 169HB

C.8 Tensile Creep Modulus E_T Graph – Polyurea 269 Specimen, @ Stress 32.25 psi

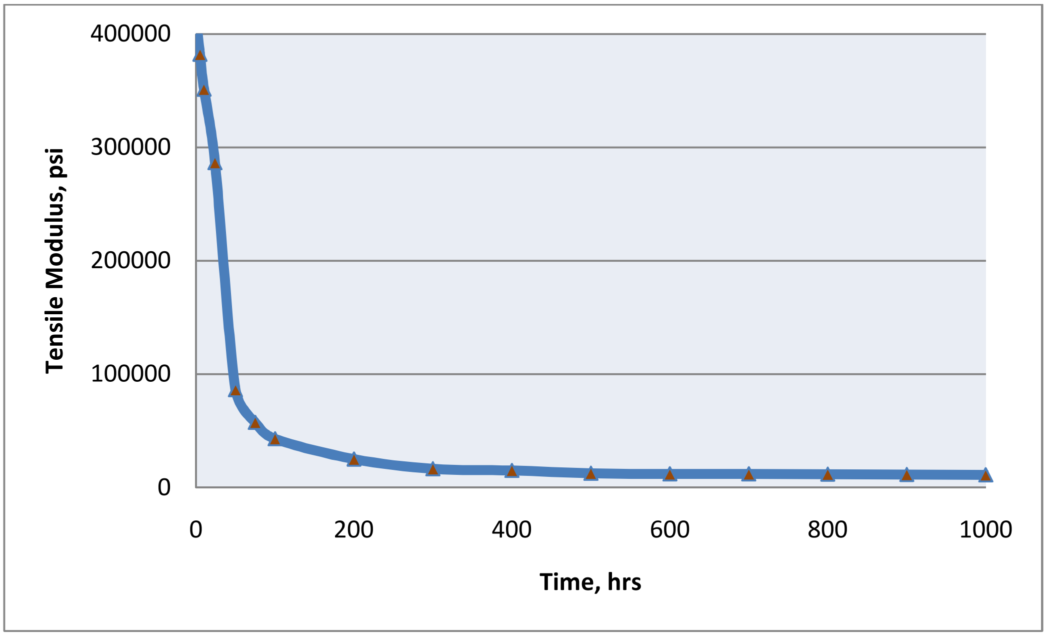


Figure C.8 – Tensile Modulus E_T (psi) vs. Time (hours) for Polyurea 269

C.9 Tensile Creep Modulus E_T Graph – Polyurea 269 Specimen, @ Stress 32.25 psi

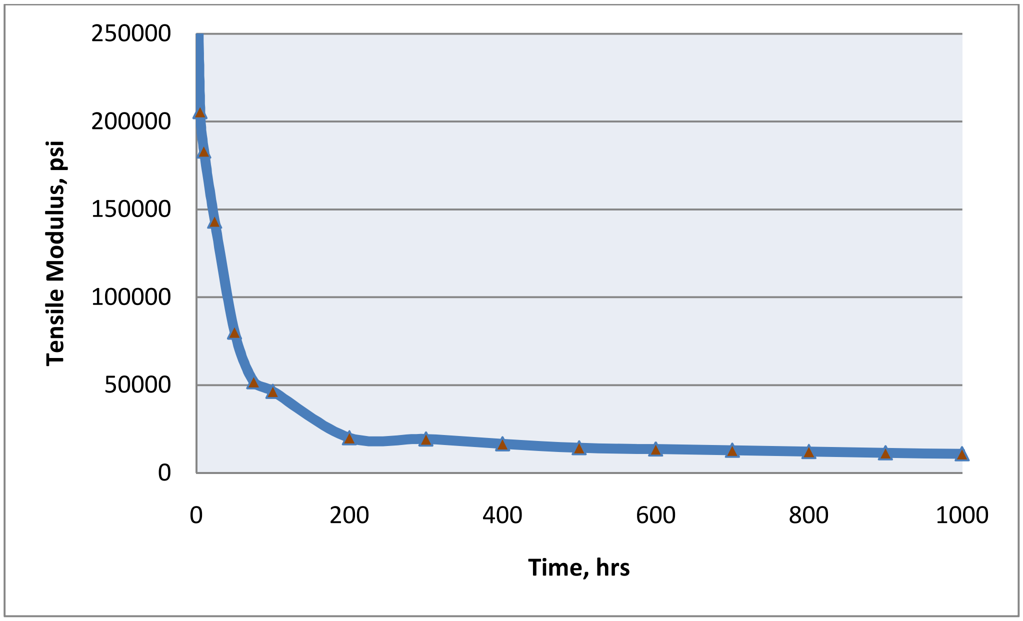


Figure C.9 – Tensile Modulus E_T (psi) vs. Time (hours) for Polyurea 269

C.10 Tensile Creep Modulus E_T Graph – Polyurea 269 Specimen, @ Stress 48.38 psi

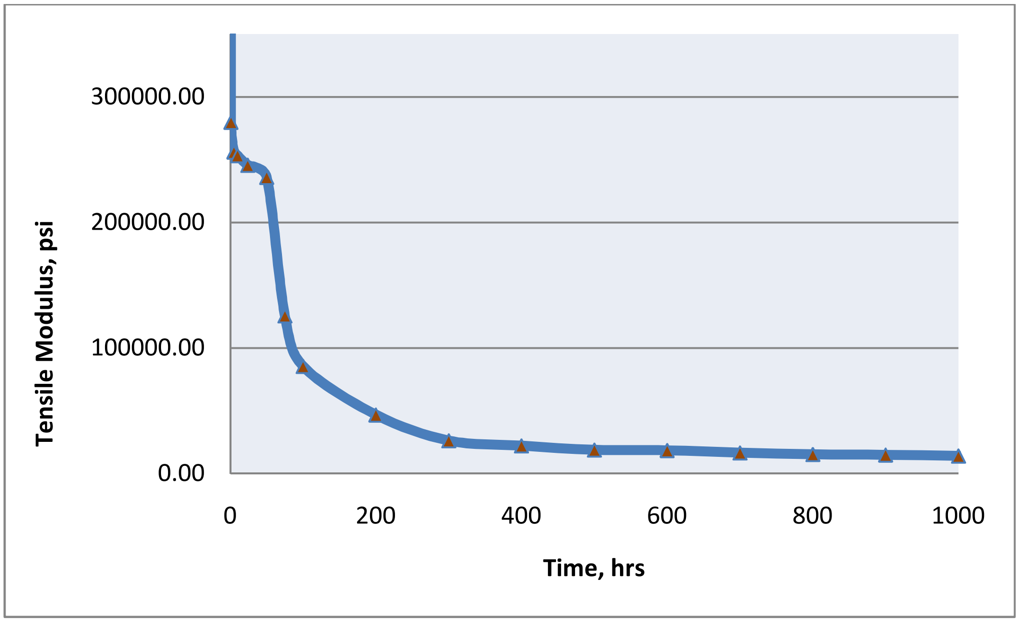


Figure C.10 – Tensile Modulus E_T (psi) vs. Time (hours) for Polyurea 269

APPENDIX D

FLEXURAL CREEP STRAIN DATA

D.1 Flexural Creep Strain Data – Polyurea 169 Specimen, @ Stress 33.87 psi.

Creep of Polyurea 169 Flexural Loading at Room Temperature

Specimen = LF-1-169

Load, lbs = 0.01

Stress, psi = 33.87

Duration = 1000 hrs

Date	Time (hrs)	Temperature ^{o}F	Deflection (mm)	Strain	% Strain
20-Jan-10	0.0167	71	0.0250	0.00010	0.0194
20-Jan-10	1	71	0.0380	0.00020	0.0292
20-Jan-10	5	71	0.0640	0.00040	0.0490
20-Jan-10	10	71	0.0690	0.00050	0.0528
21-Jan-10	24	71	0.0760	0.00050	0.0585
22-Jan-10	50	70	0.0820	0.00062	0.0631
24-Jan-10	75	70	0.0820	0.00063	0.0631
25-Jan-10	100	70	0.0880	0.00068	0.0680
29-Jan-10	200	72	0.1140	0.00087	0.0875
02-Feb-10	300	73	0.1270	0.00097	0.0972
06-Feb-10	400	71	0.1520	0.00117	0.1166
10-Feb-10	500	72	0.1650	0.00126	0.1263
14-Feb-10	600	69	0.1710	0.00131	0.1312
18-Feb-10	700	69	0.1760	0.00135	0.1350
22-Feb-10	800	69	0.1905	0.00146	0.1460
26-Feb-10	900	70	0.2007	0.00154	0.1540
02-Mar-10	1000	71	0.2134	0.00163	0.1600

D.2 Flexural Creep Strain Data – Polyurea 169 Specimen, @ Stress 27.09 psi.

Creep of Polyurea 169 Flexural Loading at Room Temperature

Specimen = LF-2-169

Load, lbs = 0.08

Stress, psi = 27.097

Duration = 1000 hrs

Date	Time (hrs)	Temperature ^{o}F	Deflection (mm)	Strain	% Strain
20-Jan-10	0.0167	71	0.0200	0.00010	0.0153
20-Jan-10	1	71	0.0400	0.00030	0.0306
20-Jan-10	5	71	0.0500	0.00030	0.0383
20-Jan-10	10	71	0.0550	0.00040	0.0421
21-Jan-10	24	71	0.0650	0.00050	0.0497
22-Jan-10	50	70	0.0850	0.00060	0.0651
24-Jan-10	75	70	0.0900	0.00060	0.0689
25-Jan-10	100	70	0.0950	0.00070	0.0727
29-Jan-10	200	72	0.1100	0.00080	0.0842
02-Feb-10	300	73	0.1450	0.00110	0.1110
06-Feb-10	400	71	0.1735	0.00133	0.1330
10-Feb-10	500	72	0.1775	0.00136	0.1360
14-Feb-10	600	69	0.1800	0.00138	0.1378
18-Feb-10	700	69	0.1835	0.00140	0.1404
22-Feb-10	800	69	0.1895	0.00145	0.1450
26-Feb-10	900	70	0.1930	0.00148	0.1477
02-Mar-10	1000	71	0.1945	0.00149	0.1488

D.3 Flexural Creep Strain Data – Polyurea 169 Specimen, @ Stress 40.64 psi.

Creep of Polyurea 169 Flexural Loading at Room Temperature

Specimen = LF-3-169

Load, lbs = 0.12

Stress, psi = 40.64

Duration = 1000 hrs

Date	Time (hrs)	Temperature ^{o}F	Deflection (mm)	Strain	% Strain
22-Jan-10	0.0167	71	0.030	0.00020	0.023
22-Jan-10	1	71	0.045	0.00030	0.034
22-Jan-10	5	71	0.055	0.00040	0.042
22-Jan-10	10	71	0.060	0.00040	0.046
23-Jan-10	24	71	0.070	0.00050	0.054
24-Jan-10	50	70	0.100	0.00070	0.077
27-Jan-10	75	70	0.105	0.00080	0.080
28-Jan-10	100	70	0.115	0.00080	0.088
01-Feb-10	200	72	0.130	0.00090	0.100
05-Feb-10	300	73	0.190	0.00140	0.145
09-Feb-10	400	71	0.230	0.00176	0.176
13-Feb-10	500	72	0.230	0.00176	0.176
17-Feb-10	600	69	0.240	0.00184	0.184
21-Feb-10	700	69	0.245	0.00188	0.188
25-Feb-10	800	69	0.248	0.00189	0.189
01-Mar-10	900	71	0.250	0.00191	0.191
05-Mar-10	1000	70	0.253	0.00193	0.193

D.4 Flexural Creep Strain Data – Polyurea 169HB Specimen, @ Stress 33.87 psi.

Creep of Polyurea 169HB Flexural Loading at Room Temperature

Specimen = LF-4-169HB

Load, lbs = 0.1

Stress, psi = 33.87

Duration = 1000 hrs

Date	Time (hrs)	Temperature ^{o}F	Deflection (mm)	Strain	% Strain
22-Jan-10	0.0167	71	0.038	0.00029	0.0292
22-Jan-10	1	71	0.076	0.00058	0.0583
22-Jan-10	5	71	0.116	0.00890	0.0892
22-Jan-10	10	71	0.153	0.00117	0.1172
23-Jan-10	24	71	0.183	0.00140	0.1402
24-Jan-10	50	70	0.240	0.00184	0.1837
27-Jan-10	75	70	0.304	0.00233	0.2333
28-Jan-10	100	70	0.342	0.00262	0.2624
01-Feb-10	200	72	0.485	0.00371	0.3713
05-Feb-10	300	73	0.558	0.00428	0.4277
09-Feb-10	400	71	0.850	0.00651	0.6512
13-Feb-10	500	72	0.895	0.00685	0.6853
17-Feb-10	600	69	0.990	0.00758	0.7581
21-Feb-10	700	69	1.016	0.00778	0.7776
25-Feb-10	800	69	1.270	0.00972	0.9719
01-Mar-10	900	71	1.295	0.00991	0.9914
05-Mar-10	1000	70	1.301	0.00996	0.9960

D.5 Flexural Creep Strain Data – Polyurea 169HB Specimen, @ Stress 40.64 psi.

Creep of Polyurea 169HB Flexural Loading at Room Temperature

Specimen = LF-5-169

Load, lbs = 0.12

Stress, psi = 40.64

Duration = 1000 hrs

Date	Time (hrs)	Temperature ^{o}F	Deflection (mm)	Strain	% Strain
22-Jan-10	0.0167	71	0.020	0.0001	0.0153
22-Jan-10	1	71	0.075	0.0005	0.0574
22-Jan-10	5	71	0.087	0.0006	0.0670
22-Jan-10	10	71	0.100	0.0007	0.0765
23-Jan-10	24	71	0.135	0.0010	0.1033
24-Jan-10	50	70	0.205	0.0015	0.1569
27-Jan-10	75	70	0.220	0.0016	0.1684
28-Jan-10	100	70	0.262	0.0020	0.2009
01-Feb-10	200	72	0.345	0.0026	0.2640
05-Feb-10	300	73	0.522	0.0040	0.3999
09-Feb-10	400	71	0.675	0.0052	0.5170
13-Feb-10	500	72	0.700	0.0054	0.5360
17-Feb-10	600	69	0.725	0.0055	0.5548
21-Feb-10	700	69	0.760	0.0058	0.5816
25-Feb-10	800	69	0.780	0.0060	0.5969
01-Mar-10	900	71	0.835	0.0064	0.6390
05-Mar-10	1000	70	0.852	0.0065	0.6520

D.6 Flexural Creep Strain Data – Polyurea 269 Specimen, @ Stress 33.87 psi.

Creep of Polyurea 269 Flexural Loading at Room Temperature

Specimen = LF-6-269

Load, lbs = 0.1

Stress, psi = 33.87

Duration = 1000 hrs

Date	Time (hrs)	Temperature ^{o}F	Deflection (mm)	Strain	% Strain
24-Jan-10	0.0167	71	0.020	0.00010	0.015
24-Jan-10	1	71	0.210	0.00160	0.161
24-Jan-10	5	71	0.600	0.00450	0.459
24-Jan-10	10	71	0.720	0.00550	0.551
25-Jan-10	24	71	0.960	0.00730	0.735
27-Jan-10	50	70	0.985	0.00750	0.754
29-Jan-10	75	70	1.250	0.00950	0.957
31-Jan-10	100	70	1.620	0.01240	1.240
03-Feb-10	200	72	2.280	0.01740	1.745
07-Feb-10	300	73	3.645	0.02790	2.790
11-Feb-10	400	71	5.055	0.03860	3.869
15-Feb-10	500	72	5.500	0.04200	4.209
19-Feb-10	600	69	5.950	0.04550	4.554
23-Feb-10	700	69	6.500	0.04970	4.975
27-Feb-10	800	69	6.930	0.05304	5.300
03-Mar-10	900	70	7.000	0.05357	5.360
07-Mar-10	1000	70	7.350	0.05625	5.625

D.7 Flexural Creep Strain Data – Polyurea 269 Specimen, @ Stress 27.09 psi.

Creep of Polyurea 269 Flexural Loading at Room Temperature

Specimen = LF-7-269

Load, lbs = 0.08

Stress, psi = 27.09

Duration = 1000 hrs

Date	Time (hrs)	Temperature ^{o}F	Deflection (mm)	Strain	% Strain
24-Jan-10	0.0167	71	0.055	0.00040	0.042
24-Jan-10	1	71	0.227	0.00170	0.174
24-Jan-10	5	71	0.370	0.00280	0.283
24-Jan-10	10	71	0.490	0.00370	0.375
25-Jan-10	24	71	0.675	0.00510	0.517
27-Jan-10	50	70	1.175	0.00890	0.899
29-Jan-10	75	70	1.465	0.01120	1.121
31-Jan-10	100	70	1.772	0.01350	1.357
03-Feb-10	200	72	1.825	0.01390	1.397
07-Feb-10	300	73	2.075	0.01580	1.588
11-Feb-10	400	71	2.695	0.02063	2.063
15-Feb-10	500	72	2.950	0.02258	2.258
19-Feb-10	600	69	3.105	0.02376	2.376
23-Feb-10	700	69	3.350	0.02564	2.564
27-Feb-10	800	69	3.700	0.02832	2.832
03-Mar-10	900	70	4.105	0.03142	3.142
07-Mar-10	1000	70	4.500	0.03444	3.444

D.8 Flexural Creep Strain Data – Polyurea 269 Specimen, @ Stress 20.32 psi.

Creep of Polyurea 269 Flexural Loading at Room Temperature

Specimen = LF-8-269

Load, lbs = 0.06

Stress, psi = 20.32

Duration = 1000 hrs

Date	Time (hrs)	Temperature ^{o}F	Deflection (mm)	Strain	% Strain
24-Jan-10	0.0167	71	0.055	0.00042	0.042
24-Jan-10	1	71	0.150	0.00115	0.115
24-Jan-10	5	71	0.235	0.00180	0.180
24-Jan-10	10	71	0.290	0.00222	0.222
25-Jan-10	24	71	0.420	0.00321	0.321
27-Jan-10	50	70	0.705	0.00540	0.540
29-Jan-10	75	70	0.900	0.00689	0.689
31-Jan-10	100	70	1.070	0.00819	0.819
03-Feb-10	200	72	1.740	0.01332	1.332
07-Feb-10	300	73	2.420	0.01852	1.852
11-Feb-10	400	71	3.450	0.02640	2.640
15-Feb-10	500	72	3.770	0.02885	2.890
19-Feb-10	600	69	3.990	0.03054	3.050
23-Feb-10	700	69	4.290	0.03283	3.280
27-Feb-10	800	69	4.480	0.03429	3.430
03-Mar-10	900	70	4.850	0.03712	3.710
07-Mar-10	1000	70	5.200	0.03980	3.980

APPENDIX E

FLEXURAL CREEP STRAIN GRAPH

E.1 Flexural Creep Strain Data – Polyurea 169 Specimen, @ Stress 33.87 psi

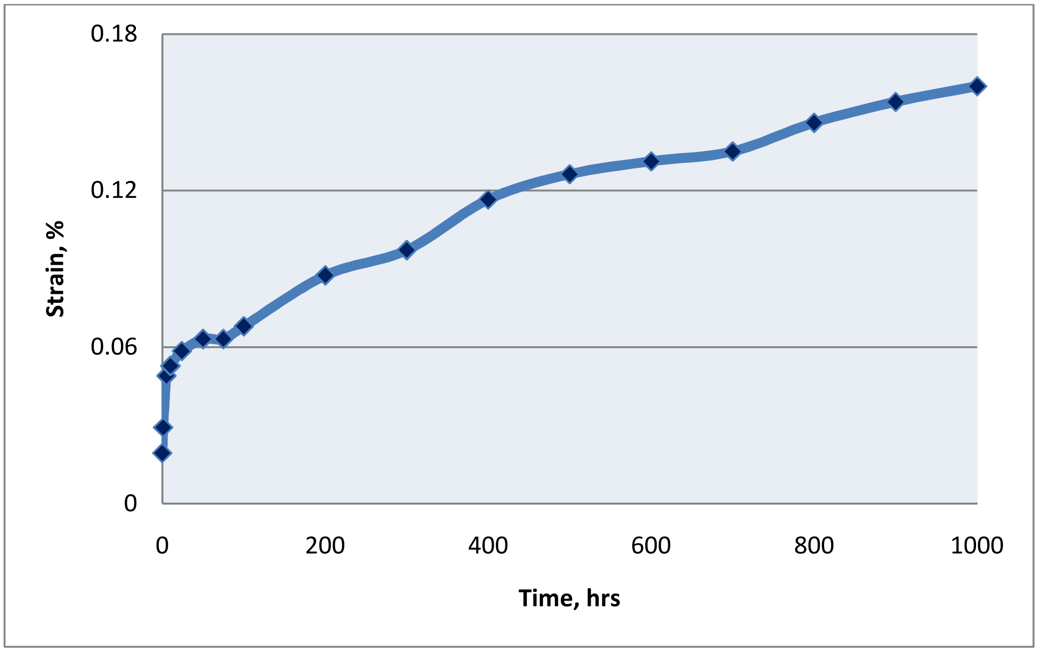


Figure E.1 – Strain (%) vs. Time (hours) for Polyurea 169

E.2 Flexural Creep Strain Data – Polyurea 169 Specimen, @ Stress 27.09 psi

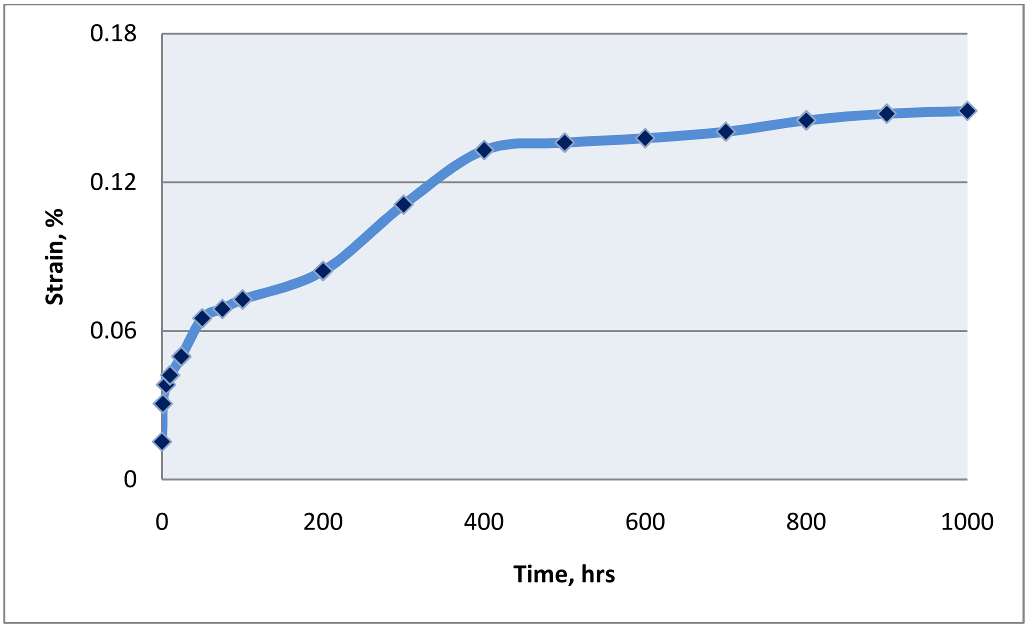


Figure E.2 – Strain (%) vs. Time (hours) for Polyurea 169

E.3 Flexural Creep Strain Data – Polyurea 169 Specimen, @ Stress 40.64 psi

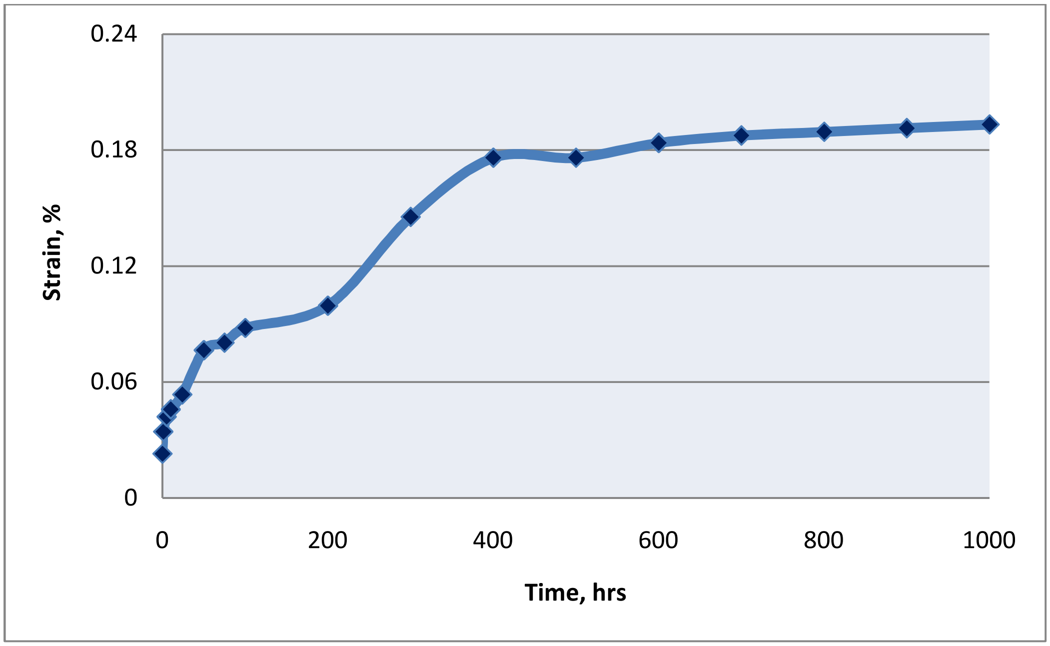


Figure E.3 – Strain (%) vs. Time (hours) for Polyurea 169

E.4 Flexural Creep Strain Data – Polyurea 169HB Specimen, @ Stress 40.64 psi

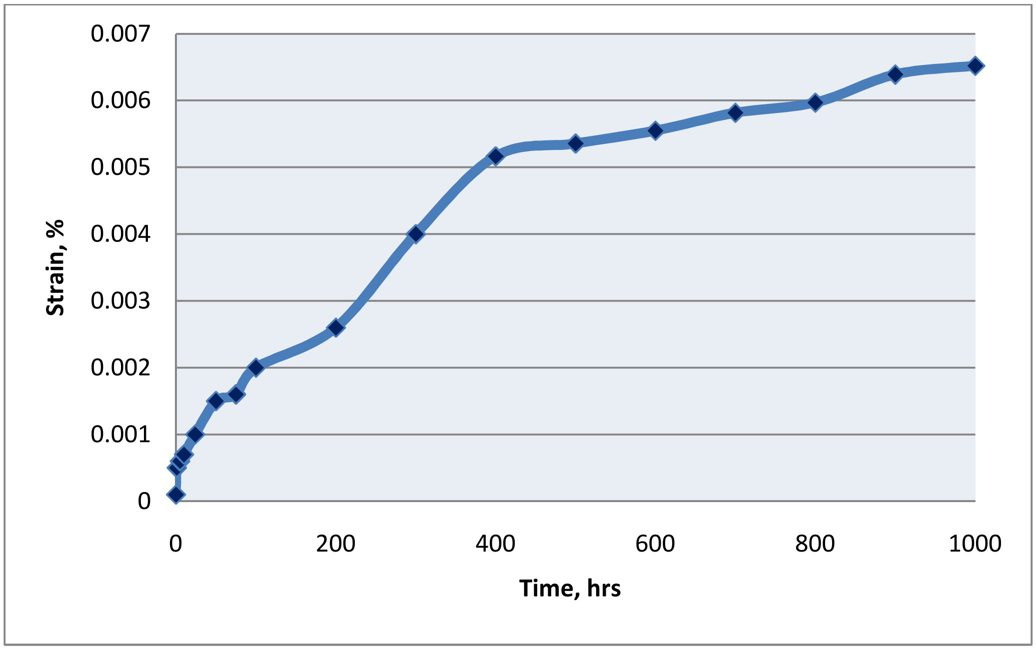


Figure E.4 – Strain (%) vs. Time (hours) for Polyurea 169HB

E.5 Flexural Creep Strain Data – Polyurea 169HB Specimen, @ Stress 33.87 psi.

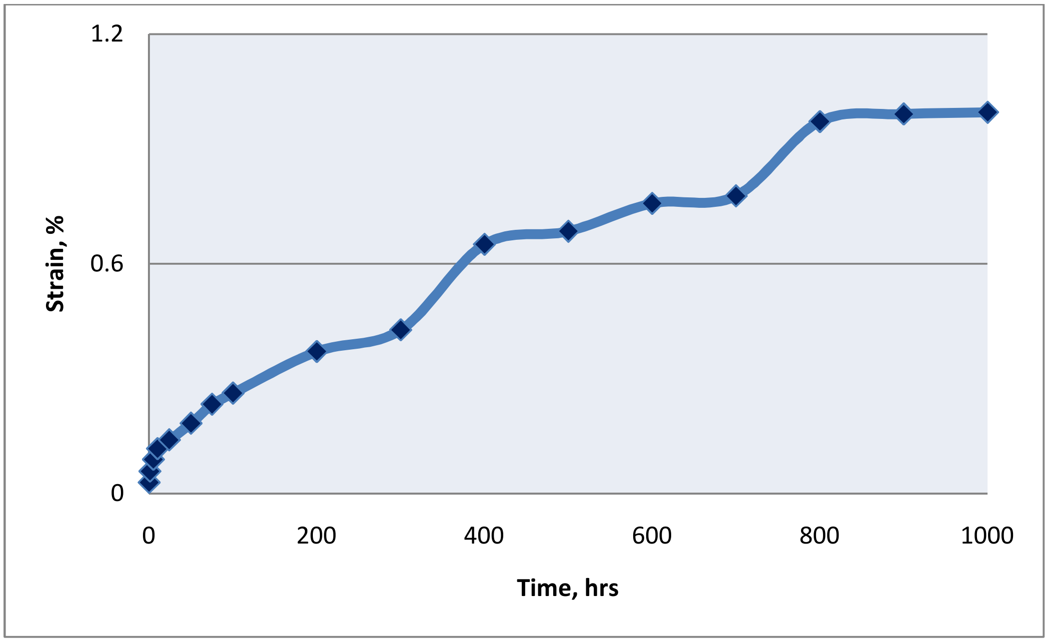


Figure E.5 – Strain (%) vs. Time (hours) for Polyurea 169HB

E.6 Flexural Creep Strain Data – Polyurea 269 Specimen, @ Stress 33.87 psi

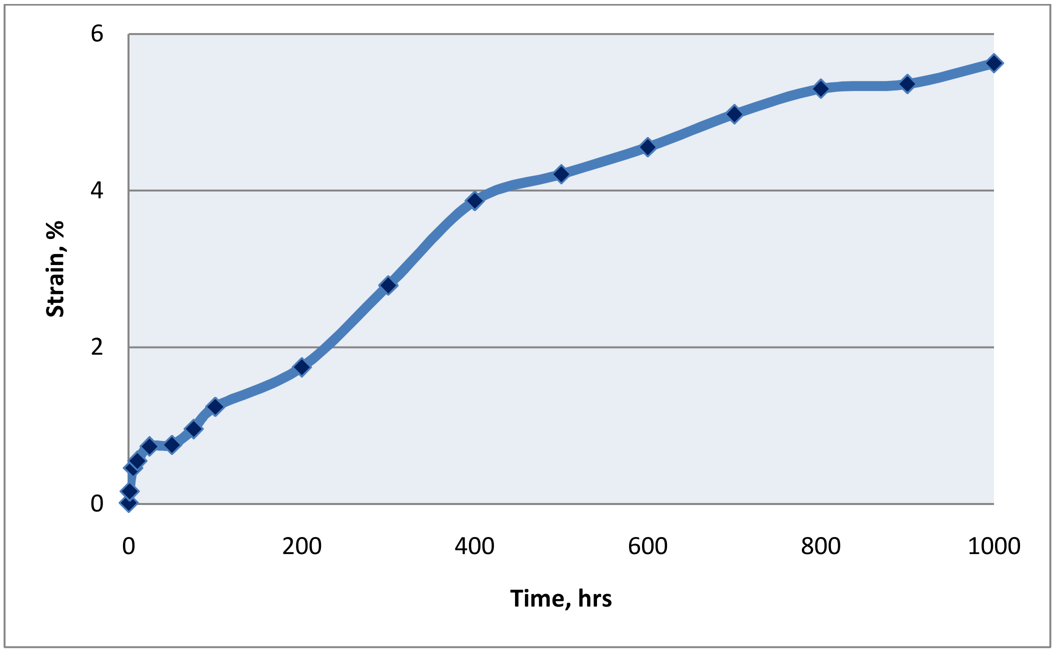


Figure E.6 – Strain (%) vs. Time (hours) for Polyurea 269

E.7 Flexural Creep Strain Data – Polyurea 269 Specimen, @ Stress 27.09 psi

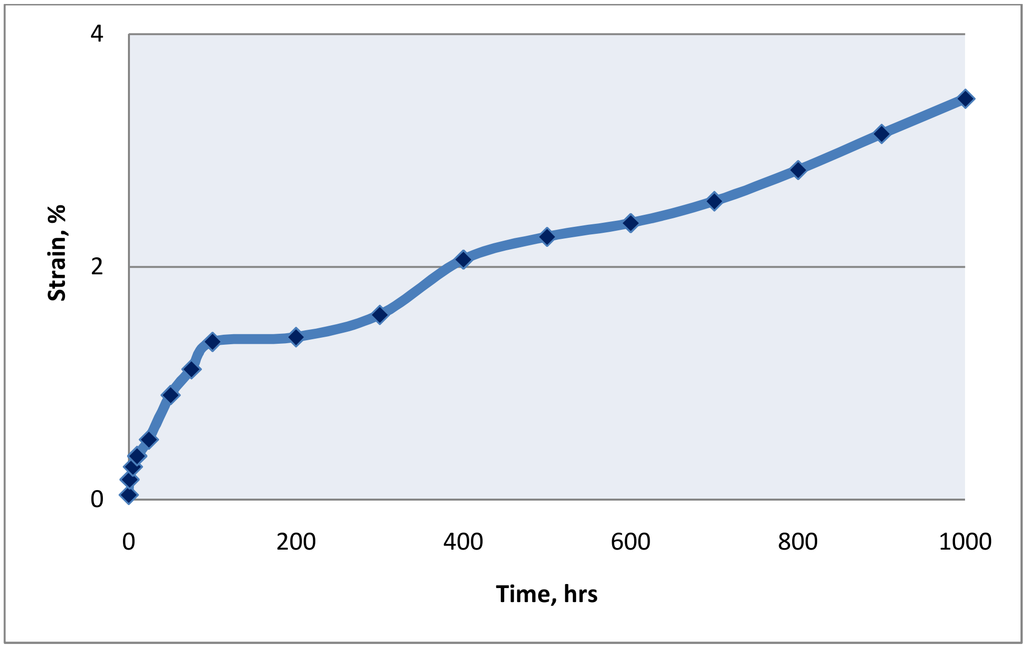


Figure E.7 – Strain (%) vs. Time (hours) for Polyurea 269

E.8 Flexural Creep Strain Data – Polyurea 269 Specimen, @ Stress 20.32 psi

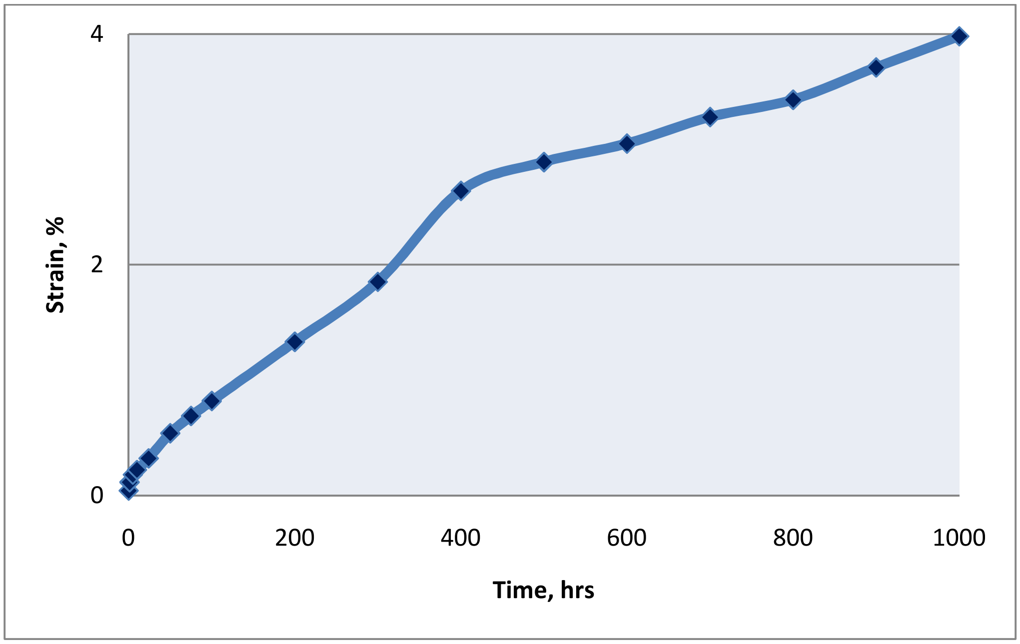


Figure E.8 – Strain (%) vs. Time (hours) for Polyurea 269

APPENDIX F

FLEXURAL CREEP MODULUS GRAPH

F.1 Flexural Creep Modulus E_F Data – Polyurea 169 Specimen, @ Stress 33.87 psi

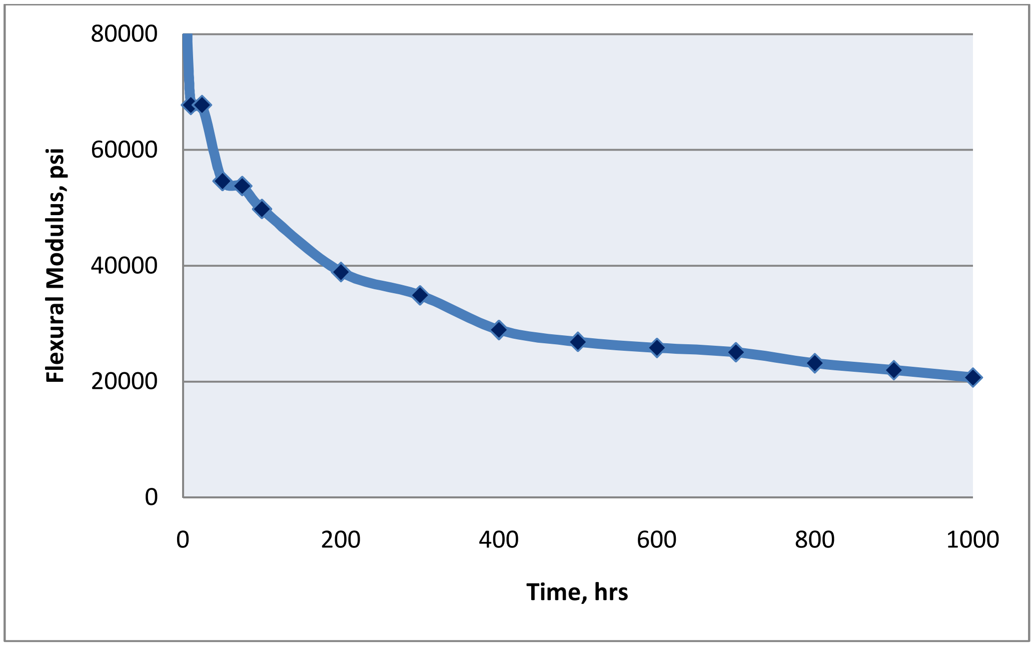


Figure F.1 – Flexural Modulus E_F (psi) vs. Time (hours) for Polyurea169

F.2 Flexural Creep Modulus E_F Data – Polyurea 169 Specimen, @ Stress 27.09 psi

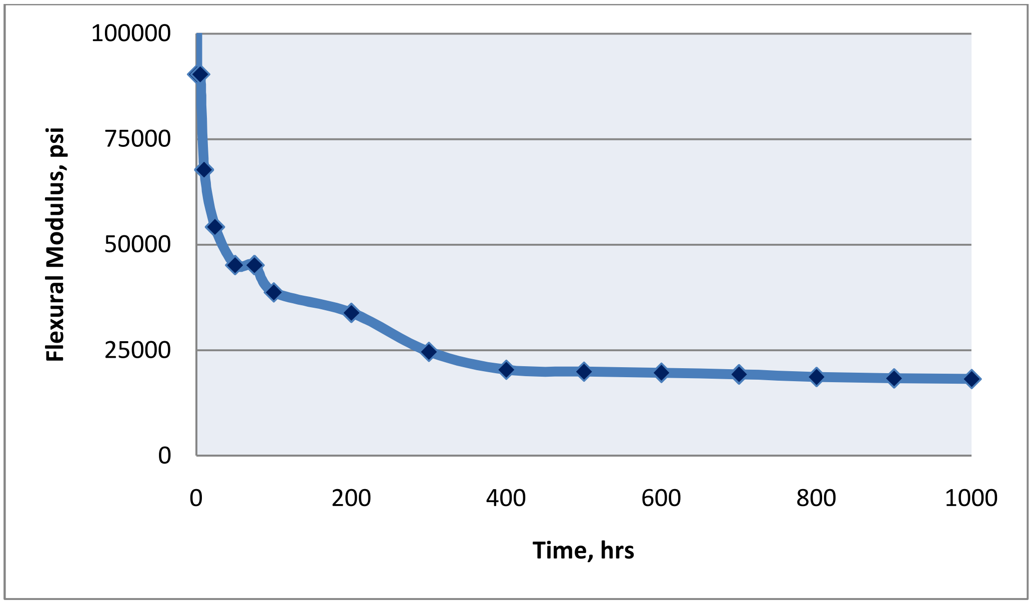


Figure F.2 – Flexural Modulus E_F (psi) vs. Time (hours) for Polyurea 169

F.3 Flexural Creep Modulus E_F Data – Polyurea 169 Specimen, @ Stress 40.64 psi

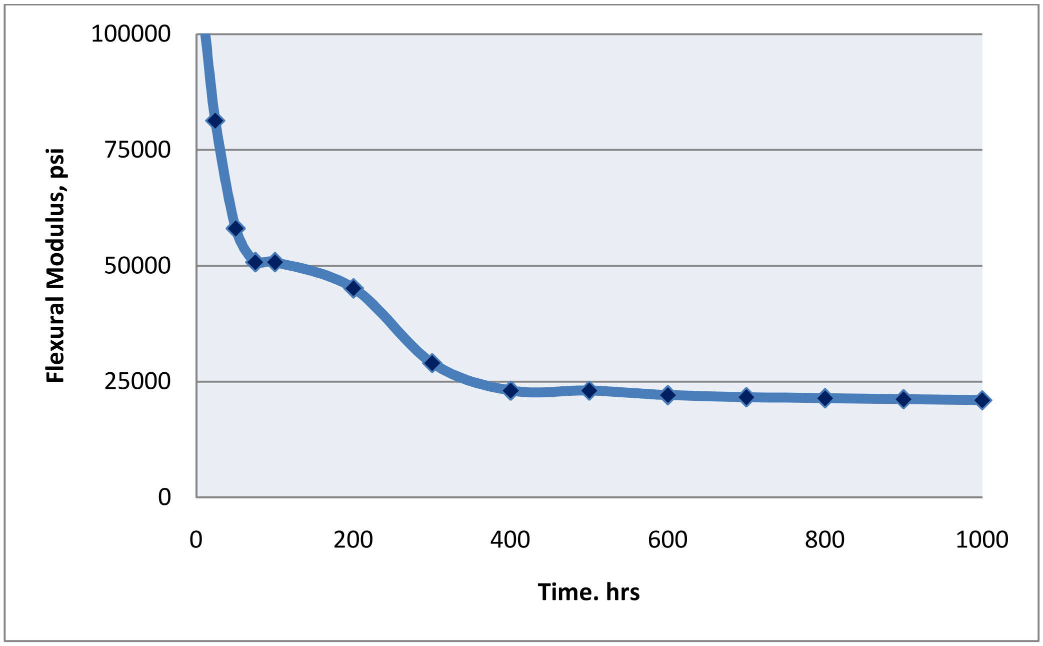


Figure F.3 – Flexural Modulus E_F (psi) vs. Time (hours) for Polyurea 169

F.4 Flexural Creep Modulus E_F Data – Polyurea 169HB Specimen, @ Stress 40.64 psi

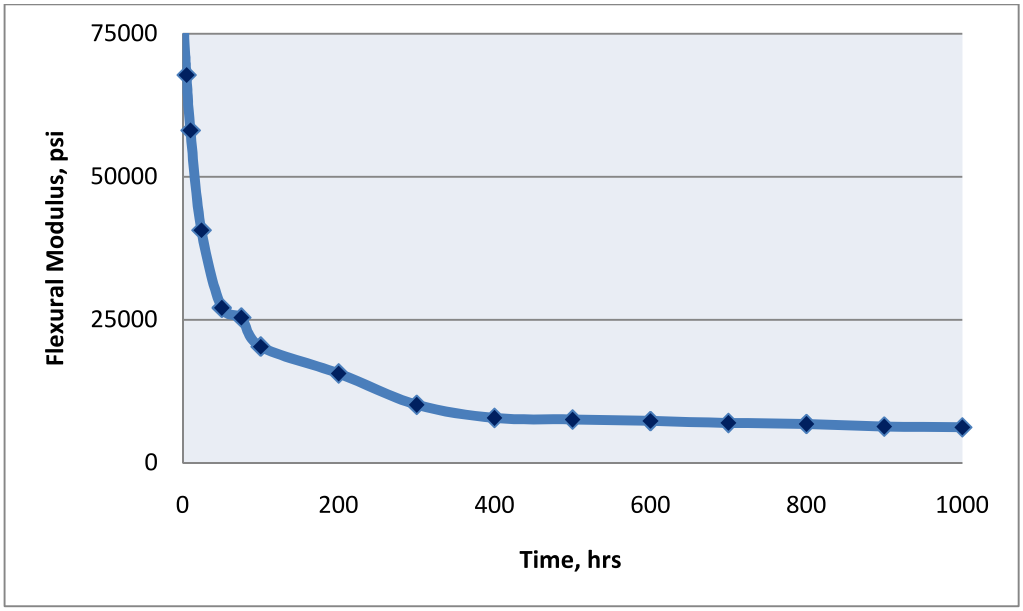


Figure F.4 – Flexural Modulus E_F (psi) vs. Time (hours) for Polyurea 169HB

F.5 Flexural Creep Modulus E_F Data – Polyurea 169HB Specimen, @ Stress 33.87 psi

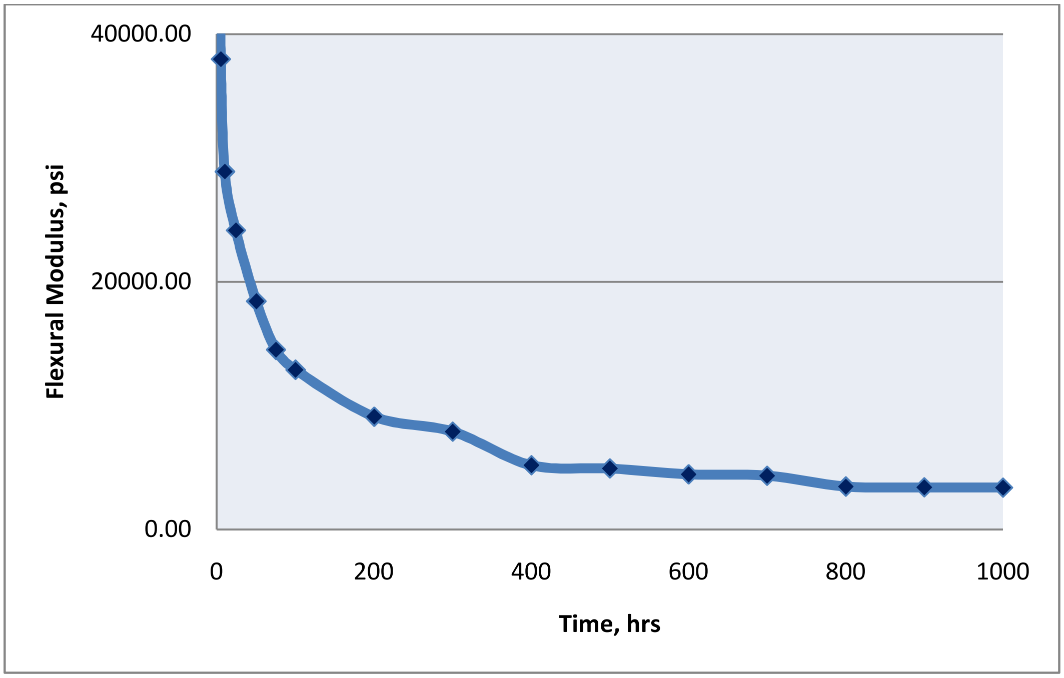


Figure F.5 – Flexural Modulus E_F (psi) vs. Time (hours) for Polyurea 169HB

F.6 Flexural Creep Modulus E_F Data – Polyurea 269 Specimen, @ Stress 33.87 psi

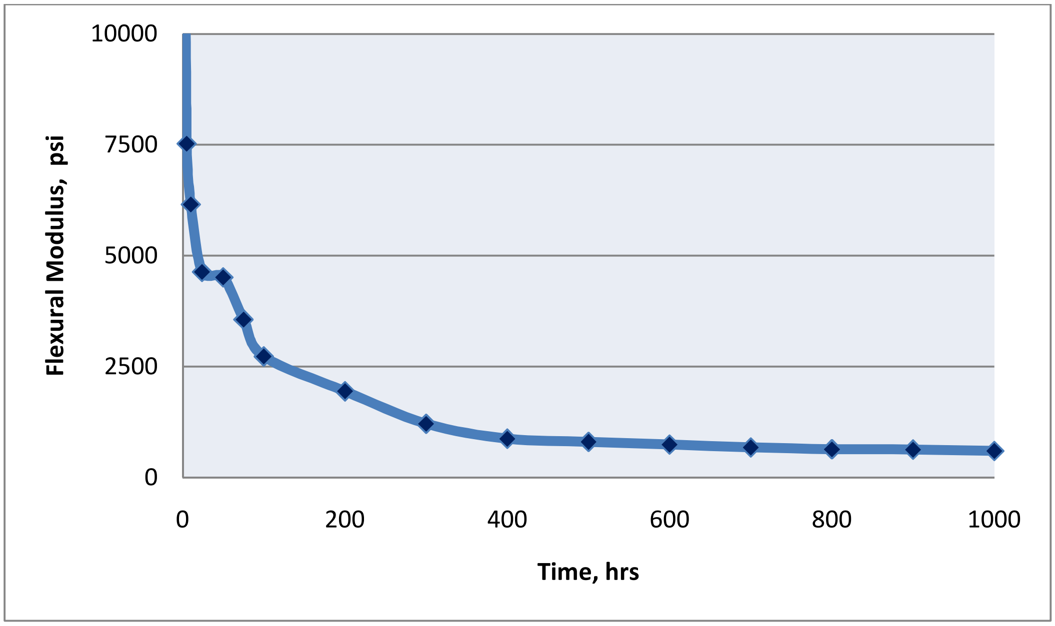


Figure F.6 – Flexural Modulus E_F (psi) vs. Time (hours) for Polyurea 269

F.7 Flexural Creep Modulus E_F Data – Polyurea 269 Specimen, @ Stress 27.09 psi

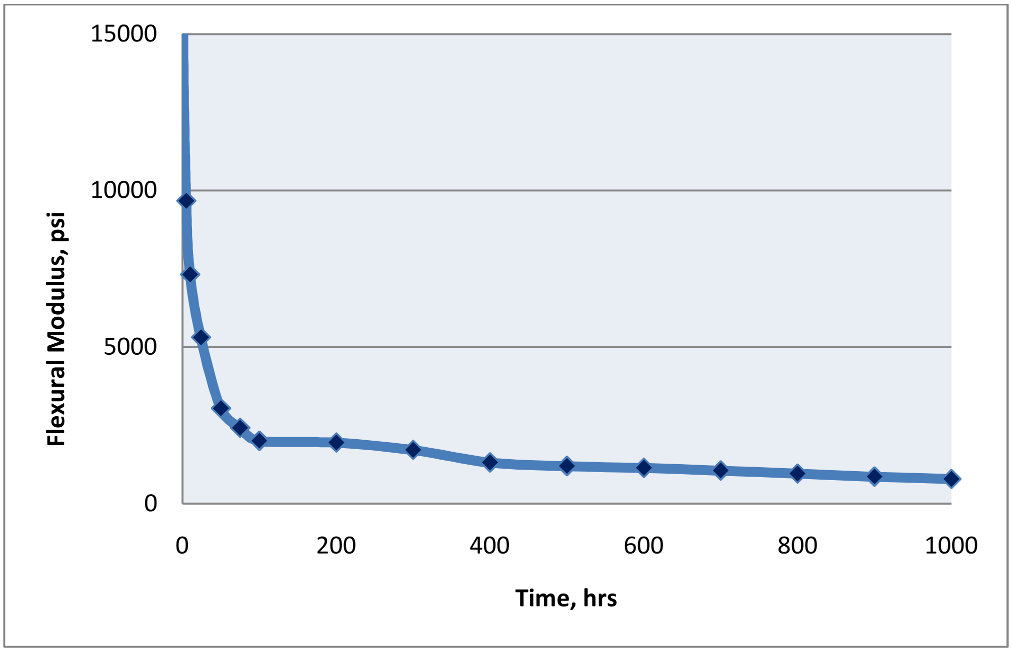


Figure F.7 – Flexural Modulus E_F (psi) vs. Time (hours) for Polyurea 269

F.8 Flexural Creep Modulus E_F Data – Polyurea 269 Specimen, @ Stress 20.32 psi

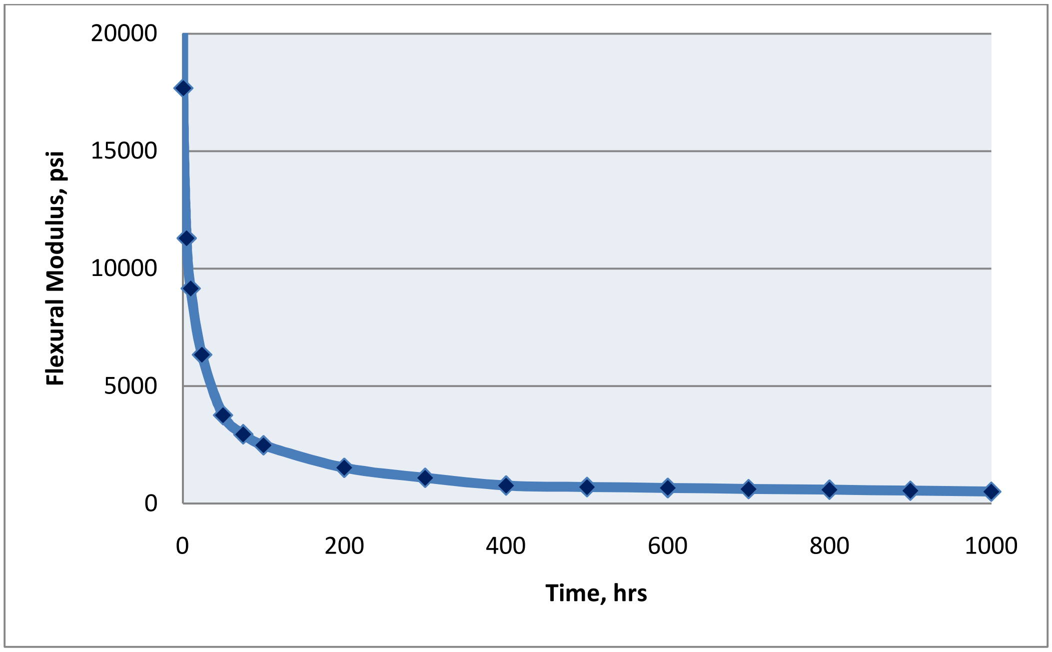


Figure F.8 – Flexural Modulus E_F (psi) vs. Time (hours) for Polyurea 269

APPENDIX G

LIST OF ABBREVIATIONS AND SYMBOLS

LIST OF ABBREVIATIONS AND SYMBOLS

ASCE	American Society of Civil Engineers
ASTM	American Society for Testing and Materials
AWWA	American Water Works Association
CATT	The Centre for Advancement of Trenchless Technologies
CCTV	Closed-circuit television
CIPP	Cured-in-Place-Pipe
EPA	Environmental Protection Agency
ISO	International Organization for Standardization
JTE	Journal of Testing and Evaluation
LF	Long-term Flexural
LT	Long-term Tensile
MS	Mild Steel
TTS	Time-Temperature Superposition
VOC	Volatile Organic Compound
WLF	Williams-Landel-Ferry
A	Cross-sectional Area
A_t	Shift Factor
C	Ovality Correction Factor
D_o	Mean Outer Lining Diameter
Δ	Deflection
E	Elastic Modulus of the Material
E_F	Long-term Flexural Modulus
E_R	Activation Energy Associated with the Relaxation
E_T	Long-term Tensile Modulus
ε	Strain that Occurs under the given Stress
F	Applied Force
J_o	Time independent Creep Compliance
J_t	Time Dependent Creep Compliance
K	Enhancement Factor
ΔL	Change in Length
L_o	Original Length
L_t	Length at any Given Time
η	Viscoelasticity of the material
σ	Experimental stress

REFERENCES

Aktaa, J., & Schinke B. (1996) "C*reep Lifetime Under Constant Load and Constant Stress: Theory and Experiment*" American Society For Testing and Materials (1996) 24(4) 212-222.

Alegre, H., J. Baptista, E. Cabrera, J. Cubillo, P. Duarte, W. Hirner, W. Merkel and R. Parena. 2006. "*Performance Indicators for Water Supply Services"*. Second Edition, London: International Water Association Publishing.

Alireza V. A., Isaacs. J., Mcgee. J., and Nematnasser. S. Primeaux II, D. J. (2004), "*An Experimentally-Based Viscoelastic Constitutive Model for Polyurea, Including Pressure and Temperature Effects*," Polyurea Elastomer Technology: History, Chemistry & Basic Formulating Techniques.

American Society of Civil Engineers (ASCE), (2006). "*Report Card for America's Infrastructure; Drinking Water*". American Society of Civil Engineers. Reston, VA.

American Society of Civil Engineers (ASCE) (2009). "*Report Card for America's Infrastructure*." Reston, VA. Available at: http://www.asce.org/reportcard/2009/grades.cfm <accessed on February 2009>

ASTM F 1216 (2009), "*Standard Practice for Rehabilitation of Existing Pipelines and Conduits by the Inversion and Curing of a Resin-Impregnated Tube*," American Society for Testing Materials, West Conshohocken, Pa.

ASTM D2990 (2009), "*Standard Test Methods for Tensile, Compressive, and Flexural Creep and Creep-Rupture of Plastics*." American Society for Testing and Materials, West Conshohocken, Pa.

ASTM D638 (2008), "*Standard Test Method for Tensile Properties of Plastics*." American Society for Testing and Materials, West Conshohocken, Pa.

ASTM D790 (2007), "*Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials.*" American Society for Testing and Materials, West Conshohocken, Pa.

AWWA (2001). “*Manual of Water Supply Practices M28: Rehabilitation of Water Mains*”, American Water Works Association, Denver

AWWA (2006). “*Service Life Analysis of Water Main Epoxy Lining*” American Water Works Association, Denver.

AWWA (2006). “*Infrastructure Reliability: Service Life Analysis of Water Main Epoxy Lining,*” American Water Works Association, Denver.

Barbero, E., & Rangarajan, S. (2005) “*Long-Term Testing Of Trenchless Pipe Liners*,” American Society for Testing and Materials (ASTM), West Conshohocken, PA.

Batra, S. (2009). “*Creep Rupture and Life-Prediction of Polymer Composite*,” M.S Thesis, West Virginia University, VA, 2009.

McCrum, Buckley, and Bucknell (2003). "*Principles of Polymer Engineering*," 117-176.

Copon Hycote 169HB, “*Technical Guidance Note: Semi Structural Polymeric Lining System*,” Company Brochure, E. Woods Company, United Kingdom. <accessed on December 2009>

Deb, A.K., Y.J. Hasit, and C. Norris. 1999. “*Demonstration of Innovative Water Main Renewal Techniques*”. Denver, CO: AWWARF, AWWA.

Ding. H. Z., Wang. Z. D., Phan-Thien. N. and Reol. J (1979). “*Time–Temperature Superposition Method for Predicting the Performance of Paper by Extrapolating Accelerated Ageing Data to Ambient Conditions*” 23 (4) 451–456.

Environmental Protection Agency (EPA), 2002. “*The Clean Water and Drinking Water Infrastructure Gap Analysis”*. United States Environmental Protection Agency. Washington, DC.

Ferry JD. “*Viscoelastic Properties of Polymers*.” Chichester: Wiley, 1980.

Findley, W. N . and Khosla. G. (1956) “An Equation for Tension Creep of Three Unfilled Thermoplastics,” Society of Petroleum Engineers Technical Journal December 1956, 20-25.

Findley W. N, (1987) “*26 Years Creep and Recovery of Poly (Vinyl Chloride) and Polyethylene*,” Polymer Engineering and Science 27(1987): 582-585.

Findley, W. N, (1944) “*Creep Characteristics of Plastics,*” Symposium on Plastics, American Society for Testing and Materials (1944):18.

Findley, W. N., Lai, S. N., and Onaran, K. (1989). "*Creep and relaxation of nonlinear viscoelastic materials, with an introduction to linear Viscoelasticity*" Dover Publications, NY.

Guan, S.W. (2003). "*100% Solids Polyurethane and Polyurea Coatings Technology,"* Coatings World, pp.49-58.

Guermazi. N., Elleuch. K., Ayedi. H.K., Kapsa. Ph., Raghavan. J., and Meshii. M. (1997) "*Ageing Effect on Thermal, Mechanical and Tribological Behaviour of Polymeric Coatings Used for Pipeline Application*", Composite Science Technology, 57, 375.

Guerrero, J.N., (1999). "*Flexural Creep Analysis of Recycled Polymeric Structural Elements*" PhD Dissertation, Louisiana State University and Agriculture and Mechanical College.

Guidetti, G.P., Rigosi, G.L., Marzola, R., 1996. "*The Use of Polypropylene in Pipeline Coatings*." Progress in Organic Coating. 27, 79–85.

Harris, G.M., Lorenz, A., 1993. "*New Coatings for the Corrosion Protection of Steel Pipelines and Pilings in Severely Aggressive Environments*." Corrosion Science. 35, 1417–1423.

Heavens, J.W. (1997). "*The Trenchless Renovation of Potable Water Pipelines*." Proceeding of Annual Conference of American Water Works Association, Atlanta, GA.

ISO 899-1 (2003), "*Plastics - Determination of Creep Behavior - Part 1: Tensile Creep*." International Organization for Standardization, Geneva, Switzerland.

ISO 899-2 (2003), "*Plastics - Determination of Creep Behavior - Part 2: Flexural Creep by Three-point Loading*." International Organization for Standardization, Geneva, Switzerland.

Joachim, Markus. G., Christian. P, and W. Johannes, "*Polymer Test,"* 18, 257(1999).

Kamimura, T., Kishikawa, H., 1998. "Mechanism *of Cathodic Disbonding of Three Polyethylene Coated Steel Pip*es." Corrosion 54, 979–987.

Knight, M. (2005) "*Evaluation of Sanexen Technologies "AQUA-PIPE" Watermain Rehabilitation Product*," The Centre for the Advancement of Trenchless Technologies, Toronto, Canada.

Kulkarni, T., Kanchwala, M., Najafi, M., Natwig, G. and Perez, M. (2009). "*Renewal of Water Distribution Pipes using Elastomeric Polyurea Lining.*" Underground Construction Technology Conference, Tampa, Florida.

Lacroix, Tougui. F., Berton. A., Ranganathan. G. and Neelakantan. N. (2007). “*Tensile Creep Studies on Filled Polychloroprene Elastomer,*” Journal of Testing and Evaluation (JTE) N. R. Vol 35(4), 449-454.

Leng, A., Streckel, H., Stratmann, M., 1998a. “*The Delamination of Polymeric Coatings from Steel. Part 2: First Stage of Delamination, Effect of Type and Concentration of Cations on Delamination, Chemical Analysis of the Interface.*” Corrosion Science. 41, 579–597.

Li, R. (2000), “*Time-temperature Superposition Method for Glass Transition Temperature of Plastic Materials,*” Materials Science and Engineering A278, 36–45.

Lin, H., “*Creep Charaterization of CIPP Material Under Tension, Compression and Bending*,” M.S Thesis, Lousiana Tech University, LA, 1995.

Mallick, P.K (2008), “*Fiber-Reinforced Composites: Materials, Manufacturing and Design*,” Marcel Dekker Inc., New York, USA.

Miller, E., and Sterrett, T. (1988). “*An Evaluation of Analytical Expressions for the Representation of Plastics Creep Data,”* Journal of Elastomers and Plastics, Vol. 20(4), 346-362.

Mock.W., and Balizer.E, “*Polyurea Properties and Enhancement of Structures under Dynamic Loads*.” Airlie, VA (2005).

Najafi, M., & Gokhale, S. (2005). “*Trenchless Technology: Pipeline and Utility Design, Construction, and Renewal*”, New York: McGraw-Hill.

Park BD, Balatinez JJ. (1998) “*Short-term Flexural Creep Behavior of Wood-fiber/Polypropylene Composites Polymer Composites,”* 19(4):377–82.

Polimerov, M. (1972). “*Prediction of the Deformation and Fracture of Polymeric Material*” Institute of Polymer Mechanics, Academy of Sciences of the Latvian SSR, Riga, No. 3, pp. 498-514

Pomeroy CD. (1978) “*Creep of engineering materials.”* Cambridge U.K.

Primeaux II, D. J., (2000). “*Polyurea Spray Coating Systems*,” Primeaux Associates LLC.

Riande. E., Galleja. R. D., Prolongo. M. G., Masegosa. R. M., and Salom. C. (2000). “*Polymer Viscoelasticity Stress and Strain in Practic*e”, Marcel Dekker A.G, Switzerland.

Scotchkote 269, (2009). “*Rapid Setting Polymeric Lining 269*,” Design Guide for Polyurea Lining, Company Brochure, 3M Water Infrastructure.

Scotchkote 269, (2010). “*Rapid Setting Polymeric Lining 269*,” Installation Guide for Polyurea Lining, Company Brochure, 3M Water Infrastructure.

Shah, V. (1983). “*Handbook for Plastics Testing Technology*,” Wiley Interscience Publication, NY.

Straughan, W. T., Guice, L. K., and Mal-Duraipandian, C., *"Long-Term Structural Behavior of Pipeline Rehabilitation Systems*," ASCE Journal of Infrastructure Systems, December 1995.

Thomson, W., Guice. L. K., Straughan, W.T., Norris, C.R., Bennett, R. D., and Iseley, D.T., (1996). ATTC Report on “*Long-Term Structural Behavior of Pipeline Rehabilitation Systems - Closure*,” No-Dig Engineering, Vol. 3(4).

Tobolsky, A.V. (1967) “*Properties and Structure of Polymers*,” Wiley, New York, pp. 144–159

Vinogradov, G.V., Malkin, A.Y. (1980) “*Rheology of Polymers*,” Mir, Moscow, pp. 238–248.

Williams, J. G., (1980). “*Stress Analysis of Polymers*,” Ellis Horwood Limited, England.

WIN (2000). “*Clean and Safe Water for the 21st Century; A Renewed National Commitment to Water and Wastewater Infrastructure*,” Water Infrastructure Network. USA.

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