TESTING AND DESIGN LIFE ANALYSIS OF POLYUREA LINER MATERIALS

by

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Presented to the Faculty of the Graduate School of
The University of Texas at Arlington in Partial Fulfillment
of the Requirements
for the Degree of

MASTER OF SCIENCE IN CIVIL ENGINEERING

THE UNIVERSITY OF TEXAS AT ARLINGTON
December 2013

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ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my academic advisor and committee chair, Dr. Mohammad Najafi, P.E., F. ASCE. I appreciate his technical help and financial support for both my study and research. He introduced me to trenchless technologies and never doubted my capabilities. Without his guidance and persistent help, this testing and thesis would not have been possible.

I would also like to express my appreciation to Dr. Mostafa Ghandehari and Dr. Siamak Ardekani for taking time out of their busy schedule and giving me the profound honor of working under their supervision.

I am thankful to Dr. Mario Perez and Dr. Ryan Prince of 3M Water Infrastructure for providing technical advice and funding for this research. I am also grateful to all the UT- Arlington faculty and staff members, as well as colleagues and friends who provided any form of help during my studies as a graduate student. Twenty months spent at the Center for Underground Infrastructure Research and Education (CUIRE) were both interesting and fruitful.

I am grateful to Mr. Mustafa Kanchwala for initiating these series of experiments under direct supervision of Dr. Najafi in 2010 and his concept and test setup were used for other same experiments in CUIRE.

Finally, I would like to thank my parents and family for their endless love and encouragement throughout the course of my study at The University of Texas at Arlington.

November 25, 2013

ABSTRACT

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Certainly, water pipes, as part of an underground infrastructure system, play a key role in maintaining quality of life, health, and wellbeing of human kind. As these potable water pipes reach the end of their useful life, they create high maintenance costs, loss of flow capacity, decreased water quality, and increased dissatisfaction.

There are several different pipeline renewal techniques available for different applications, among which 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-on technique. It is applied to structurally enhance the host pipe and provide a barrier coating against further corrosion or deterioration.

The purpose of this study was to establish a relationship between stress, strain and time. The results obtained from these tests were used in predicting the strength of the polyurea material during its planned 50-year design life. In addition to this, based on the 10,000 hours experimental data, curve fitting and Findley power law models were employed to predict long-term behavior of the material. Experimental results indicated that the tested polyurea material offers a good balance of strength and stiffness and can be utilized in structural enhancement applications of potable water pipes.

TABLE OF CONTENTS

APPENDIX

LIST OF ILLUSTRATIONS

Figure Page

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1. Background

Pipeline systems have been in use for decades and are in need of renewal, replacement or repair due to significant deterioration. Renewal of existing water pipelines using “trenchless technology” has become more popular worldwide over the past few decades. In this family of methods, also known as NO-DIG technologies, the need for surface excavation is minimized or eliminated. Corrosion, age, pipe environment, operational factors, climate and many other issues play significant roles in the deterioration and subsequent failure of pipeline systems. The American Society for Testing and Materials (ASTM) classifies pipe deterioration into "partial deterioration" and “full deterioration" categories. Partially deteriorated pipe can carry soil and surcharge loads, but the weakened pipe structure is unable to resist hydrostatic loads. In the fully deteriorated condition, the pipe is present but is no longer considered to support the soil and the surcharge loads (ASTM F1216-2009).

The focus of this research is on using polyurea as a lining material to extend the service life of the partially deteriorated potable water pipelines. Polyurea is a relatively new lining material to be sprayed to the interior surface of the deteriorated host pipes using spray techniques. Polyurea enhances the structural ability of the host pipe. For the purpose of this study, commercially available polyurea composites are used. This rapid setting polymeric product is developed for long-term corrosion protection and potential structural renewal of portable water pipes. This innovative spray-on application addresses problems of water discoloration and odor as well.

1.2. Current Condition of Water Pipelines

Aging pipes and a lack of funding have made the renewal and maintenance of water pipelines a major challenge for engineers, utility owners, and decision makers. The American Water Works Association (AWWA) estimates that nearly $1 trillion is needed in critical drinking water pipeline replacement over the next 25 years to keep up with the demand for a growing population (ASCE Report Card, 2013). Efficient utilization of water pipeline designated funds will require managers and decision makers to employ optimal allocation and effective prioritization when managing infrastructure improvements.

Many factors such as age, hydraulic parameters of the fluids inside pipes, pipe material and soil conditions affect the deterioration rate of buried pipes. Often times, a number of these factors rather than an individual one determine the pipe condition (Figure 1.1). Figure 1.2 is a general example of pipe deterioration rate over time.

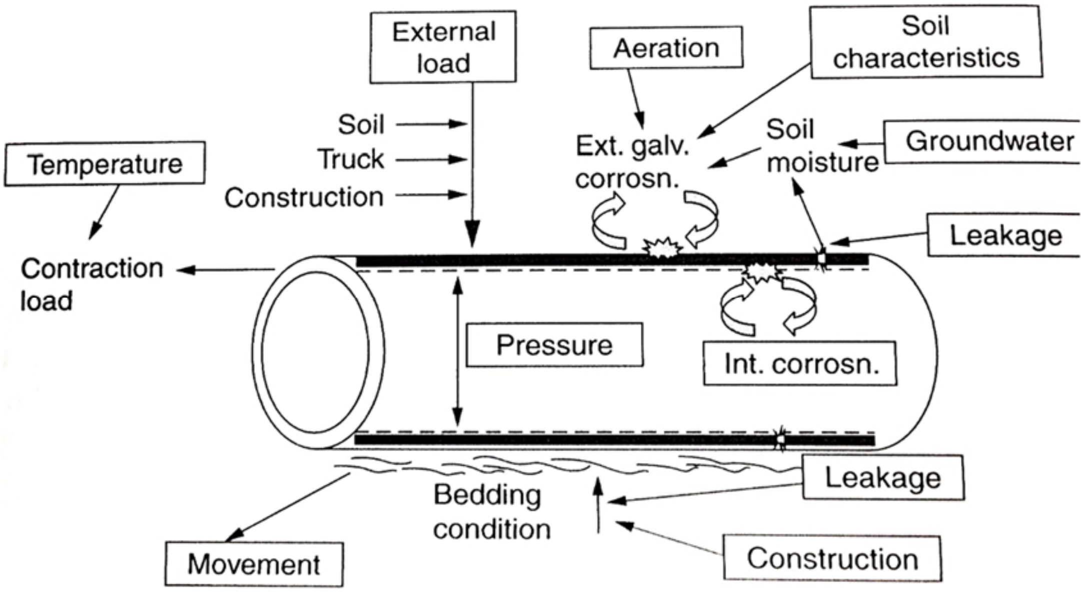
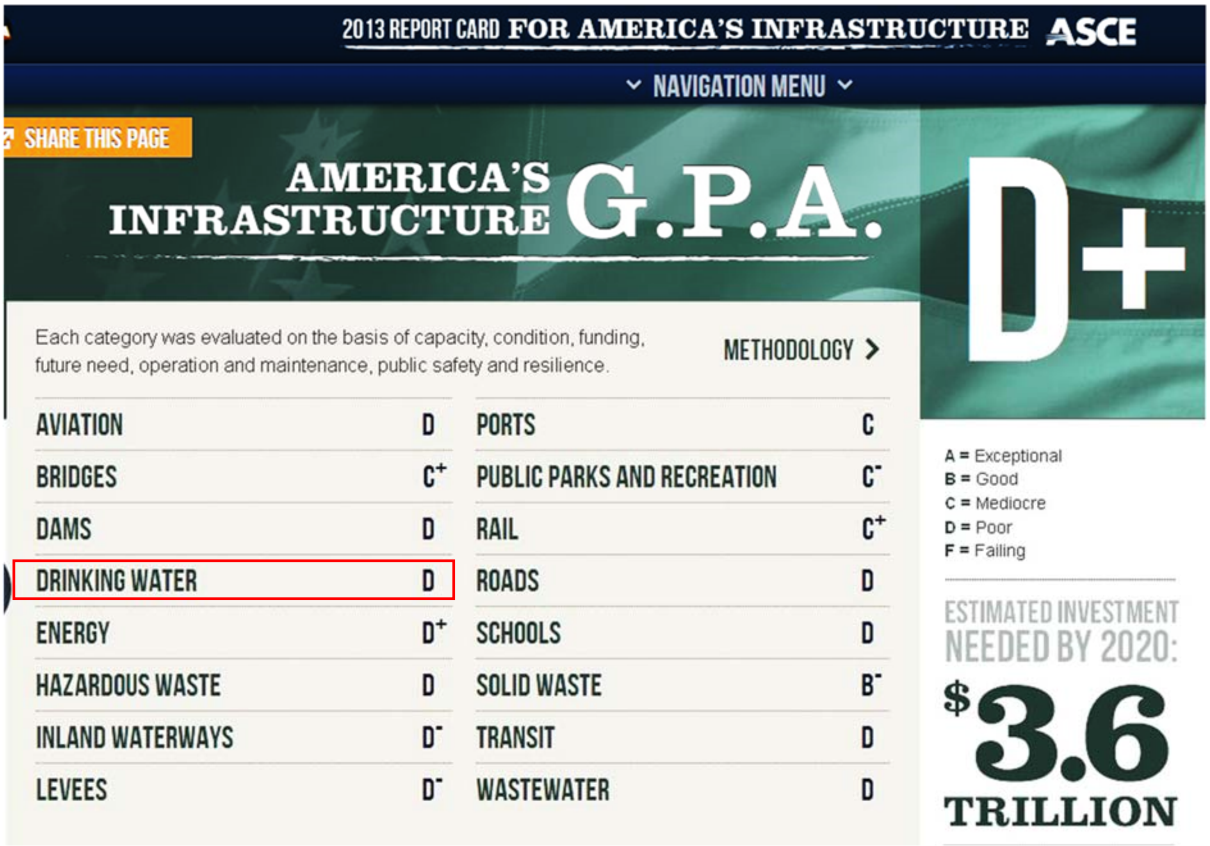


Figure 1.1 - Factors to Determine Pipe Condition (Source: Najafi & Gokhale, 2005)

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

The overall service of the pipeline system is affected by each of its components that are at the same time part of an integrated structure. The fact that most water pipes are buried also adds complexity to the problem due to the difficulty in assessing their condition. Water pipe asset management is, therefore, a complex and challenging subject, and it is currently an important agenda item for water supply stakeholders in industrialized countries (Alegre et al., 2006).

United States' infrastructure and drinking water systems were graded with "D^{+}" and "D" respectively by The American Society of Civil Engineers (ASCE) Report Card for the year 2013, as shown in Figure 1.3 (ASCE, 2013). ASCE further estimates that the total cost of infrastructure repair and replacement for 16 categories including drinking water has increased from $1.6 trillion in 2005 to $2.2 trillion in 2009 to $3.6 trillion in 2013 (ASCE, 2013).



2013 REPORT CARD FOR AMERICA'S INFRASTRUCTURE ASCE

NAVIGATION MENU

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AMERICA'S INFRASTRUCTURE G.P.A.

D+

Each category was evaluated on the basis of capacity, condition, funding, future need, operation and maintenance, public safety and resilience.

METHODOLOGY

AVIATION	D	PORTS	C
BRIDGES	C+	PUBLIC PARKS AND RECREATION	C-
DAMS	D	RAIL	C+
DRINKING WATER	D	ROADS	D
ENERGY	D+	SCHOOLS	D
HAZARDOUS WASTE	D	SOLID WASTE	B-
INLAND WATERWAYS	D-	TRANSIT	D
LEVEES	D-	WASTEWATER	D

A = Exceptional
B = Good
C = Mediocre
D = Poor
F = Failing

ESTIMATED INVESTMENT NEEDED BY 2020:

$3.6 TRILLION

Figure 1.3 - ASCE Report Card, GPA “D” for Drinking Water and Wastewater (ASCE, 2013)

Cast iron has been the major material used in manufacturing water pipes installed in the United States from late 1800's to late 1960's. Over time, deteriorating conditions have caused reduction in both structural integrity and hydraulic capacity of these pipes. Service and traffic disruptions as a result of pipe bursts or flooding are examples of pipe failures that interrupt everyday life. These issues highlight the importance of proper management and maintenance of pipeline systems.

A recent increase in the number of pipe failures has intensified the need for the renewal of pipelines to stop their degradation. Figure 1.4 shows the total water main replacement and growth needs (AWWA, 2011). When lined, the corroded pipes should see a reduction in the rate of further deterioration. While specific causes of pipe degradation is not fully understood, but as explained in this thesis, polyurea linings can potentially improve the 50-year life expectancy of these old and deteriorated pipelines.

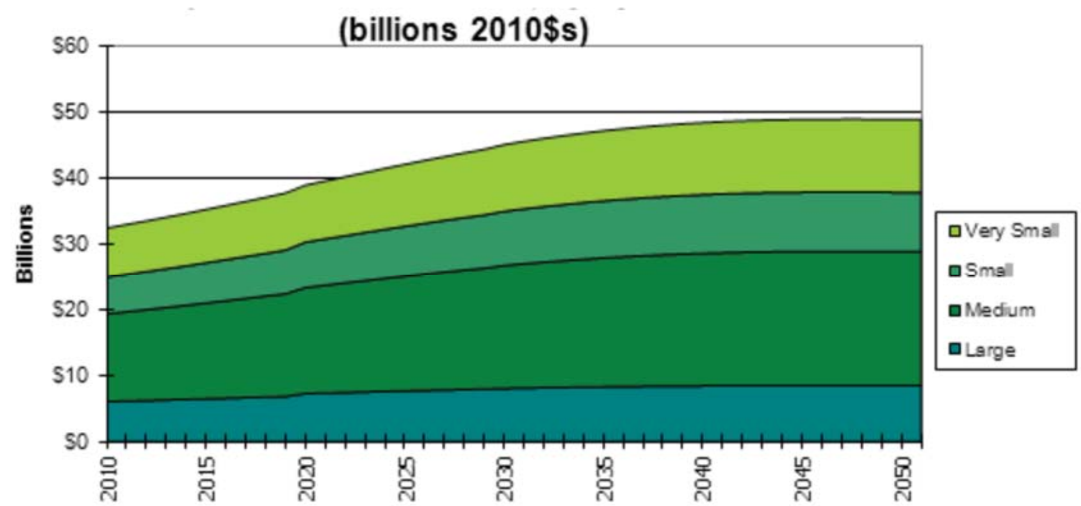

Figure 1.4 - Total Water Main Replacement and Growth Needs by System Size (AWWA, 2011)

1.3. Trenchless Water Pipeline Renewal Methods

Advantages of using the trenchless technology include minimum social costs and fewer disturbances to adjacent utilities and structures as well as minimum surface and subsurface excavations. Conventional open-cut construction methods involve the need to restore surfaces such as sidewalks, pavement, landscaping, and so on, which greatly increase the project costs (Najafi and Gokhale, 2005). In addition to the increased costs, there are social and environmental factors associated with open-cut method, i.e., its adverse impacts on the community, businesses, and commuters due to air pollution, noise and dust, safety hazards and traffic disruptions. Consideration of these factors makes the polyurea lining a worthwhile method in pipeline renewal. Najafi and Gokhale (2005) provide description of these technologies, their applications and their advantages and limitations. Figure 1.5 presents a list of these methods. For purpose of this thesis, the following sections provide a short description of renewal methods.

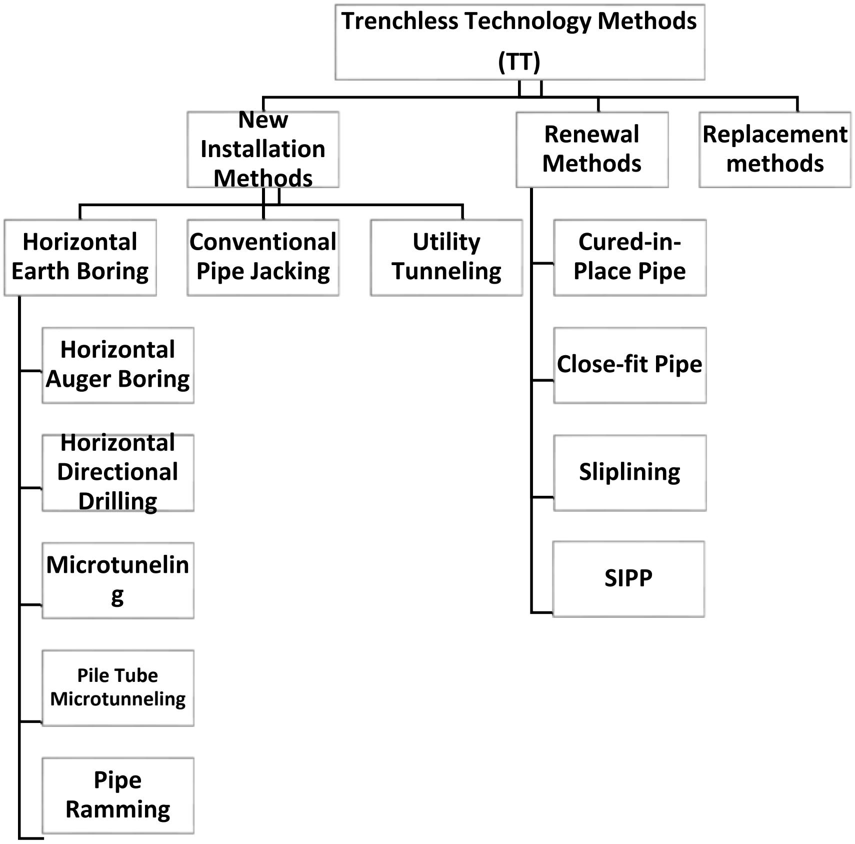

Figure 1.5 – Different Trenchless Techniques (Najafi & Gokhale, 2005)

1.3.1. Cured In Place Pipes (CIPP)

CIPP is used for rehabilitation of pipelines by installing a resin-saturated flexible tube which is firmly formed to the host pipe and cured using either pressurized steam or hot water or ultraviolet radiation (UV). Figure 1.6 shows some basic steps of CIPP lining installation.

Figure 1.6 – CIPP Installation (Source: http://prod.inliner.net/Brands/Inliner-Technologies.aspx, Accessed on 10/25/2013)

1.3.2. Close-Fit Pipe (CFP)

CFP is a method for renewal of the water pipe by inserting a deformed polyethylene pipe into the host pipe. The polyethylene pipe is than inflated with air or water pressure which causes a close fit to the host pipe. Figure 1.7 shows the diameter reduction procedure for CFP installation.

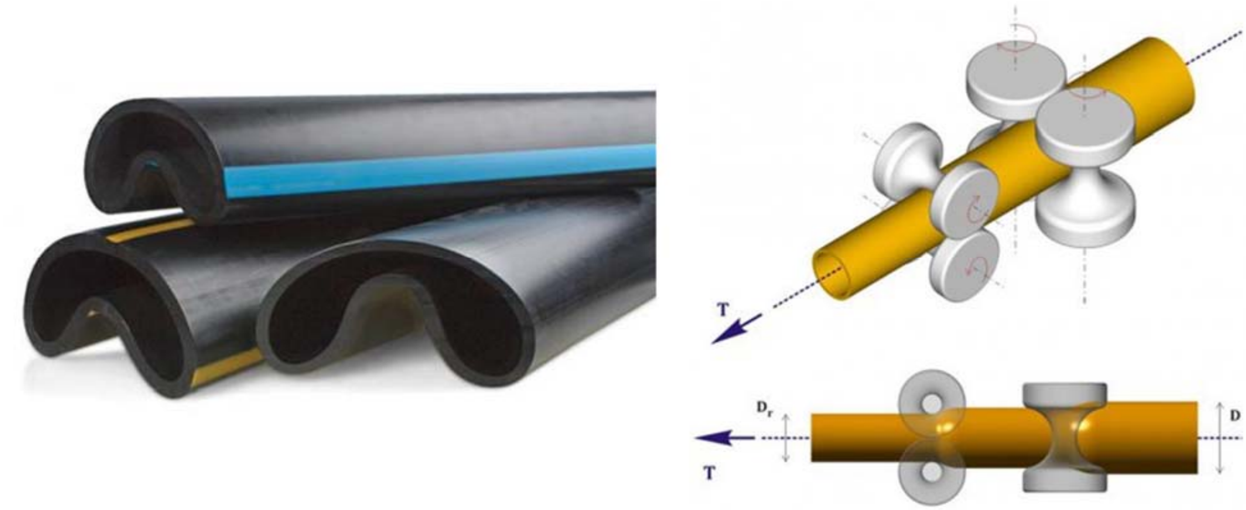

Figure 1.7 – CFP Liner Formation
(Source: http://www.mswmag.com/editorial/2013/01/pipe_relining_system_seals_without_epoxy_or_curing, Accessed on 10/23/2013)

1.3.3. Sliplining (SL)

In the sliplining or SL method, pipe renewal takes place by inserting (pulling or pushing) a continuous and watertight polyethylene, PVC, or fiberglass liner pipe into the host pipe. Figure 1.8 shows SL installation.

Figure 1.8 – Sliplining Installation (Source: http://www.midwestmole.com/slip-lining.php, Accessed on 10/24/2013)

1.3.4. Spray-In-Place Pipe (SIPP)

SIPP is one of the pipe renewal methods which is carried out by spraying a cement mortar or resin base material into the interior of the pipe. Polyurea linings are commonly used for spray-in-place pipe (SIPP) applications. A brief introduction to polyurea material is covered in next section. Figure 1.9 shows SIPP installation and the centrifugal nozzle used for application.

Figure 1.9 – SIPP Installation (Left) and Nozzle (Right) (Source: Najafi, 2010)

1.4. Polyurea Lining Material

1.4.1 History of Polyurea

Polyurea is a name given to a wide range of polymeric materials that have been extensively used in the lining industry in solid elastomeric or rigid form. Polyurea was introduced in 1989 by the Texaco Chemical Company (Kanchwala, 2010). Initially, it was not regarded as effective as it was advertised to be, especially in the coating industry. This negative view, however, was challenged by Alireza et al. (2004) who presented several promising mechanical properties of polyurea, not only in coating applications, but also in reinforcement of metal structures against blast and impact loads.

According to Guermazia et al. (1997), polymers with urea bonding – (NH) (CO) (NH) – can be produced with exothermic reaction of the main component, di- or polyisocyanate and amine molecules (Figure 1.10); this process involves faster reaction time, and acts as a suitable substance of spray used in lining applications. Polyurea also has high degree of chemical resistance, which means that their linings can provide improved wetting and cure times (Primeaux II, 2000).

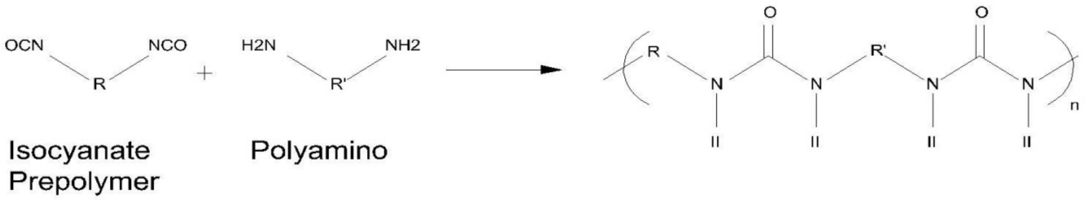

Figure 1.10 - Polyurea Formation Reaction (Primeaux II, 2000).

1.4.2. Advantages

In drinking water pipeline renewal, polyurea application sets up rapidly to ensure minimum disruption of service. If the pipe's internal surface is smooth and tubercle-free, the spray lining will work to avoid discontinuities at joint areas and will have a constant thickness along the length of the pipeline. A centrifugal nozzle is used to form the lining resulting in a high build system that is both inert and corrosion resistant. Kanchwala (2010) defined some benefits of polyurea linings, as follow:

1) *Rapid (Same Day) Return to Service* -- made possible by the rapid-setting polyurea lining;

2) *Prevention of Leakage from Corrosion Holes, Cracks, and Failed Pipeline* -- which provides a continuous pressure-tight envelope inside the existing pipeline. Designed to span corrosion holes and joint gaps, the Class III liner material does not replace the host pipe, but works in conjunction with it to prevent further corrosion and leakage;

3) *Prevention of Flow Capacity Problems Arising from Pipe Tuberculation and Deposits* -- The polyurea lining's smooth surface helps maximize the flow capacity, providing a low friction coefficient of the thin-walled lining;

4) *Prevention of Pipeline Internal Corrosion Problems* -- due to the polyurea lining's highly effective and corrosion-resistant barrier;

5) *Prevention of Water Quality Problems Associated with Internal Corrosion* -- lining resists tuberculation and its smooth surface prevents the formation of other pipe deposits;

6) *Prevention of Volatile Organic Compound (VOCs)* -- According to Volatile Organic Compounds by Gas Chromatography and Mass Spectrometry (EPA Method 8260), polyurea does not contain any volatile organic compounds (VOCs), which are the main source for air pollution;

7) Structural Integrity and Design Life of Host Pipe

AWWA M28, defines four categories to classify lining materials as shown in Table 1.1.

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

Polyurea linings used for this study structurally renew the old pipe by giving them a new design life and they were given a Class IV rating based on above classification table (3M Water Infrastructure)

1.4.3. Phases of Polyurea Lining Installation

The life of any lining material is highly dependent on the proper installation procedure. Various factors play an important role in the successful installation of polyurea lining. These include material transportation from shop to the site, ambient temperatures at the site, and cleanliness of the internal surface of the host pipe including its condition, geometry, alignment and defects. Different phases of polyurea lining installation are depicted in Figure 1.11.

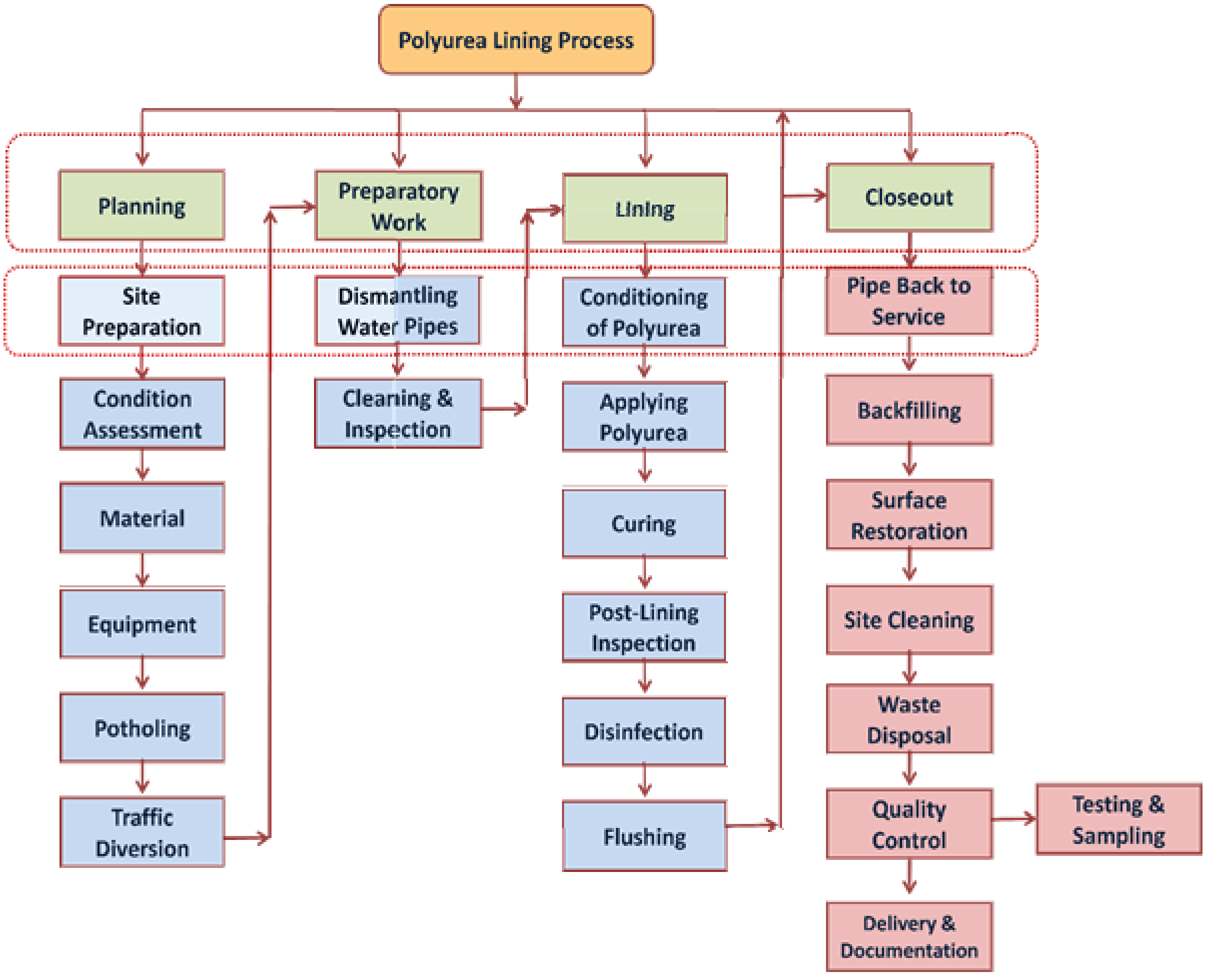

Figure 1.11 - Phases of the Polyurea Lining Installation Process (Kanchwala, 2010)

1.5 Need Statement

As said earlier, performance of water pipes gradually diminishes over time, resulting in high maintenance costs and causing poor water quality, leakage problems, and loss of pressure. Reduction of structural integrity and instances of leakage are most common in older cast iron water mains. The majority of these issues are the result of some combination of corrosion, soil movement, traffic loads, and operating pressures, among other factors. About half of the water pipes in the North American water system are made of cast iron; they were installed without lining prior to the 1950’s. Even if these water pipes are structurally intact, they show some level of tuberculation which results in reduction of hydraulic capacity and water quality issues (Figure 1.12)

Figure 1.12 - Intensity of Tuberculation Present in Some Cast Iron Water Pipes
(Source: 3M Water Infrastructure)

Spray-on lining materials such as cement mortars, epoxy, and polyurethane have been used in the water industry and have performed well for a number of years. Because of the recent introduction of polyurea as a new product for use in the renewal of corroded underground water pipes, it is necessary to determine the long-term strength of the lining material and to ensure that it is able to span holes caused by corrosion, without failing. Creep takes into account the total deformation under a constant stress after a specific time at a given temperature which is very useful in the design of polymer pipe liners. The long-term tensile and flexural creep are some of the basic parameters in helping to determine a pipe's life expectancy.

1.6. Objectives and Scope

As mentioned above, the main goal of this thesis is to determine the long-term strength of three different polyurea composites based on their tensile and flexural creep properties. This research will quantify the influence of constant stress on the long-term behavior of the liner material. Specifically, objectives of this research are:

- Extrapolate experimental creep strain responses of tested polyurea using Findley's Power Law and Fitting Curve.
- Evaluate long-term mechanical properties over the design life of tested polyurea at room temperature.

1.7. Research Methodology

The background information required for this research was obtained through literature search. As stated earlier, this research is based on analyzing the long-term tensile and flexural creep properties of polyurea composites. To attain these mechanical properties, the following tests were conducted:

1.7.1. Long-Term Flexural Creep Test

The methodology for the long-term flexural creep included:

- Applying constant load to polyurea specimens and measuring their 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 up to 10,000 hours.
- Plotting the percent of creep strain against time.

1.7.2. Long-Term Tensile Creep Test

The methodology for the long-term tensile creep properties included:

- Applying constant load to dumbbell shaped polyurea specimens and measuring their elongation as a function of time.
- Recording strain response using strain gages attached to the specimens and measuring elongation at time intervals of 1, 6, 12, 30 min; 1, 2, 5, 20, 50, 100, 200, 500, 700 and up to 10,000 hours.
- Plotting the percent of creep strain against time.

1.7.3. 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 testing is short, the following steps are followed to extrapolate the results and build a prediction model.

- Develop a long-term design model using the curve fitting method, predicting the strain response for various specimens and comparing with other methods.

- Predict the design life based on results obtained from the 10,000-hour creep test and extrapolate it as described in ASTM D2990 to ensure design of least 50-years.
- Determine the creep strain using Findley's Power Law to extrapolate strain to 50-years and predict the reduction in strength.
- Evaluate and compare the percentage increase in strain over 50-years using Curve Fitting and Findley's Law.

1.8. Expected Outcome

From testing results conducted with this thesis, polyurea can potentially be considered a Class IV liner (i.e., structural liner), and can provide some structural enhancement to the host pipe. Some of the outcomes of this thesis are:

- A theoretical analysis of experimental data using Findley's power law and curve creep models.
- A comparison of both experimental and theoretical analysis data used to predict polyurea liner design life.
- A comparison of the theoretical analysis data using Findley's power law and the curve model in predicting design life.

1.9. Structure of this Thesis

Chapter 1 started with an introduction to pipeline deterioration and needs for renewal of water pipes. Chapter 1 also presented thesis's objectives, need statement and methodology expected outcome.

Chapter 2 presents the literature review and background information on how methods of long-term performance curves were generated from short-term experimental results. A short history of polyurea applications in the pipe lining industry is provided along with the most relevant research regarding creep and how it affects the behavior of plastic pipeline materials.

In Chapter 3, laboratory tests with ASTM and ISO procedures are presented to determine the mechanical characterization of the polyurea composite. This chapter provides details of testing procedure.

Also Experimental long-term tests on tensile and flexure were discussed in Chapter 3 with results clarified through figures, tables and discussion.

Chapter 4 presents data collection and analysis to predict design life using Findley’s power law and log-fitting curve methods. The results explain polyurea liner behavior and show how these models can predict the liner design life. Finally, Chapter 5 provides the conclusions and limitations of this research along with recommendations for future research.

1.10. Chapter Summary

This chapter presented status of the water pipeline industry in the U.S. and outlined benefits of trenchless technologies, such as polyurea lining, to renew deteriorating water pipelines. Polyurea lining materials are briefly introduced in this chapter with their material properties and advantages. This chapter also presented thesis’ objectives, scope, need statement and expected outcome.

CHAPTER 2

LITERATURE REVIEW

2.1. Introduction to Polymers

Over the years, extensive research has been conducted on structural behavior of pipeline rehabilitation systems. Stiffness and stability of the liner pipe under external hydrostatic pressure is important for the design limit of all types of plastic linings (Schrock and Gumbel 1997).

Thanks to technological advances in the production of polymeric materials over the last few decades, there has been an increase of their use in industrial applications; one such application has been in pipe linings (Guidetti et al., 1996; Harris and Lorenz, 1993; Kamimura and Kishikawa, 1998; Leng et al., 1986). Recently, the use of polymer based linings such as polyurethane, epoxy, and polyurea have become more common. These polymer linings represent a durable, high performance and economical coating suitable for pipe protection (Kanchwala, 2010). Table 2.1 presents a general comparison of conventional lining materials used in industry.

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

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

However, aggressive environments can affect liner life by impacting deterioration of their physical and mechanical properties. To more effectively study the process of deterioration over a period of time, it is important that laboratory tests be carried out to accelerate the effects of specific conditions in order to study their performance (Guermazia, et al., 1997). Most importantly, by undertaking these tests, we will be able to better understand polyurea materials' long-term creep behavior and its effect on a polyurea liner system's durability and dimensional stability. Predicting the long-term integrity of any polymeric composite structure depends on the viscoelastic properties of these materials (Guermazia, et al., 1997).

Most polymers exhibit large creep strains at room temperature and at low stress levels. At higher temperatures or at higher stress levels, 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) examined 11 analytical expressions used for creep data and reported to what extent they fitted experimental data available in literature. The materials investigated were acetal, acrylonitrile butadiene styrene (ABS), nylon 6/6, polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), polyurethane (PU) and thermoplastic polyurethane elastomer (TPU) (Lacroix et al., 2007). Miller and Sterrett (1988) provided a relationship between the rupture time (hrs.), stress (psi), and temperature (^{o} C).

2.2. Creep Properties and Theories

Creep can be defined as an increase in strain over time as applied at a constant level of stress. When placed under a constant and sustained load, plastic material will continuously deform until failure occurs. The initial strain can be roughly estimated in relation to its stress-strain modulus. Under this strain the material will indefinitely continue to deform with time until rupture or yielding causes failure. The primary region occurs in the early stages of loading when the creep rate undergoes a marked and rapid decrease, after which it reaches a steady state, known as the secondary creep stage, followed by a rapid increase of creep; the tertiary stage, and finally results in a break. While all plastics experience creep to some extent, not all plastics experience all three stages of creep; for example, some materials do not undergo a secondary stage, and not all plastics experience the stages in the same manner. Tertiary creep only occurs at high stresses and in ductile materials. The degree of creep depends on several factors, such as the type of plastic, the magnitude of the load, the temperature and time. In polymers, creep occurs due to a combination of elastic deformation and the viscous flow of polymer molecules, commonly known as viscoelastic deformation (Park and 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 its material properties. When a polymer experiences cooling from a relatively high temperature (causing it to experience a state of increased molecular activity), to a relatively cooler temperature (where the time taken for its molecules to move to their relaxed state increases), physical aging occurs (Riande et al., 2000). The effect of temperature on the response of creep behavior can be quantitatively observed in Figure 2.1.

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

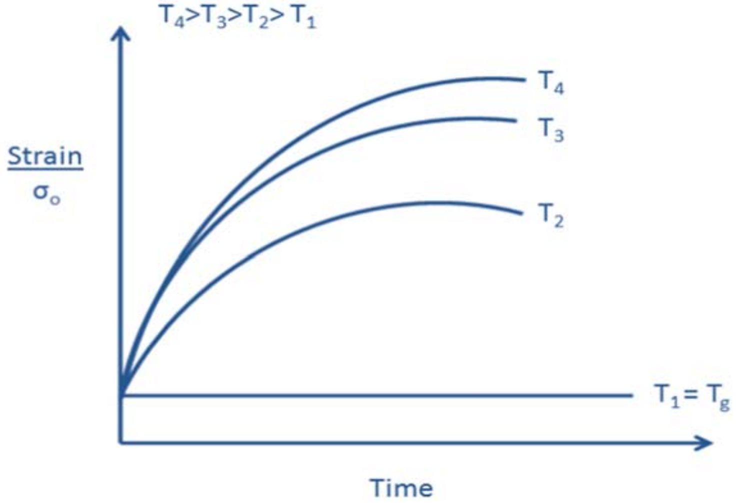

Figure 2.1 - Influence of Temperature on the Strain of Creep Experiment (Riande et al., 2000)

During actual usage, the loading cycles tend not to be so constrained, and the aging process occurs during both the loading cycle and variations in temperature. The key to using polymers to their full potential lies with the ability to determine the aging impacts and the long-term responses of such materials. Depending on the region of viscoelastic behavior, the mechanical properties of polymers differ significantly. Stress–strain behavior for various polymer types is illustrated in Figure 2.2

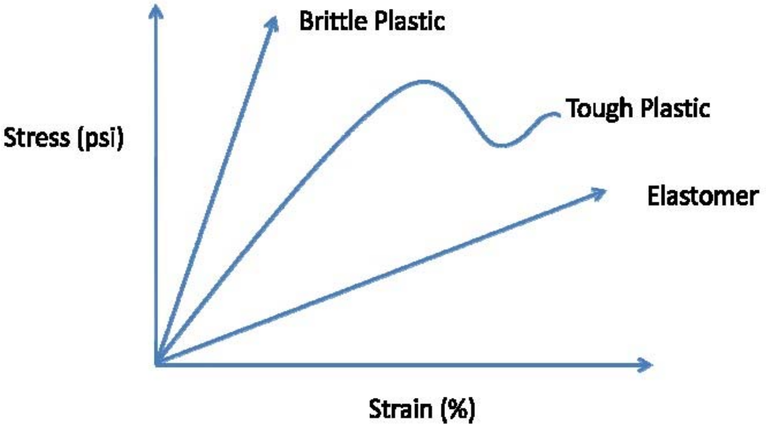

Figure 2.2 - Stress–Strain Behavior of Various Polymers (Riande et al., 2000)

2.2.2. Time - Temperature Superposition

No reliable methods or techniques currently exist to accurately predict the direct long-term aging behavior of polymer (Ding et al., 1979). There are many chemical and physical changes that take place in polymers under natural aging conditions, most occurring very slowly. In order to speed up this aging condition for testing purposes, high temperatures are often used to accelerate the changes. It, therefore, becomes necessary to demonstrate these changes which occur during an accelerated aging process and compare them to the changes that occur during the natural aging of the polymer at ambient conditions (Erhardt and Mecklenburg, 1995). Time-temperature Superposition (TTS) was first documented 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 through the use of molecular structure models (Ding et al., 1979). Previous experiments have demonstrated that the elastic modulus (E) of a polymer is influenced by the dynamic loading and the response time. Time-temperature Superposition indicates that the response time function of the elastic modulus at a given temperature is strikingly similar to 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 the alignment of the individual experimental data points on the master curve and is generally described using one of two common theoretical equations. The first of these equations is the Williams-Landel-Ferry (WLF) equation shown as 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 actor ($mol^{-1}s^{-1}$)

The glass transition temperature (T_g), is the temperature at which the amorphous phase of the polymer is converted between rubbery and glassy states (Ding et al., 1979). 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 (Ferry, 1980). The equation also assumes that, as the free volume of the material increases, its viscosity rapidly decreases. The other equation commonly used is the Arrhenius Equation 2.2 (Li, 1999):

$$\log A_t = \frac{E_R}{R(T-T_0)}$$ Equation 2.2

where,

E_R = Activation Energy Associated with the Relaxation (kJ/mol)

R = Gas Constant, (8.314 J/mol K)

T = Measurement Temperature, (K)

T_0 = Reference Temperature, (K)

A_t = Shift Factor, ($mol^{-1}s^{-1}$)

The Arrhenius equation is typically used to describe behavior outside the glass transition region, but it 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 which exhibits 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 et al., 2003). Viscoelasticity was further examined in the late 20th century when synthetic polymers were engineered and began to be used in a wide 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, and Voigt models are most commonly used to represent the properties of creep (Shah, 1983). The springs and dashpots can be combined to develop mathematically amenable models of viscoelastic behavior. The Maxwell and Kelvin elements are subjected to a creep test over an extended period of time as examples of the behavior of combinations of different springs and dashpots; 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.

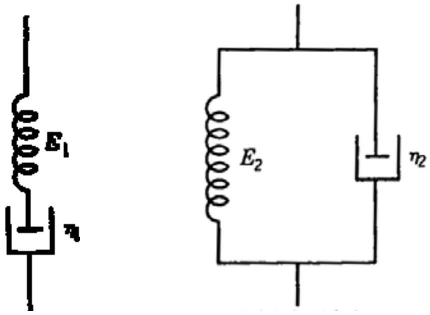

Figure 2.3 - The Maxwell (Left) & Kelvin (Right) Elements, Spring Dashpot Models (Riande et al., 2000)

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 equation for spring is expressed in Equation 2.3 (Riande et al., 2000):

$$\sigma = E_{\varepsilon} \qquad \text{Equation 2.3}$$

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

$$\frac{d_{\varepsilon}}{d_t} = \frac{1}{E} * \frac{d_{\sigma}}{d_t} \qquad \text{Equation 2.4}$$

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

$$\frac{d_{\varepsilon}}{d_t} = \frac{\sigma}{\mathrm{n}} \qquad \text{Equation 2.5}$$

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

$$\frac{d_{\varepsilon}}{d_t} = \frac{1}{E} + \frac{\sigma}{\mathrm{n}} \qquad \text{Equation 2.6}$$

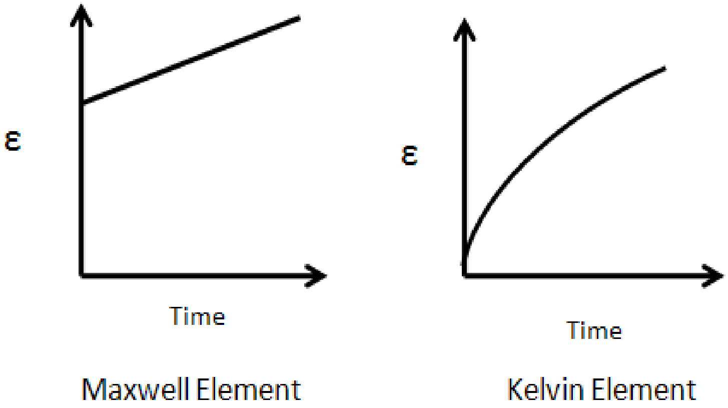

Figure 2.4 - Creep Behavior of Maxwell and Kelvin Elements (Riande et al., 2000)

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; however, the model gives a very good representation of the creep behavior over a very short time frame. The Kelvin-Voigt element expresses a combination of spring and dashpot occurrences in parallel. The Kelvin-Voigt model can be represented in Equation 2.7 (Riande et al., 2000):

$$\sigma(t) = E\varepsilon_{(t)} + \frac{nd\varepsilon(t)}{d_t} \qquad \text{Equation 2.7}$$

where,

σ = Experimental Stress, psi

$\varepsilon_{(t)}$ = Strain that Occurs under the given Stress,

E = Elastic Modulus of the Material

ɳ = Viscosity of the Material

2.2.4. Findley model

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

$$\varepsilon(t) = \varepsilon_0 + mt^n \qquad \text{Equation 2.8}$$

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).

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 et al., 2000). The stress-strain relationship in the simplest loading case of creep is given by Equation 2.9 (Maksimov et al., 1975):

$$\varepsilon = J_0\sigma(t) + \int_0^t J_t\,(t-\tau)\,\frac{d\sigma(\tau)}{d\tau}\,d\tau \qquad \text{Equation 2.9}$$

where,

J_0 = Instantaneous Creep Compliance

J_t = Time Dependent Creep Compliance

t = Time.

K = Creep Kernel, The kernel function K (t-T) characterizes the strain developing after application of a loading impulse, and usually is expressed by a sum of exponents.

$$K(t-s) = \sum_{i=1}^{k} \frac{A_\mathrm{i}}{\tau_\mathrm{i}} \mathrm{e}^{-\frac{t-s}{\tau_\mathrm{i}}}$$ Equation 2.10

where A_i and Ti are discrete relaxation spectrum.

2.3. Previous Research on Polyurea

Over the past decades, many researchers have carried out a great deal of research work on the aging of polymer materials resulting in some useful findings. The behavior of liner materials encased in a host pipe requires complex analysis techniques. To study the liner behavior under varying internal pressures, it is important to investigate the influence of these different parameters on the behavior of the material. Polymer materials have viscoelastic behavior, meaning that creep behavior of the material influences the polymer liner performance. Creep strains in the matrix of polymers are dependent upon the percentage of creep rupture stress induced in a member and temperature.

Polyurea is one of the most widely used materials in the lining industry and recent studies have revealed that polyurea can provide mechanical responses not only in lining applications for PVC and other pipeline compositions but also in metal structure reinforcement structures designed to withstand blast and impact loads (Alireza et al., 2004).

Kanchwala (2010) focused on predicting the long-term testing of polyurea composite. The goal of his tests 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. Although he employed curve fitting and Findley power law models to predict long-term behavior of the material, his analysis is based on 1000 hrs which was insufficient to predict the 50-year life of this material. In this study, different polyurea composites were subjected to similar long-term loading application for a period of 10,000 hours which is more than 3 times of minimum data collection of 3,000 hrs recommended by ASTM D2990.

2.3.1. Creep Test of Cured-In-Place Pipe Material

In 1995, Lin published his tests results involving long-term tensile, compression, and bending tests performed on 14 samples (4 tensile, 4 compression and 6 for bending) using cured-in-place pipe (CIPP) for 3,000 hrs at Louisiana Tech University in Ruston. Findley's equation was used as a baseline to predict the life of CIPP materials. ASTM F1216-2009 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 the design of CIPP liner materials. The tests were conducted based on ASTM D2990, Standard Test Method for Tensile Compressive and Flexural and Creep Rupture of Plastics.

The apparatus used was a bending table, a lever loading mechanism and support structures for conducting the test. The bending test used four stress levels: 1,000 psi, 2,000 psi, 3,000 psi, 4,000 psi. For each stress level two specimens were tested. Similarly, for the tensile tests, four stress levels were selected: 1,000 psi, 1,500 psi, 2,000 psi and 2,500 psi, and with each stress, two specimens were tested; a summary of the results are presented in Tables 2.2 and 2.3. The results obtained from the completion of 3,000 hours of testing are as follows.

Table 2.2 - 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**	**1,000 h**	**3,000 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 2.3 - 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**	**1,000 h**	**3,000 h**
1,000	751,390	506,485	288,405	256,360
1,500	510,255	393,095	258,390	243,745
2,000	449,790	365,690	259,260	243,890
2,500	374,970	337,270	255,635	239,685

The results obtained from the 3,000 hrs of testing concluded that the flexural creep modulus was 44% of the short-term flexural elastic modulus. Similarly, the average tensile creep modulus was 38% of the short-term tensile elastic modulus. Although common CIPP materials are different from polyurea, the fact that all polymers exhibit high entropic elasticity above the glass-transition temperature (Ligia et al., 2009) makes these previous research results a good starting point to compare the results of this study.

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

The Centre for the Advancement of Trenchless Technology (CATT) at the University of Waterloo conducted a series of long-term tests 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 D2990-01. The initial load selected for the test was 25% of yield stress which was determined using ASTM D 790. Observed test data were used to predict the design life for 50-years (Knight, 2005).

Six test specimens were cut with water-jetting from a resin plate of dimensions approximately 3.63 in. long by 0.76 in. wide by 0.181 to 0.189 in. deep. The test results for two specimens at 1,000, 3,000, 6,000 and 10,000 hrs were summarized and shown in Table 2.4 & Table 2.5. Figures 2.5 and 2.6 show the vertical deflection and the creep modulus for the 10,000 hour of load application.

Table 2.4 - 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	135,832
S1-1	10,000	1.461	0.69	125,202

Table 2.5 - 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 the creep modulus are given in Table 2.6 for two specimens. They include modulus values based on:

- Measurements at 10,000 hours
- ASTM D2990 for 50-year creep modulus
- Equal weighted for 50-year creep modulus.

Table 2.6 - Creep Modulus at 10,000 hours and estimated 50-year Modulus (Knight, 2005)

Sample	10,000 hours of Test Data (psi)	Regression of all 10,000 hours of Test Data (psi)	Regression of 1,000 hours of 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-year design life was 50% of the short-term modulus. Industry 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).

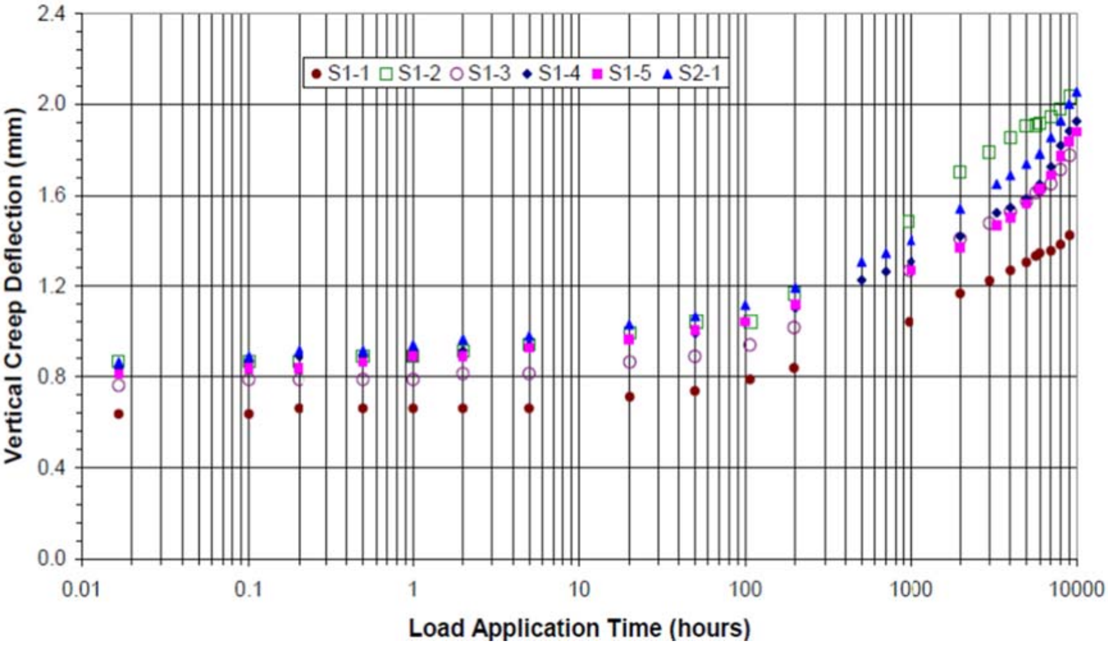

Figure 2.5 - Vertical Creep Displacement for CIPP up to 10,000 hrs for Continuous Loading (Knight, 2005)

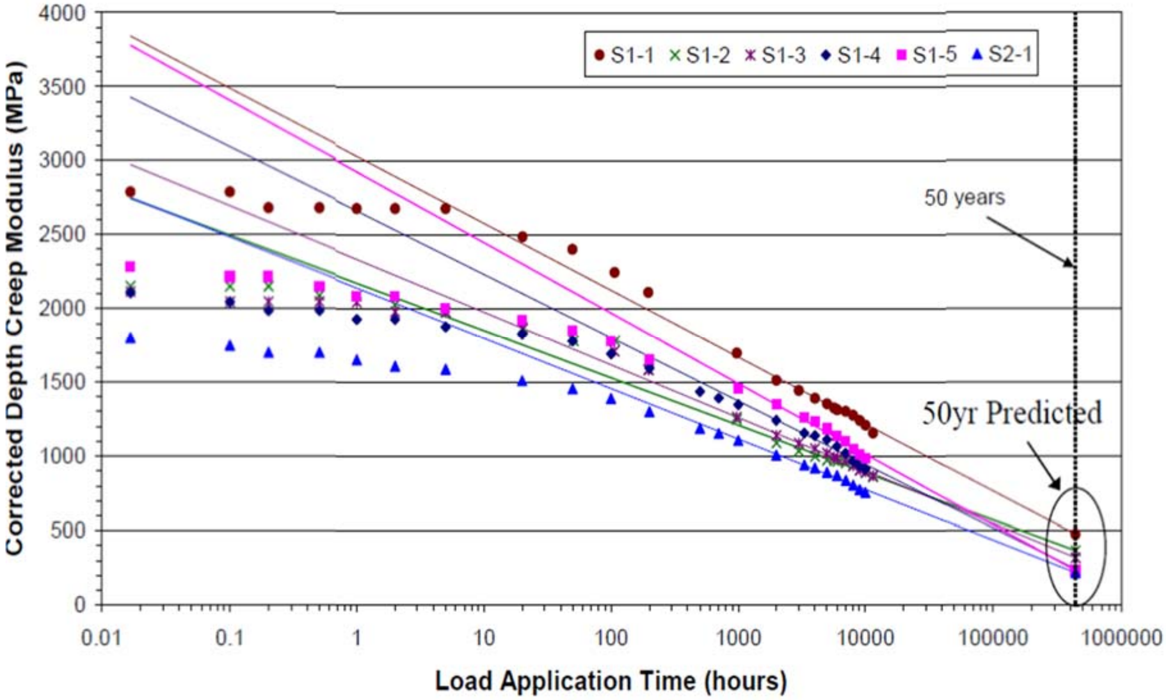

Figure 2.6 – 50-Year Creep Modulus of CIPP using Regression Analysis of 1,000 hrs. (Knight, 2005)

2.4. Testing Standards

Following testing methods were used to evaluate long-term properties of polyurea materials:

2.4.1. ASTM D2990

ASTM D2990-01 Standard Test Methods for Tensile, Compressive and Flexural Creep and Creep Rupture of Plastics describes the measurement of creep and creep-rupture properties of plastics under specific environmental conditions, mainly temperature and humidity. The method described is excellent for future experimentation in that it not only describes the test apparatus and calculations, but also includes a background discussion of the basic concepts. This standard gives the test procedure for determining the long-term tensile & flexural creep modulus.

2.4.2. ISO 899-1-03

Although ISO 899 Parts 1 and 2 address the Flexural Creep and Creep Rupture of Plastics, they 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, while ISO 899 Part 2 addresses flexural creep. Compressive creep is not addressed in ISO 899. Neither ASTM D2990 nor the ISO specifications specify the test load for the samples. ISO standard 889-2 2003 has the user select a stress value appropriate to the application envisaged for the material undergoing testing or to choose a stress where 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 a discussion of the method used for the determining of tensile creep in plastics. These plastics are generally comprised of standard test specimens examined under specified, controlled conditions such as those of pretreatment, temperature, and humidity. The method described is suitable for use with rigid and semi-rigid, non-reinforced, filled and fiber-reinforced plastic materials in the form of dumb-bell-shaped test specimens molded directly or machined from sheets or pre-molded articles.

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

2.4.3. ASTM F1216 Design Principle

ASTM F1216-2009 pertains to the renewal of pipelines and conduits for 4 to 108 in. (100 to 2,700 mm) diameters by using a procedure which involves the fitting of a resin-impregnated, flexible tube inserted into the existing, damaged, conduit using a hydrostatic head or air pressure. While this standard does not directly relate to polyurea lining, it is the only design concept for any pipeline rehabilitation installation. This pipe rehabilitation process can be used in a variety of gravity and pressure affected applications. The ASTM standard's provides design criteria for partially and fully deteriorated pipe conditions according to various load factors such as soil, water, and live load (see Figures 2.7 and 2.8).

For partially deteriorated pipe conditions, a polyurea lining inserted into an existing water pipe provides increased support for external hydrostatic loads applied due to groundwater. The standard also addresses the need to tolerate internal pressure while spanning the various holes in the existing pipe wall. The original pipe must withstand the soil and surcharge loads throughout the expected design life of the renewed pipe. The soil surrounding the existing pipe must be capable of providing sufficient lateral support, which means that the pipe can only support longitudinal fissures and distortion of up to 10% of its diameter.

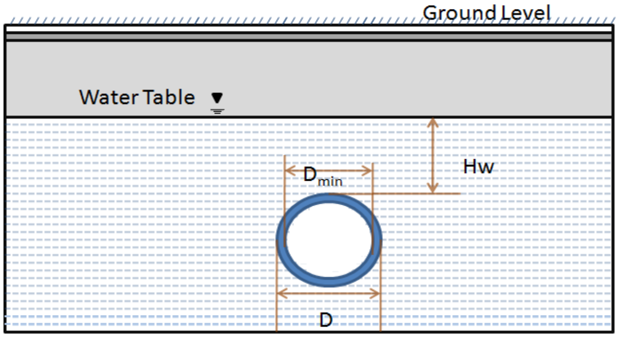

Figure 2.7 - Partially Deteriorated Design Example (Najafi & Gokhale, 2005)

A pipe in a fully deteriorated condition is no longer structurally sound, cannot support soil and live loads, resulting in the pipe losing its original shape. Corrosion causes deterioration and is a result of fluids, atmosphere, and soil interacting with a weakened pipe. This weakened state does not happen overnight. The condition usually occurs after years of stress due to applied loads.

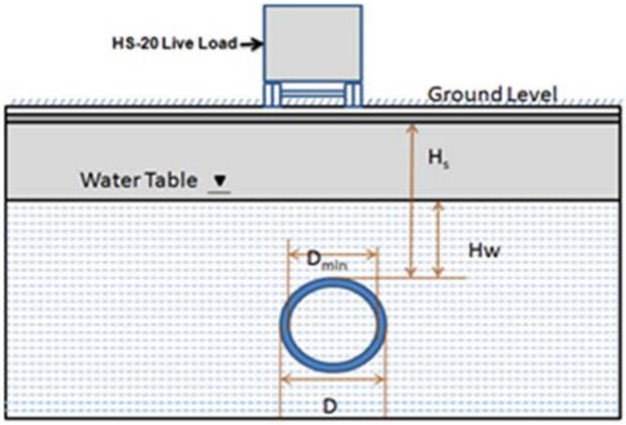

Figure 2.8 Fully Deteriorated Design Example (Najafi & Gokhale, 2005)

ASTM F1216-2009, uses Equation 2.12 for determining the thickness of liner material for partially deteriorated pressure pipe.

$$t = \frac{D_0}{\left(\frac{2KE_LC}{P_WN(1-v^2)}\right)^{\frac{1}{3}}+1} \qquad \text{Equation 2.12}$$

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 2.13 for Polyurea:

$$q = \frac{Mean\ Diameter - Minimum\ Diameter}{Mean\ Diameter} * 100 \qquad \text{Equation 2.13}$$

To calculate the Ovality Reduction Factor (C) for polyurea using Table 2.7:

Table 2.7 - Typical Ovality Factor 'C' for Partially and Fully Deteriorated Conditions (Doherty, 2008)

Ovality q, %	0	1	2	4	5	6	8	10
Factor C	1	0.91	0.84	0.7	0.64	0.59	0.49	0.41

Selection of long-term modulus of elasticity (EL) for a polyurea composite is an important objective in this study. The selection of EL depends on the design life of the material. For example, if the design life of this material is 50 years, the corresponding value of EL will also be for that period of time.

ASTM F1216 design equations are often used to evaluate design parameters for the successful renewal of pipes. Although polyurea is a different material compared to CIPP, in most cases, the design equations remain the same with some exception due to modifications.

2.5. Chapter Summary

This chapter introduced several methods, models and past research covering the prediction of long-time creep properties of polymeric materials. Monitoring the structural behavior of piping systems is an important task for water company operators and managers. Pipe analysis has always been interdisciplinary so as to bring together a variety of experts who cab collectively address all operating characteristics and issues of the material both structural and mechanical. The major technical barrier preventing the widespread use of polyurea composites is a lack of long-term strength and performance data. One of the most important factors impacting the long-term durability and dimensional stability of polyurea materials is their long-term creep behavior.

CHAPTER 3

TESTING DETAILS

3.1 Introduction

Understanding the mechanical properties of polymers is essential to optimum use for different applications. Because of their viscoelastic nature, it is necessary to perform long-term creep experiments on polymeric materials to have a better understanding of polymers' mechanical properties.

Tests developed in this research analyze tensile and flexural creep properties of polyurea composites, which calculate the long-term behavior of polyurea for lining applications over a 50-year life span using collected data for 10,000 hours.

To attain creep properties, ASTM standards D2990, D638 and D790 were followed, as described in Chapter 2. All specimens were custom made regarding their shape and size, and the test set-up was according to ASTM guidelines.

This chapter presents the test setup, test samples and test procedure followed for carrying out long-term testing. The selection of material dimensions and test apparatus were custom fabricated according to ASTM D790, D638 and D2990 requirements. Based on collected data from these experiments, a prediction of long-term behavior of polyurea lining material will be accomplished.

3.2. Long Term Flexural Creep Test

3.2.1. Introduction

Bending characteristics is one of the most important physical appearances in pipe or lining materials. Flexural deformation is a function of load and time, and different components and polymers can undergo different flexural deformations. Some of these deformation phases are listed below:

- Linear viscoelasticity is when the strain-time function is distinguishable in load response and creep (Sik Kim and Muliana, 2009).
- Nonlinear Viscoelasticity is when the strain-time function is not distinguishable in load response and creep (Sik Kim and Muliana, 2009).

Nonconformity of flexural deformations can occur, such as non-linear viscoelastic and linear-viscoelastic deformation in different polymers based on their molecular structures and arrangements. The deformation behavior of samples depends on the polymer specifications as well as on loading conditions. Collected results from experiment were calibrated and standardized in accordance with ASTM D2990 standard.

3.2.2. Flexural Creep Specimens and Test Apparatus

Figure 3.5 shows the test setup according to ASTM D790 standard. Figure 3.1 shows the flexural specimens used for the long-term flexural creep test.

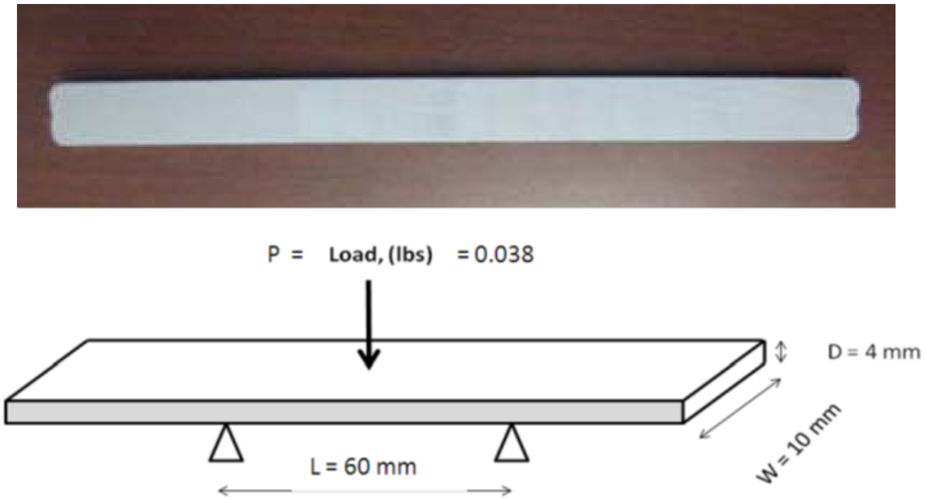

Figure 3.1- Specimen for Flexural Creep Experiment

The test frame was made of mild steel 2.0 in. x 2.0 in. (50 mm x 50 mm) angle frames, and steel fasteners. The frame held eight specimens with each sample sitting on a pair of steel rods for support. The rods rested on the steel frame and were designed to move easily so as to adjust to different specimen sizes. Also, an adjustable clamp with two bolts on each side was designed to hold the dial gauge in the right place. The specimen rested on the rods at a distance, which was 16 times the thickness of the sample to be tested. The load for each specimen was hung from a string at the center of the specimen span, and the dial gauge was pointed at the center of the specimen’s midpoint. Figure 3.2 demonstrates a schematic diagram for a 3-point bending test setup.

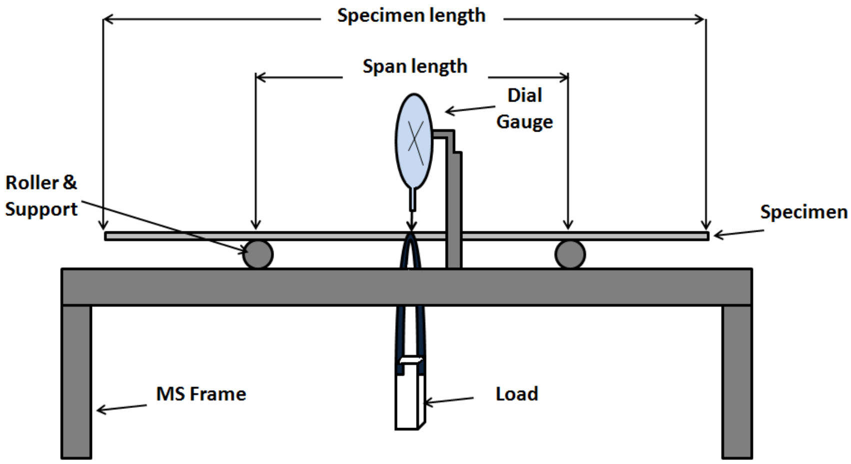

Figure 3.2- Schematic Diagram for 3-Point Bending Flexural Test Setup

3.2.3. Long-Term Flexural Creep Calculations

Flexural stress was calculated using Equation 3.1 (ASTM D790, Section 12.2)

$$Flexural\ Stress\ (\sigma) = \frac{3PL}{2WD^2} \qquad \text{Equation 3.1}$$

where,

σ = Stress, psi,

P = Load, lbs.

L = Span, in.

W = Specimen width, in.

D = Specimen depth, in.

As described in ASTM D790, where the maximum strain occurs, it can be calculated for any deflection using Equation 3.2:

$$\varepsilon_{(t)} = \frac{6\Delta d}{L^2} \qquad \text{Equation 3.2}$$

where,

$\varepsilon_{(t)}$ = Maximum strain, in. /in.

Δ = Maximum deflection at mid-span, in.

d = Depth, in.

L = Span, in.

According to ASTM D790, flexural creep modulus is calculated by Equation 3.3:

$$Flexural\ Creep\ Modulus\ (E_F) = \frac{L^3 P}{4wd^3\Delta} \qquad \text{Equation 3.3}$$

where;

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

P = Applied Force, lbs

w = Width of the Test Specimen, in.

d = Thickness of the Specimen, in.

Δ = Deflection at Mid-span at Time (t), in.

3.2.4. Flexural Test Procedure

Polyurea specimens were subjected to a constant mid-span bending load to determine flexural properties of material. Summary of testing procedure is listed below:

1- Width and thickness of sample at mid-span (where the dial gauge is located) were precisely measured and recorded.

2- Four custom made polyurea samples were placed on a three-point bending system with a support span 16 times greater than the beam depth (56 mm).The sample beams were placed on supports and a dial gauge with graduations of 0.01 mm was rested at the beam's mid-span position to show the bending deformation.

3- The load was applied to the specimen within 5 seconds and the conforming deformation was recorded as per the ASTM requirements.

4- Strain-time graph was calculated and plotted for each sample.

5- Flexural modulus vs. time was calculated for each sample.

Figure 3.3 shows the test apparatus and specimens for this long-term flexural creep test.

Figure 3.3- Test Apparatus and Specimens for Flexural Test

3.3. Long Term Tensile Creep Test

3.3.1. Introduction

There are several ways to calculate and record the elongation of a tensile sample for long-term experiments. One of the most precise methods is to use strain gauges to measure and amplify small deflections in length over time. The output of these strain gauges are cannot be measured in units; hence, the best way to describe them is in percentage. The tensile strain values are determined at specified time intervals at 1, 5, 20, 50, 100, 200, 300, and up to 10,000 hours and these interval recordings were used to plot a creep rupture curve.

3.3.2. Tensile Creep Specimens and Test Apparatus

For long-term tensile testing, total number of six samples were used. All specimens were provided by their OEM (original equipment manufacturer) and were coded as G-T series for tensile testing. As mentioned before, test specimens and apparatus were made according to ASTM D638. Figure 3.4 shows the tensile specimens used for long-term tensile creep test.

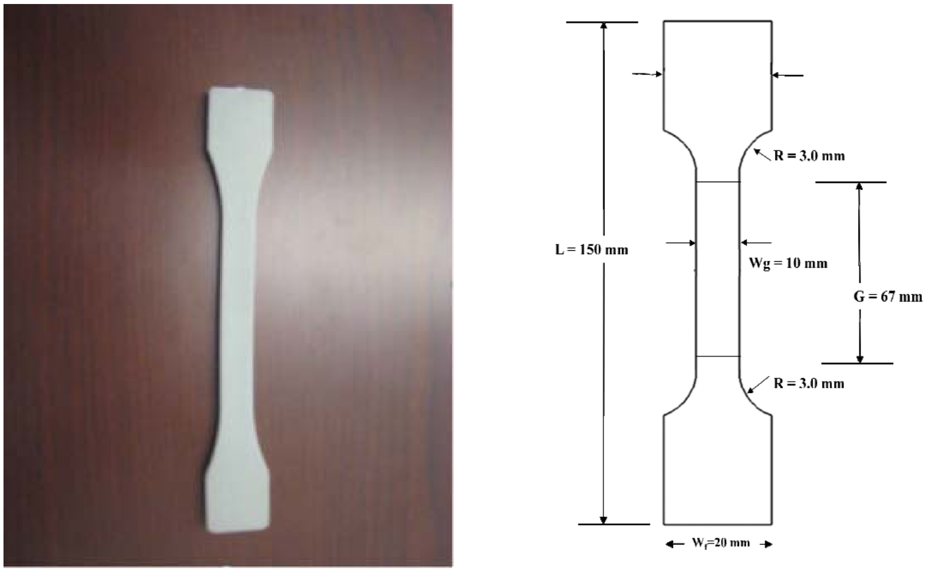

Figure 3.4- Specimen for Tensile Creep Test

The test frame and apparatus were custom fabricated and used a simple loading appliance, which operated at a constant temperature. The test frame was fabricated with Mild Steel (MS) 2 in. x 2 in. (50 mm x 50 mm) angles. The frame could test 12 specimens at the same time with each sample clamped between two square plates. Model EA-06-250BF-350 VISHAY strain gauges with a strain range of ±5% were used to record strains at specific time intervals, as described in ASTM D2990. A GAK-2-AE-10 strain gage application kit was also used to mount strain gauges to the specimen. Strain gages were mounted axially at a midway point based on the specimen's length as shown in Figure 3.5 and were connected to the data logger

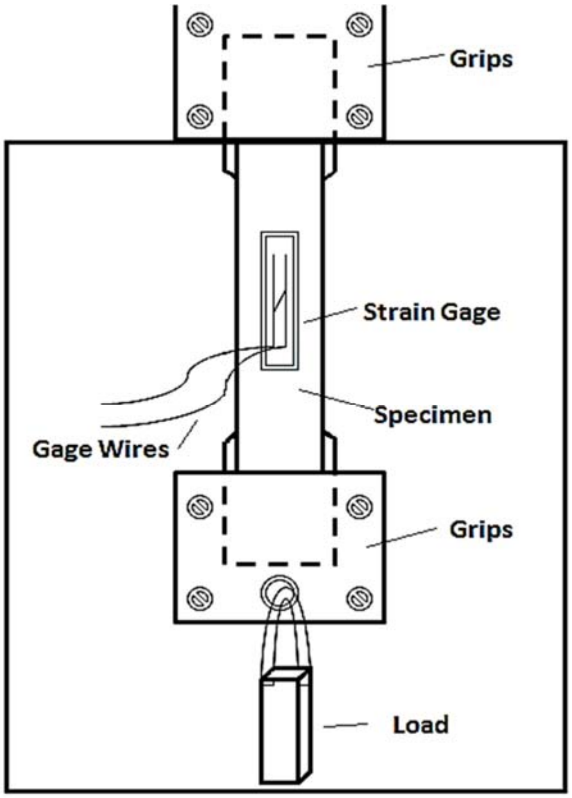

Figure 3.5 - Strain Gauge Location

3.3.3. Long-Term Tensile Creep Calculations

Tensile stress was calculated by dividing the applied load per unit area of the specimen's initial cross section, as shown in Equation 3.4:

$$Tensile\ Stress\,(\sigma) = \frac{Force\ (F)}{Initial\ Cross\ Section\ (A)} \quad \text{Equation 3.4}$$

where,

F = Applied Force, lbs

A = Initial (t_0=0) Cross-Sectional Area at Narrow Section of the Specimen, in.^{2}

Elongation represents sample length and is determined by where the strain gauge is installed (in the middle section of the specimen as shown in Figure 3.5):

$$Extension\ (\Delta L) = L_t - L_o \quad \text{Equation 3.5}$$

where,

L_t = Length of the Specimen at Gauge Section at any Given Time (t) During the Test, in.

L_0 = Initial Length of the Specimen at Gauge Section Before Loading the Sample, in.

Tensile Creep Strain (ε_t) - Change in the length between the gauge marks, with respect to original length as produced by the applied load at any given time (t) during a creep test.

3.3.4. Tensile Test Procedure

Polyurea specimens were subjected to a constant and continuous tensile loading for 10,000 hours. This data represents the most important part of this research and was recorded at specified time intervals and was used to plot the creep rupture curve. Summary of testing procedure is listed below:

1- Width and thickness of sample at mid-span (where strain gauge is located) were precisely measured and recorded.

2- All the strain gauges were installed on the specimens as per instructions provided by manufacturer. Degreaser spray, neutralizer and conditioner chemicals were used to create an appropriate surface for strain gauge installation.

3- Specimens were placed between two custom-made steel plates for loading applications at the bottom and clamped to the test frame at the top. Figure 3.6 shows tensile specimen and strain gauge under the load.

4- Vishay Model P3 Strain Indicator and Recorder were used to record and collect data from strain gauges.

5- Strain–time graph was plotted for each sample.

6- Tensile modulus vs. time was calculated for each sample.

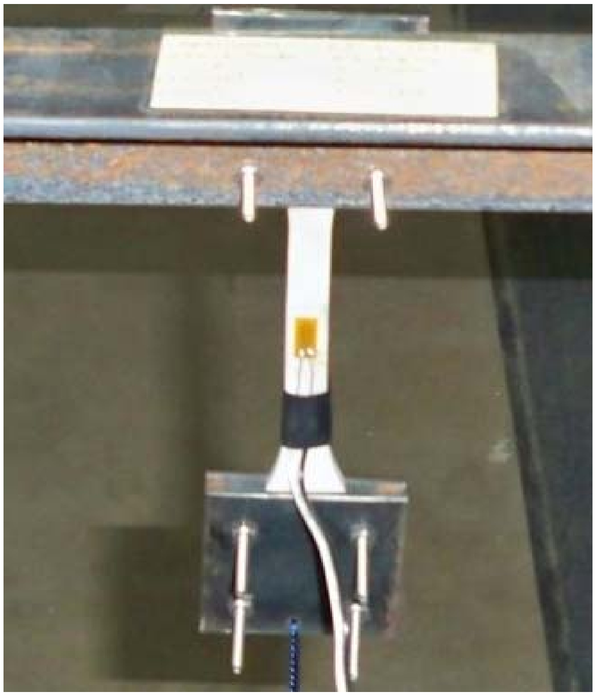

Figure 3.6- Tensile Specimen and Strain Gauge under the Load

This experiment was started with a total number of 14 specimens for tensile and 12 for flexural testing. Among those, eight specimens from each test were eliminated from analysis to avoid effect of physical shape or application imperfections since material behavior was the focus and main purpose of research; hence, a total of six tensile and four flexural specimens were used as a data set for this study.

3.4. Chapter Summary

This chapter presented an overview of experiment details and methodology and described the test apparatus for long-term flexural and tensile tests. Time-dependent factors of polyurea material and creep calculation guidelines were determined in compliance with ASTM test specifications. Time-dependent deformation under constant static load was collected for 10,000 hours to determine creep behavior of polyurea materials. Test procedure and data collection process were described in Section 3.2 and 3.3 for long-term flexural and tensile tests respectively.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1. Introduction

This chapter describes test results and evaluates creep behavior of polyurea lining materials. Experimental data and results are discussed and shown in the form of graphs and tables.

In this chapter, collected data during the experiments are shown and extrapolated to determine the design life of polyurea. Also, time dependent change in tensile and flexural creep modulus is calculated and shown as one of the key factors in evaluation and design life analysis of polyurea.

In the next two sections of this chapter, the test results are extrapolated using Findley's power law and the curve fitting model. Findley's power law is a known method to assess creep properties of polymers.

4.2. Flexural Creep Data Analysis

Bending moment is taken into account when a pipe is subjected to flexural stress. This can happen when the liner is under internal pressure (hoop stress) and is not structurally supported by the host pipe because of a hole or crack in the body of the host pipe. In these situations, pipe is no longer in a round shape and the bending moment starts to increase. Consequently, bending/flexural modulus of the liner material is one of the key parameters to study the flexural creep behavior of pipe materials under a constant bending stress.

As described in Chapter 3, four specimens of polyurea lining material were tested using a three-point bending test for a period of 10,000 hours. Mid-span deflection was recorded at specified time intervals and corresponding flexural stress, strain and creep modulus were calculated following equations 3.1, 3.2 and 3.3.

Collected data were analyzed according to ASTM D790 for bending modulus and strain calculations and ASTM D2990 for evaluation of creep behavior of material over time. Table 4.1 lists polyurea specimen properties used in long-term flexural experiment. According to the ASTM, the maximum strain in the outer surface at mid-span can be determined using Equation 3.2. Also, the bending modulus of the polyurea for the strain recorded at any given time can be calculated using Equation 3.3.

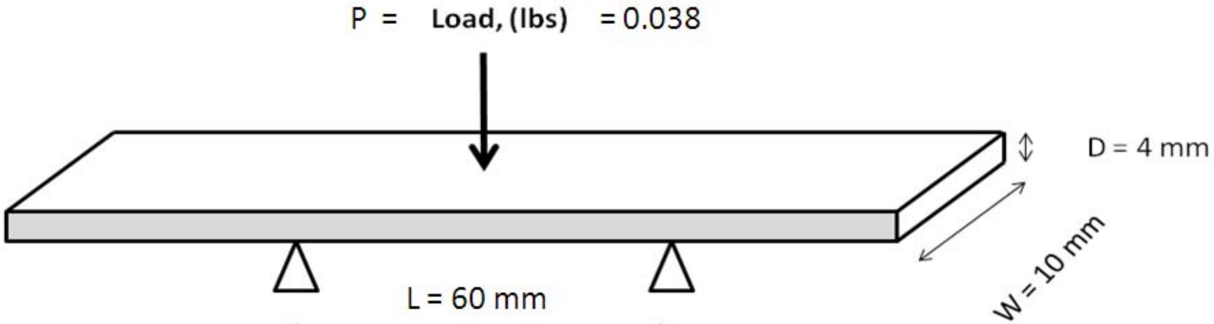

Figure 4.1 - Flexural Test Setup

Recalling Equation 3.1:

$$\sigma f = \frac{3PL}{2WD^2}$$

where:

σ_f = Stress (psi)

P = Load (lbs) = 0.038 lbs

L = Support Span (in.) = 2.362 in.

W = Width (in.) = 0.393 in.

D = Depth (in.) = 0.157 in.

$$\sigma f = \frac{3 \times 0.038 \times 2.362}{2 \times 0.393 \times 0.157^2}$$

$$\boldsymbol{\sigma_f = 13.89 \text{ psi}}$$

Table 4.1 - Flexural Specimen Properties

Thickness	0.15748	in.	4	mm
Width	0.3937	in.	10	mm
Span Length	2.3622	in.	60	mm
Load	0.038	lbs	0.07	Newton
Stress	13.89	psi	0.1	MPa
E_0 (Short-Term Modulus)	525,033	psi	3,620	MPa

4.2.1. Change in Flexural Strain over time

To conduct a long-term creep test, creep strain due to constant level of stress is recorded as a function of time. This data delivers some critical information about the time-dependent behavior of material. Summary of calculated flexural strain at various time intervals are shown in Table 4.2.

Table 4.2 – Calculated Flexural Strain for 10,000 Hours of Data Collection

Flexural Strain Summary											
Hrs Sample	1	5	20	50	100	200	500	1,000	2,000	5,000	10,000
G-F-1	1.67 E-06	6.67 E-06	1.33 E-05	2.17 E-05	3.00 E-05	4.67 E-05	1.20 E-04	3.20 E-04	1.04 E-03	1.08 E-03	1.09 E-03
G-F-2	5.00 E-06	5.00 E-06	1.17 E-05	1.83 E-05	2.33 E-05	4.00 E-05	9.33 E-05	2.77 E-04	5.53 E-04	6.00 E-04	6.07 E-04
G-F-3	1.17 E-05	1.83 E-05	2.00 E-05	2.17 E-05	2.67 E-05	5.00 E-05	1.00 E-04	2.83 E-04	8.40 E-04	8.80 E-04	8.93 E-04
G-F-4	1.00 E-05	1.50 E-05	2.17 E-05	2.33 E-05	2.67 E-05	4.67 E-05	1.07 E-04	2.80 E-04	8.67 E-04	9.00 E-04	9.00 E-04

Strain-Time graph for flexural specimens are presented in Figure 4.2. This figure shows the significant effect of time in flexural behavior of polyurea materials. As shown in Figure 4.2, specimens behaved in a similar manner day after day, and they all showed an instantaneous (0~2000 Hrs.), transient (2000~4000 Hrs.) and steady (4000~10000 Hrs.) state strain.

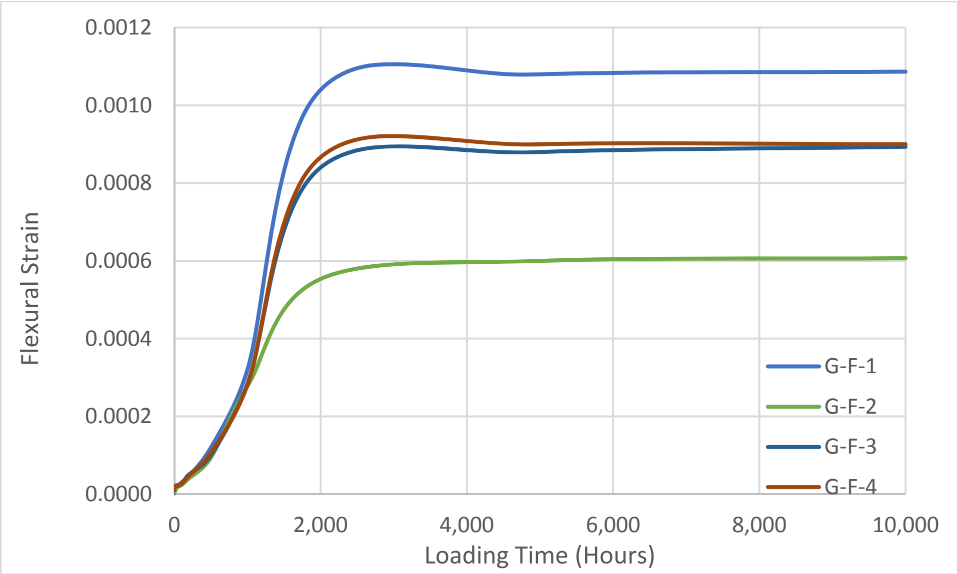

Figure 4.2 – Strain vs. Time Graphs for Long-Term Flexural Creep Test

4.2.2. Change in Flexural Modulus over Time

Creep modulus is defined as change in the ratio of applied stress to resultant strain over time. Long-term flexural modulus was subject to change during the test simply because the flexural behavior of polyurea materials is a time-dependent parameter. Figure 4.3 presents calculated flexural modulus over time for flexural creep test.

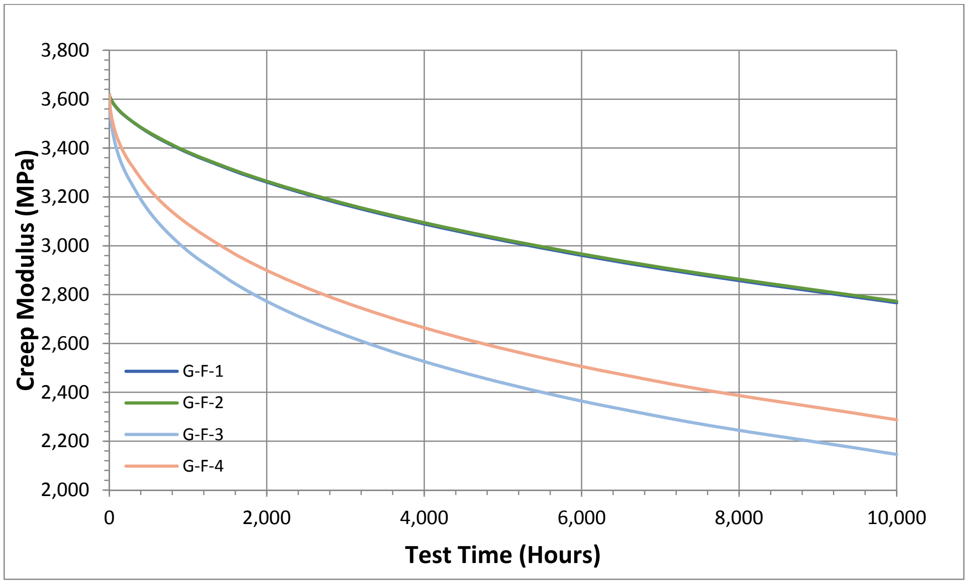

Figure 4.3 - 10,000 Hour Summary Curve Flexural Creep Modulus vs. Time

4.2.3 Summary of Flexural Creep Test Data

As mentioned before, internal (hoop) stress is one of the reasons that may result in bending moment in the liner. Buckling, also is one of those situations that may create bending tress in the liner. Buckling happens in the pipes when a pipe is subjected to external loading. When a pipe starts to buckle, it no longer keeps its circular shape. When buckling force increases, bending moment stress starts to grow in the pipe or liner material. To study the long-term behavior of polyurea material, a 3-point flexural creep test was carried out as described in Section 3.2.4.

Average flexural strain for four flexural specimens was found to be 0.0825% after the first 2000 hours of loading. Similarly, mean flexural strain was found to be 0.0865% and 0.0872% after 5,000 and 10,000 hours of loading respectively. As shown in Figure 4.3, flexural modulus shows a descending trend over time. However, flexural strain represents a linear stability which remains approximately constant during the first 2,000 hours of loading.

ASTM D2990 recommends applying a stress level that produces 1% strain after the first 1,000 hours of loading. In this experiment; however, to have a better understanding of actual flexural loading condition on a polyurea liner, a stress level of 0.1 MPa (13.89 psi) was chosen.

4.3. Tensile Creep Data Analysis

Tensile stress occurs when a pipe is subjected to internal pressure. For this test, six dumbbell shape polyurea specimens were used as described in Chapter 3. The tensile test was carried out in accordance to the test procedure described in Section 3.3.4.

Collected data were analyzed according to ASTM D638 for tensile modulus and strain calculations and ASDTM D2990 for evaluation of creep behavior of material over time. Table 4.3 lists polyurea specimen properties used in long-term tensile experiment.

Table 4.3 - Tensile Specimen Properties

Thickness	0.15748	in.	4	mm
Width	0.3937	in.	10	mm
Area	0.062	in.^{2}	40	mm^2
Load	2.5	lbs	11.12	Newton
Stress	40.323	psi	0.28	MPa
E_0 (Short-term Modulus)	195,654	psi	1,349	MPa

4.3.1. Change in Tensile Strain over Time

Creep strain (due to constant level of stress) provides some critical information about the time-dependent behavior of the material. Summary of calculated tensile strain at various time intervals are shown in Table 4.4.

Table 4.4 – Calculated Tensile Strain for 10,000 Hours of Data Collection

Tensile Strain Summary											
Hrs Sample	1	5	20	50	100	200	500	1,000	2,000	5,000	10,000
G-T-1	1.75 E-04	2.18 E-04	2.45 E-04	2.54 E-04	3.25 E-04	3.93 E-04	4.66 E-04	7.51 E-04	1.11 E-03	8.12 E-04	1.13 E-03
G-T-2	1.98 E-04	2.18 E-04	2.87 E-04	3.06 E-04	3.34 E-04	3.79 E-04	3.90 E-04	7.08 E-04	1.04 E-03	7.23 E-04	1.08 E-03
G-T-3	1.19 E-04	1.43 E-04	1.74 E-04	2.34 E-04	2.59 E-04	2.49 E-04	3.28 E-04	5.73 E-04	7.27 E-04	5.06 E-04	8.47 E-04
G-T-4	1.60 E-04	1.86 E-04	2.75 E-04	4.23 E-04	5.41 E-04	5.78 E-04	6.07 E-04	6.48 E-04	8.09 E-04	4.77 E-04	8.39 E-04
G-T-5	1.54 E-04	1.91 E-04	2.20 E-04	2.47 E-04	2.59 E-04	3.39 E-04	3.97 E-04	5.43 E-04	8.76 E-04	5.51 E-04	8.66 E-04
G-T-6	6.20 E-05	9.80 E-05	1.19 E-04	1.52 E-04	2.08 E-04	2.31 E-04	4.36 E-04	6.98 E-04	9.89 E-04	6.79 E-04	1.03 E-03

A strain-time graph for tensile specimens is presented in Figure 4.4. This Figure shows the important effect of time in tensile behavior of polyurea materials. As shown in Figure 4.4, all tensile specimens demonstrated a similar tensile behavior over the 10,000 hours of experiment. An ascending strain level was observed for the first 1800 hours of loading (which presents the short term modulus of the material), then the elasticity of polyurea reduced the strain up until 5,000 hours and finally a slightly ascending trend was observed for the last 5,000 hours of loading in the strain-time graph (Figure 4.4)

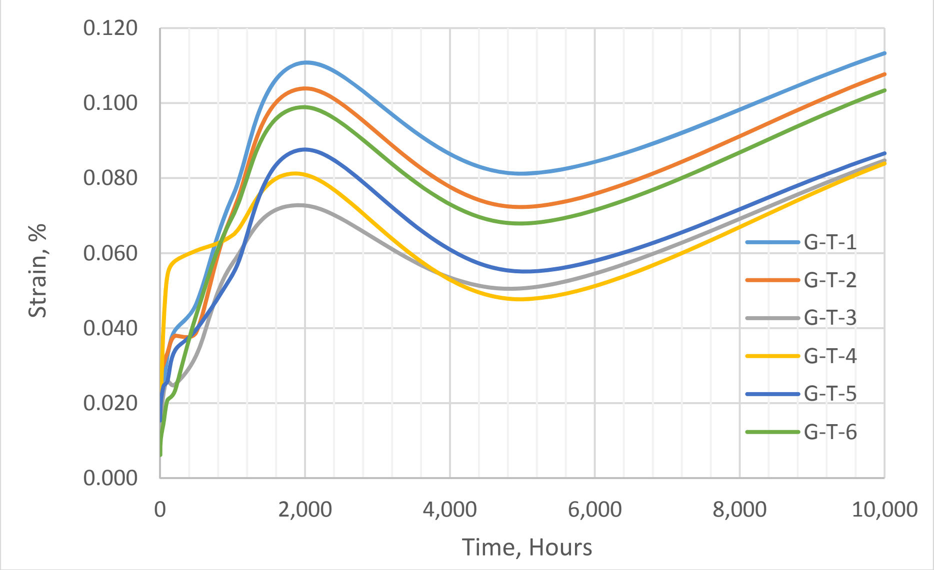

Figure 4.4 – Strain vs. Time for Long-Term Tensile Creep Test

4.3.2. Change in Tensile Modulus Over Time

As mentioned before, creep modulus is defined as change in the ratio of stress to resultant strain over time. Figure 4.5 presents calculated tensile modulus over time for a long-term tensile creep test.

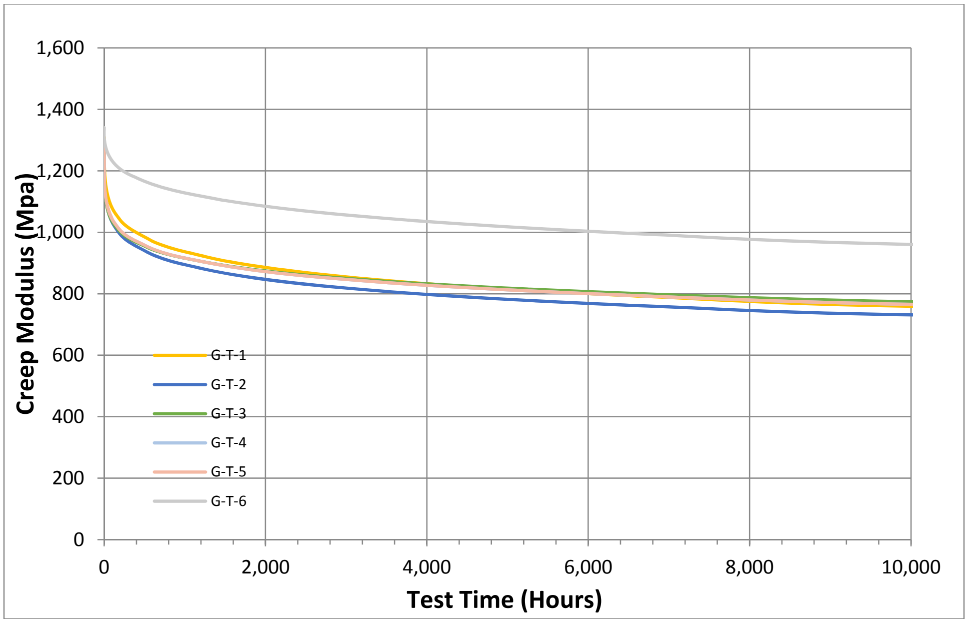

Figure 4.5 - 10,000 Hour Summary Curve for Tensile Creep Modulus vs. Time

4.3.3 Summary of Tensile Creep Test Data

Tensile creep is a key factor in design life modeling of any pipe or liner. Collected data from this experiment were strain versus time and tensile creep modulus versus time and these two important parameters are shown in Figures 4.4 and 4.5.

Mean tensile strain for six different specimens was found to be approximately 0.0925% after 2000 hours of loading. Correspondingly, average tensile strain was found to be 0.0625% and 0.0966% for 5,000 and 10,000 hours of loading respectively.

As represented in Figure 4.5, tensile modulus drops quickly during the first 1,800 hour of loading and at the same time a linear deformation behavior in strain-time graph can be seen for the first 1,800 hours. After this state, tensile stress shows a slightly steady level with an ascending trend while a descending steady trend is shown in the tensile creep modulus graph in Figure 4.5.

As mentioned before, ASTM D2990 recommends the stress level that caused 1% strain after 1,000 hours of loading. However, applied stress was chosen to be 0.278 MPa (40.323 Psi.) for all the specimens based on previous and trial tests conducted on polyurea lining materials.

As described in Chapter 1, observed data will be extrapolated using Findley's power law and curve fitting model. In the next two sections of this chapter, each model will be described and will be used to predict the creep properties of polyurea specimens for 50 years.

4.4. Findley's Power Law Model

Basically, the magnitude of strain for a long-term period of time has two parts with the following qualitative form:

$$\varepsilon = \varepsilon_o + \varepsilon_c \qquad \text{Equation 4.1}$$

where:

ε = Total strain at any time "t" after load application

ε_c = Time-dependent (creep) element of total strain at any time "t" after load application

ε_o = Initial (short-term) strain upon a stress application

Equation 4.1 is under the assumption that the stress application is constant in magnitude that it occurred instantaneously and lasted for a long period of time.

The main objective of using Equation 1 is to neglect the initial-strain component, ε_o, for simplicity of combinations of material, stress level, and time where it is negligible in magnitude in comparison to the creep component, ε_c.

In the development of an equation to define the creep comportment of polymeric materials, Findley (Findley and Khosla, 1956) used the basic form of Equation 1 and assumed that creep element of strain can be define as a function of time with two constant parameters, this is shown in Equation 4.2. :

$$e_c = m\left(\frac{t}{t_o}\right)^{n_F} \qquad \text{Equation 4.2}$$

where:

m = Material parameter (dimensionless, defined further subsequently)

n_F = Findley material parameter (dimensionless)

t = Loading time (Hours)

t_o = 1 (Hour)

So, Equation 4.1 can be written as:

$$\varepsilon = \varepsilon_o + m\left(\frac{t}{t_o}\right)^{n_F} \qquad \text{Equation 4.3}$$

While t_o assumed to be one hour, Equation 4.3 simply appears as:

$$\varepsilon = \varepsilon_o + m t^{n_F}$$ Equation 4.4

where:

ε = Total strain at any time “t” after load application

ε_o = Initial (short-term) strain upon a stress application

m = Material parameter (dimensionless, defined further subsequently)

t = Loading time (Hours)

n_F = Findley material parameter (dimensionless)

Equation 4.4 is also known as “Findley’s Power Law”. To predict strain at any given time, constants “m” and “n” should be known. Taking log from both sides of Equation 4.4 will simplify the calculation of these constants for 10,000 hours of collected data during the experiment. Therefore, Equation 4.4 can be written as follows:

$$\log(\varepsilon_t - \varepsilon_o) = \log(m) + n\log(t)$$ Equation 4.5

Now, it can be seen that “$\log(\varepsilon_t - \varepsilon_O)$” is a linear function of “$\log(t)$”. By plotting this function and finding the parameters of trend line, vertical intercept (log (m)) and slope (n) will be known.

4.4.1. Flexural Creep Parameters and Data Extrapolation

As mentioned in Chapter 3, four flexural polyurea specimens were subjected to a constant stress for a period of 10,000 hours. To obtain Findley’s coefficients “m” and “n”, a simple linear regression model was carried out for each sample on a “$\log(\varepsilon_t - \varepsilon_O)$” versus “$\log(t)$” graph. Figures 4.5, 4.6, 4.7 and 4.8 show the log graph and the trend line equation for each sample. The deflection and strain data versus time are shown in Appendix A.

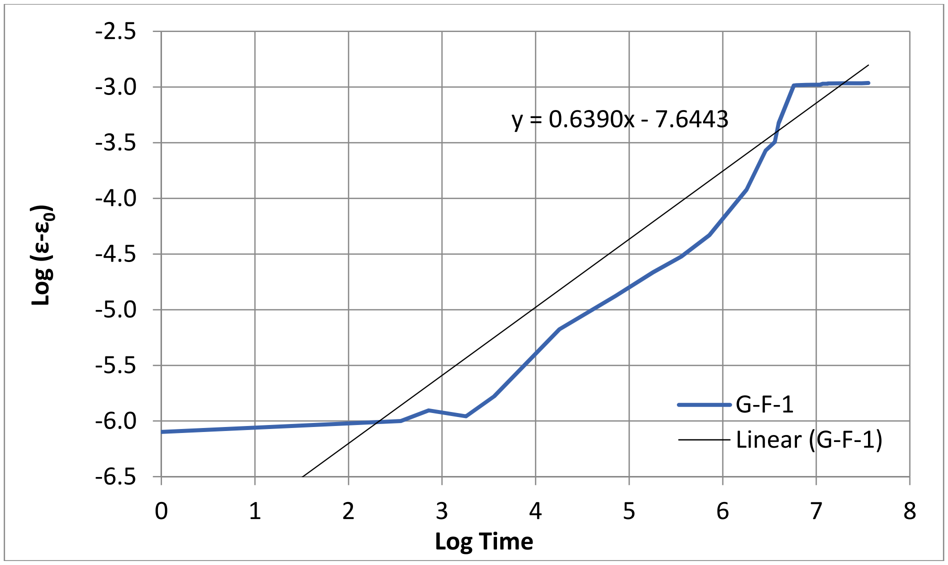

Figure 4.6 – Findley's parameters "m" and "n" for Flexural Sample G-F-1

As shown in Figure 4.6, Findley's material parameter "n" was found to be 0.6390 and material parameter "m" was equal to: $10^{-7.6443} = 2.268\,E - 08$.

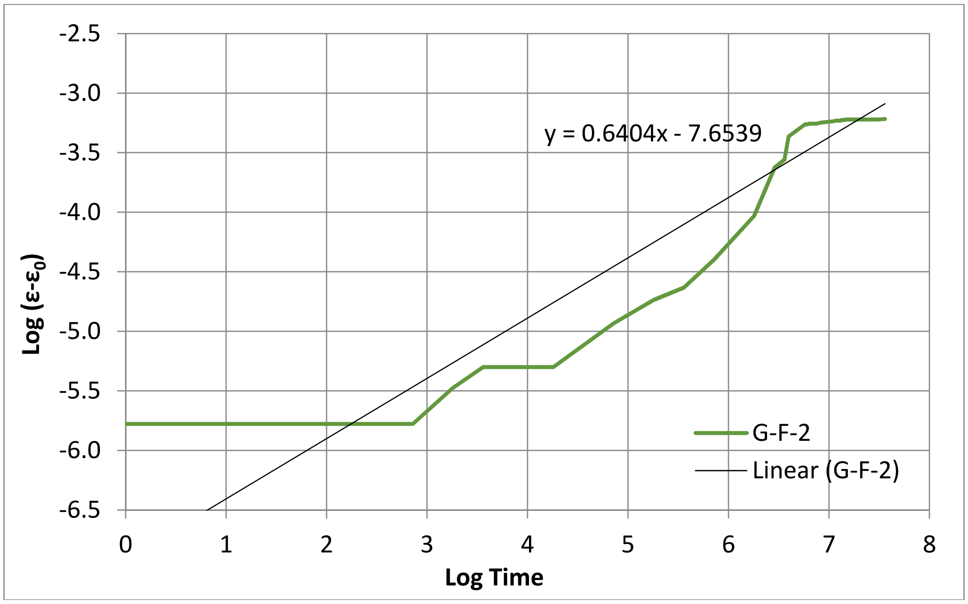

Figure 4.7 – Findley's parameters "m" and "n" for Flexural Sample G-F-2

As shown in Figure 4.7, Findley's material parameter "n" was 0.6404 making the material parameter "m" equal to: $10^{-7.6539} = 2.219\,E - 08$.

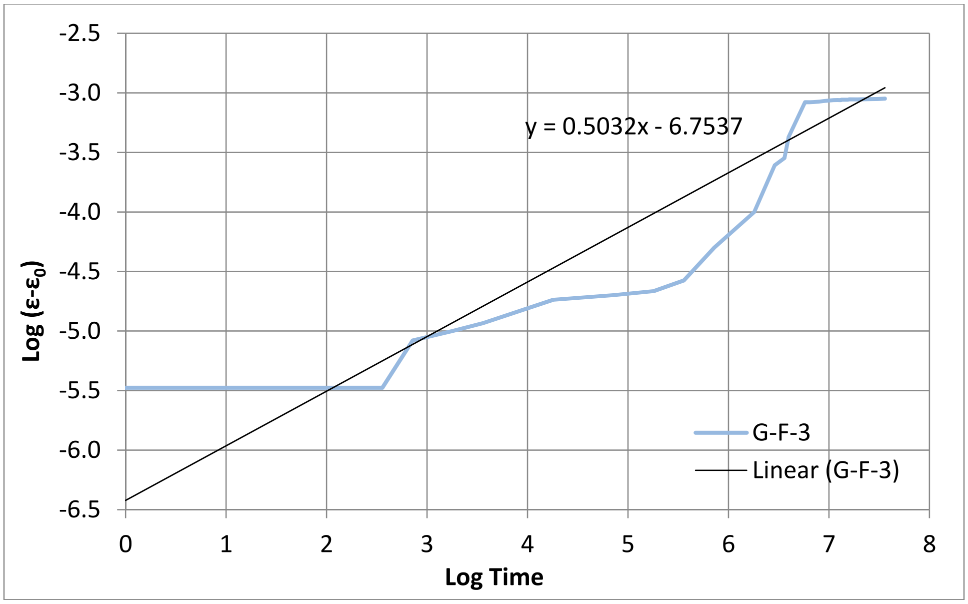

Figure 4.8 – Findley's parameters "m" and "n" for Flexural Sample G-F-3

As shown in Figure 4.8, Findley's material parameter "n" was found to be 0.5032, making the material parameter "m" equal to: $10^{-6.75379} = 1.763\ E - 07$.

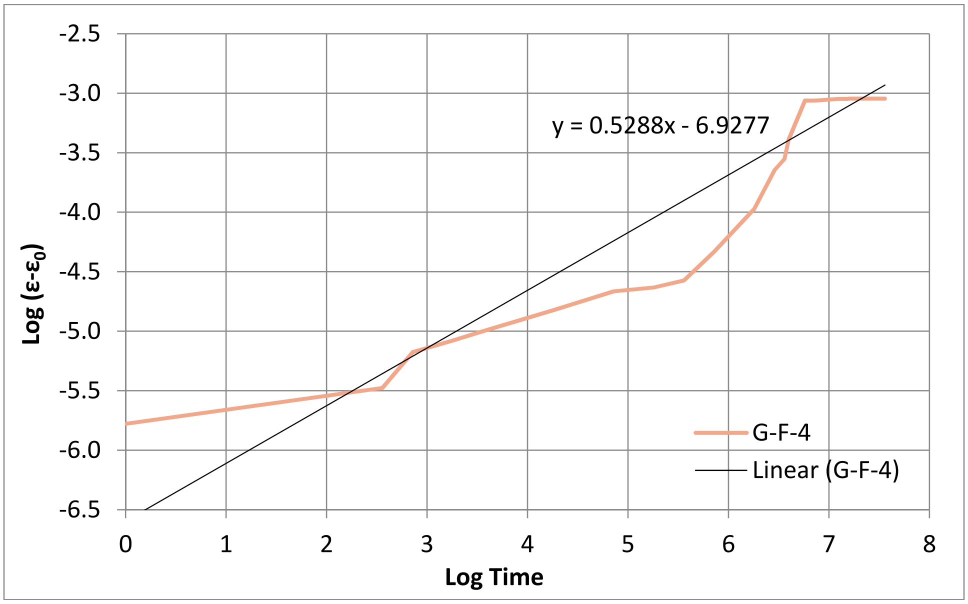

Figure 4.9 – Findley's parameters "m" and "n" for Flexural Sample G-F-4

As shown in Figure 4.9, Findley's material parameter "n" was 0.5288 making the material parameter "m" equal to: $10^{-6.9277} = 1.181\ E - 07$.

Constants “m” and “n” are now calculated and shown in Table 4.5.

Table 4.5 - Findley’s Coefficient ‘m’ & ‘n’ for The Flexural Creep Tests

Specimen	Stress (psi)	Log m	Findley’s Coefficients	
			m	n
G-F-1	13.89	-7.64	2.27E-08	6.39E-01
G-F-2	13.89	-7.65	2.22E-08	6.40E-01
G-F-3	13.89	-6.75	1.76E-07	5.03E-01
G-F-4	13.89	-6.93	1.18E-07	5.29E-01

Findley’s coefficients calculated in this section were used to compute and predict flexural strain magnitude at any time using Equation 4.4. Table 4.6 lists the predicted flexural strain up to 50 years.

Table 4.6 – Flexural Strain Predicted Using Findley’s Power Law

Flexural Strain Prediction - Findley’s Power Law									
Sample / Hours	**1**	**5**	**500**	**2,000**	**5,000**	**10,000**	**50,000**	**100,000**	**438,000**
G-F-1	8.21 E-05	1.76 E-04	2.00 E-04	3.77 E-04	6.07 E-04	9.86 E-04	2.36 E-03	3.72 E-03	9.30 E-03
G-F-2	1.69 E-04	1.73 E-04	2.85 E-04	4.61 E-04	6.88 E-04	9.75 E-04	2.43 E-03	3.70 E-03	9.26 E-03
G-F-3	3.51 E-04	3.73 E-04	7.36 E-04	1.15 E-03	1.62 E-03	2.15 E-03	4.42 E-03	6.12 E-03	1.25 E-02
G-F-4	1.78 E-04	1.94 E-04	4.83 E-04	8.35 E-04	1.24 E-03	1.71 E-03	3.78 E-03	5.37 E-03	1.15 E-02

Figure 4.10 shows predicted strain for 50-years. Using these strain values, long term flexural modulus is calculated and presented in Figure 4.11. Data is extrapolated using Findley’s Power Law (Equation 4.4)

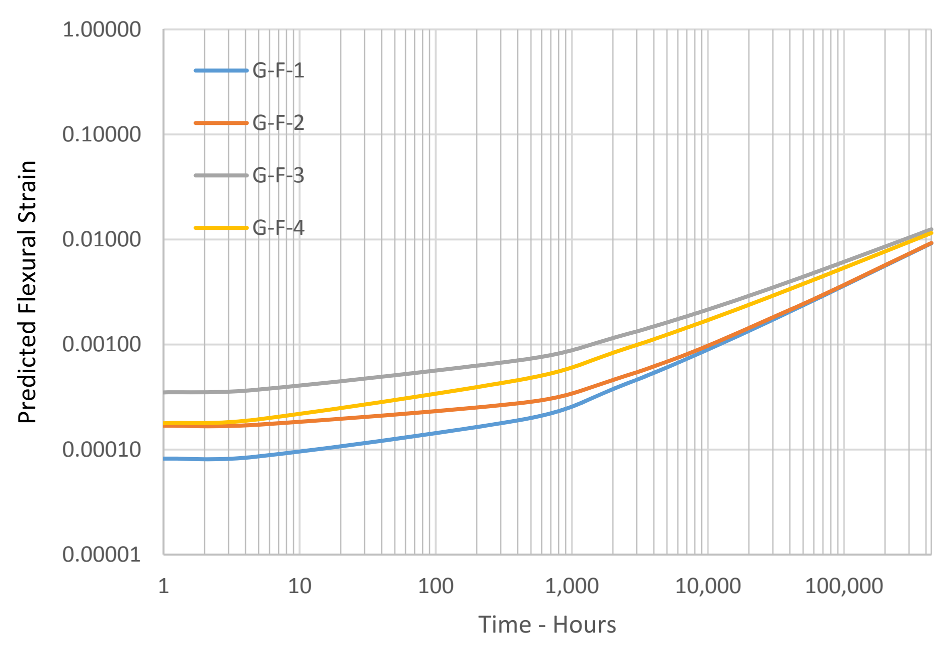

Figure 4.10 - Flexural Strain Prediction for 50 Years - Findley's Power Law

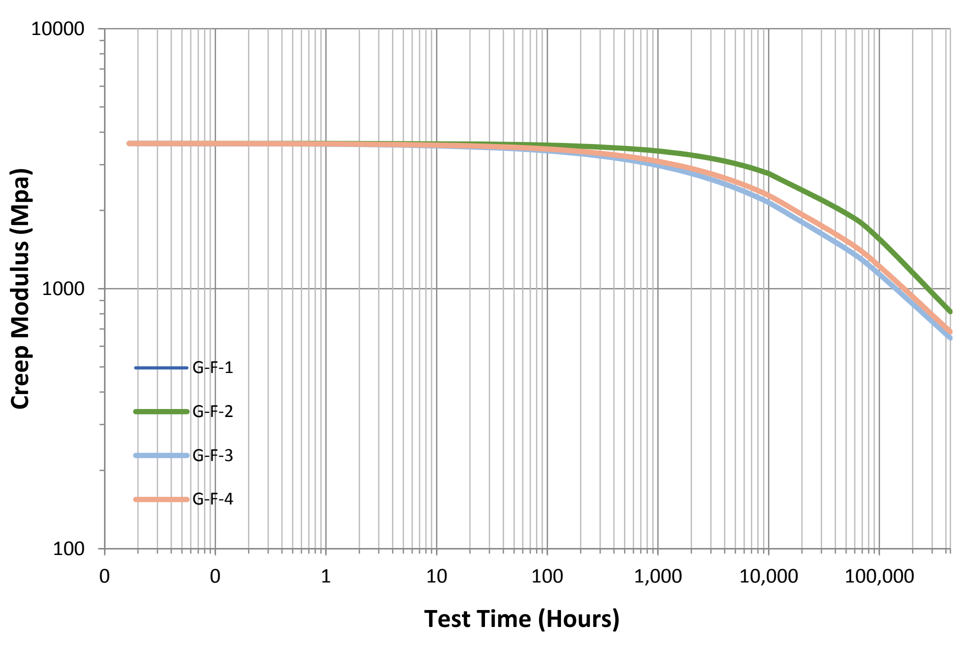

Figure 4.11 - Flexural Modulus Prediction for 50 Years - Findley's Power Law

Table 4.7 shows a comparison between experimental creep strain and calculated strain obtained from Findley's Power Law.

Table 4.7 – Comparison of Experimental and Theoretical Strain for Flexural Creep Test

Sample / Hours	**Experimental**						**Theoretical**					
	1	**5**	**500**	**2,000**	**5,000**	**10,000**	**1**	**5**	**500**	**2,000**	**5,000**	**10,000**
G-F-1	1.67 E-06	6.67 E-06	1.20 E-04	1.04 E-03	1.08 E-03	1.09 E-03	8.21 E-05	1.76 E-04	2.00 E-04	3.77 E-04	6.07 E-04	9.86 E-04
G-F-2	5.00 E-06	5.00 E-06	9.33 E-05	5.53 E-04	6.00 E-04	6.07 E-04	1.69 E-04	1.73 E-04	2.85 E-04	4.61 E-04	6.88 E-04	9.75 E-04
G-F-3	1.17 E-05	1.83 E-05	1.00 E-04	8.40 E-04	8.80 E-04	8.93 E-04	3.51 E-04	3.73 E-04	7.36 E-04	1.15 E-03	1.62 E-03	2.15 E-03
G-F-4	1.00 E-05	1.50 E-05	1.07 E-04	8.67 E-04	9.00 E-04	9.00 E-04	1.78 E-04	1.94 E-04	4.83 E-04	8.35 E-04	1.24 E-03	1.71 E-03

4.4.2. Tensile Creep Parameters and Data Extrapolation

Tensile creep test specimens were under a constant loading condition for 10,000 hours as described in Chapter 3. The procedure to obtain Findley's parameters for tensile creep test is the same as described in Section 4.4.1 for flexural creep data. To obtain Findley's coefficients "m" and "n", a simple linear regression model was carried out for each sample on a "$\log(\varepsilon_t - \varepsilon_o)$" versus "$\log(t)$" graph. Figures 4.11 to 4.16 show the log graph and the trend line equation for each sample.

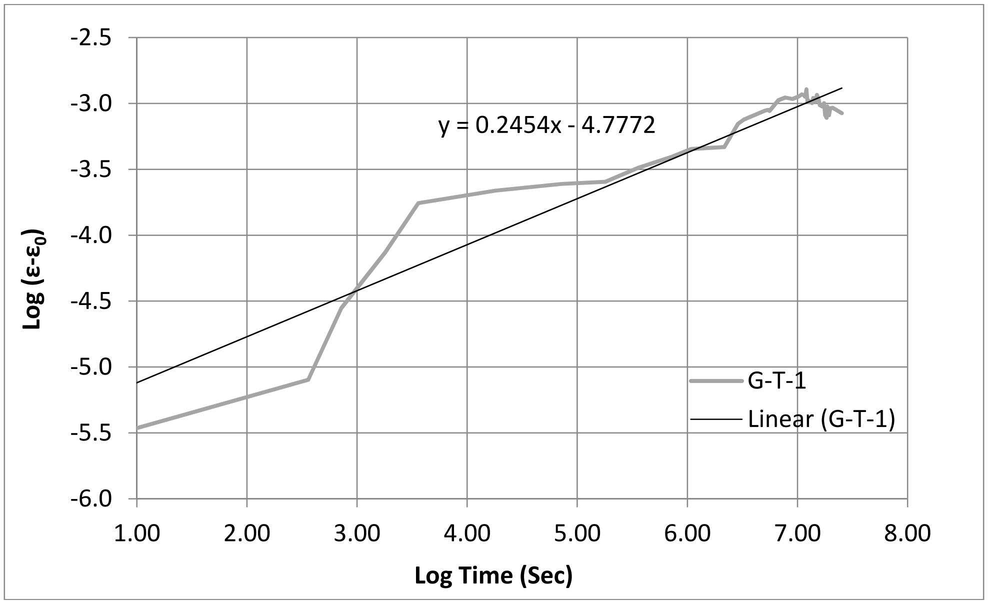

Figure 4.12 – Findley's parameters "m" and "n" for Tensile Sample G-T-1

As shown in Figure 4.12, Findley's material parameter "n" was 0.2454 making the material parameter "m" equal to: $10^{-4.7772} = 1.670E - 05$.

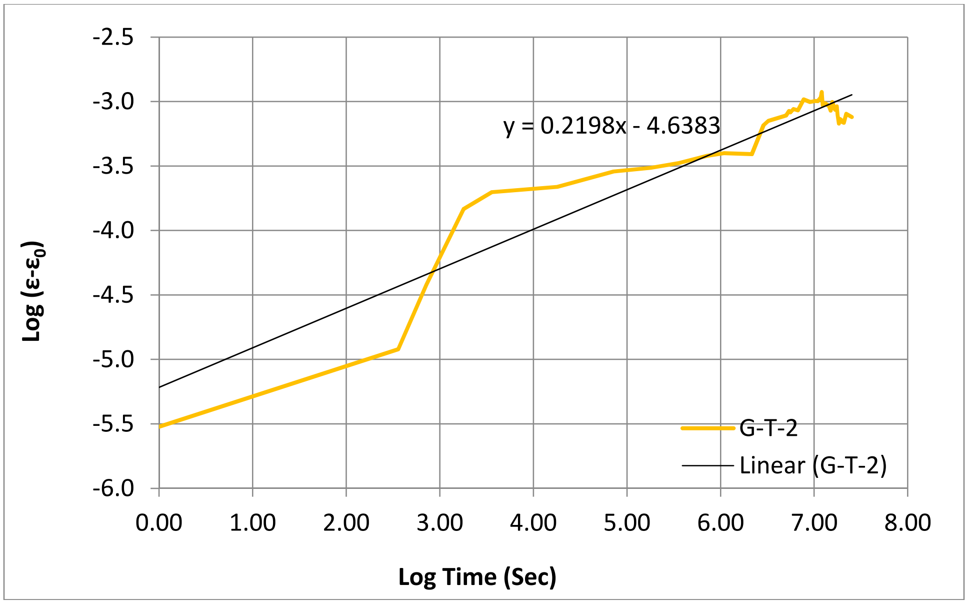

Figure 4.13 – Findley's parameters "m" and "n" for Tensile Sample G-T-2

As shown in Figure 4.13, Findley's material parameter "n" was 0.2198 making the material parameter "m" equal to: $10^{-4.6383} = 2.300E - 05$.

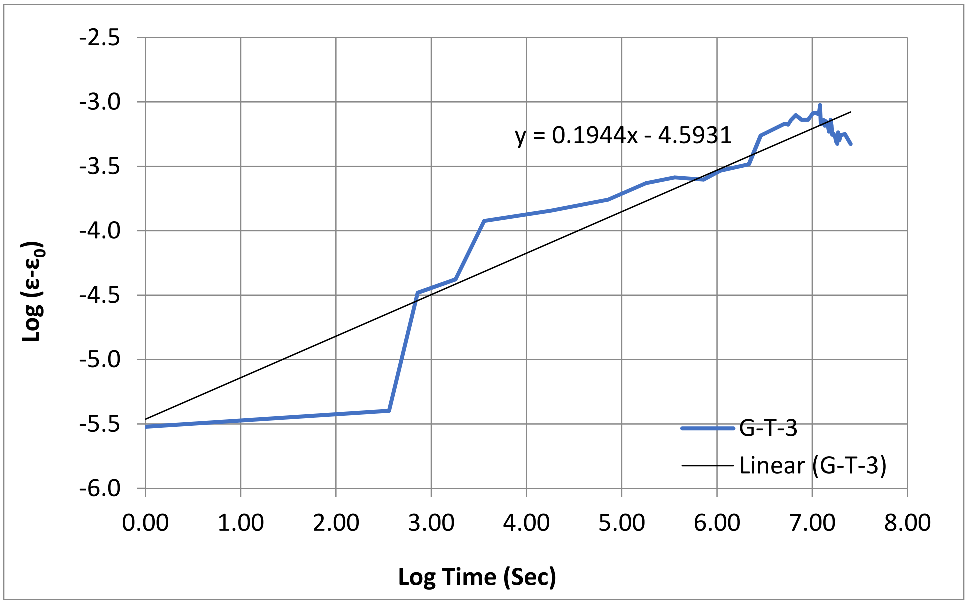

Figure 4.14 – Findley's parameters "m" and "n" for Tensile Sample G-T-3

As shown in Figure 4.14 Findley's material parameter "n" was 0.1944 making the material parameter "m" equal to: $10^{-4.5931} = 2.552E - 05$.

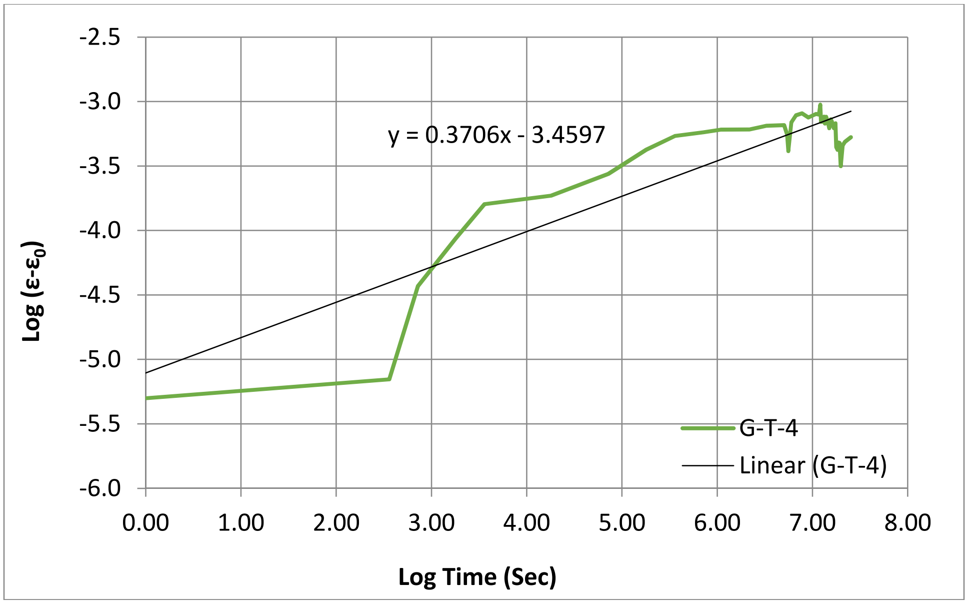

Figure 4.15 – Findley's parameters "m" and "n" for Tensile Sample G-T-4

As shown in Figure 4.15 Findley's material parameter "n" was 0.3706 making the material parameter "m" equal to: $10^{-3.4597} = 3.470E - 04$.

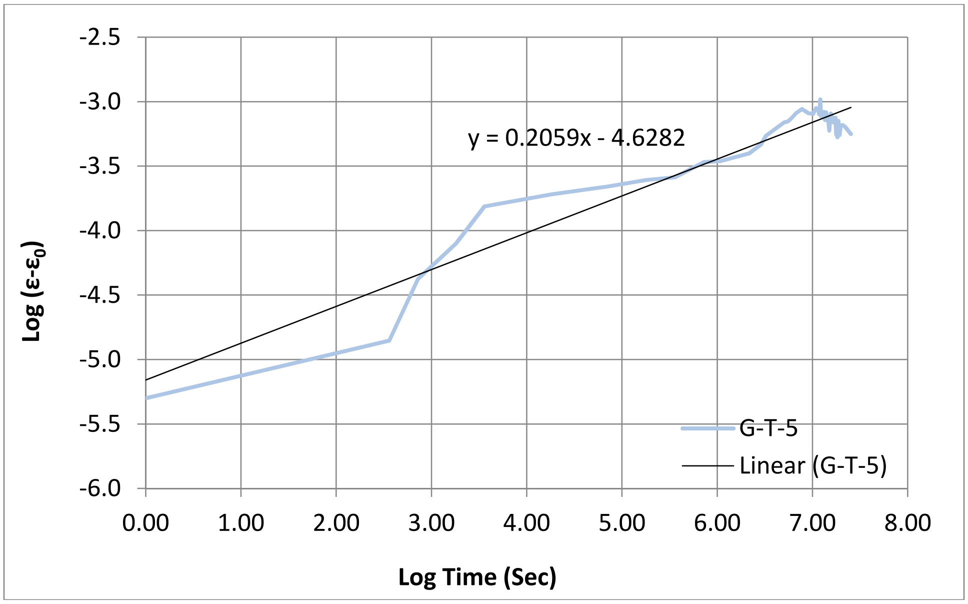

Figure 4.16 – Findley's parameters "m" and "n" for Tensile Sample G-T-5

As shown in Figure 4.16 Findley's material parameter "n" found was 0.2059 making the material parameter "m" equal to: $10^{-4.6282} = 2.354E - 05$.

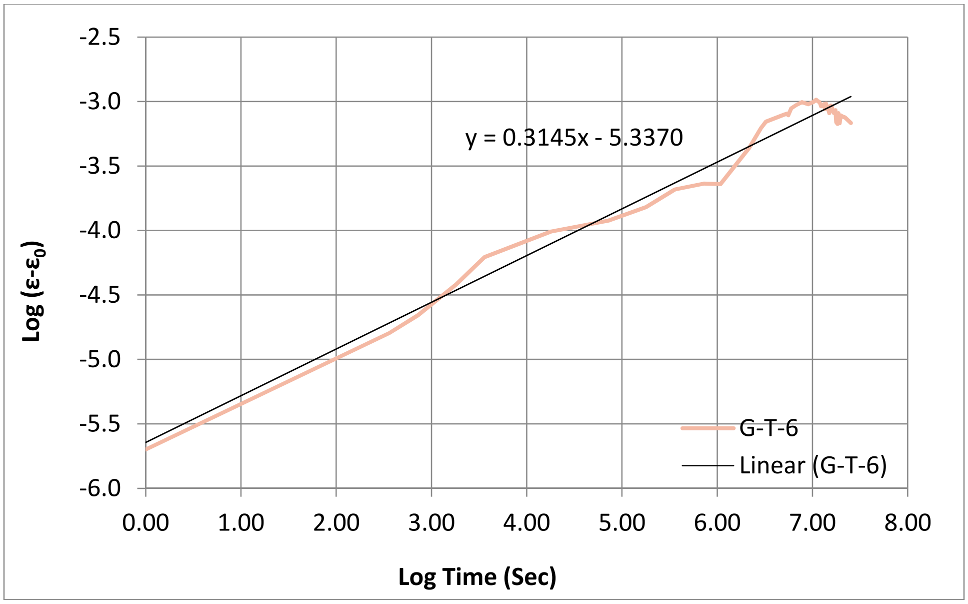

Figure 4.17 – Findley’s Parameters “m” and “n” for Tensile Sample G-T-6

As shown in Figure 4.17 Findley’s material parameter “n” was 0.3145 making the material parameter “m” equal to: $10^{-5.3370} = 4.6043E - 06$.

Findley’s coefficients for tensile creep test are summarized in Table 4.8.

Table 4.8 - Findley’s Coefficient ‘m’ & ‘n’ for The Tensile Creep Tests

Specimen	**Stress**	**Log**	**Findley’s Coefficient**	
	(psi)	**m**	**m**	**n**
G-T-1	40.323	-4.78	1.67E-05	2.45E-01
G-T-2	40.323	-4.64	2.30E-05	2.20E-01
G-T-3	40.323	-4.59	2.55E-05	1.94E-01
G-T-4	40.323	-3.46	3.47E-04	3.71E-02
G-T-5	40.323	-4.63	2.35E-05	2.06E-01
G-T-6	40.323	-5.34	4.60E-06	3.14E-01

Findley’s coefficients as calculated in this section were used to compute and predict tensile strain magnitude at any time using Equation 4.4. Table 4.9 lists the predicted flexural strain up to 50 years.

Table 4.9 – Tensile Strain Predicted Using Findley's Power Law

Tensile Strain Prediction - Findley's Power Law									
Sample / Hours	**1**	**5**	**500**	**2,000**	**5,000**	**10,000**	**50,000**	**100,000**	**438,000**
G-T-1	1.17E-03	1.25E-03	1.76E-03	2.10E-03	2.33E-03	2.60E-03	3.24E-03	3.82E-03	5.05E-03
G-T-2	1.23E-03	1.33E-03	1.88E-03	2.25E-03	2.48E-03	2.74E-03	3.35E-03	3.89E-03	5.00E-03
G-T-3	1.25E-03	1.35E-03	1.83E-03	2.14E-03	2.32E-03	2.53E-03	2.99E-03	3.39E-03	4.19E-03
G-T-4	4.40E-03	4.68E-03	5.42E-03	5.61E-03	5.75E-03	5.88E-03	6.16E-03	6.32E-03	6.62E-03
G-T-5	1.23E-03	1.33E-03	1.83E-03	2.15E-03	2.35E-03	2.57E-03	3.08E-03	3.52E-03	4.42E-03
G-T-6	1.01E-03	1.08E-03	1.37E-03	1.52E-03	1.66E-03	1.83E-03	2.30E-03	2.72E-03	3.74E-03

Figure 4.18 shows predicted strain for 50-years; data is extrapolated using Findley's power law (Equation 4.4)

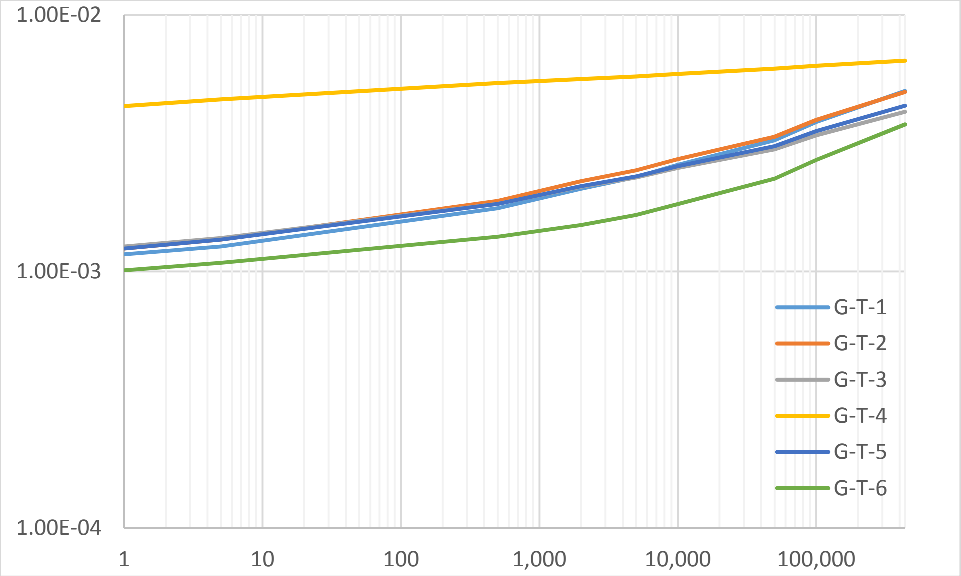

Figure 4.18 - Tensile Strain Prediction for 50 Years - Findley's Power Law

With a magnitude of constant stress and also with a predicted strain for 50 years, long-term tensile modulus can be predicted. Tensile creep modulus prediction for 50 years is shown in Figure 4.19.

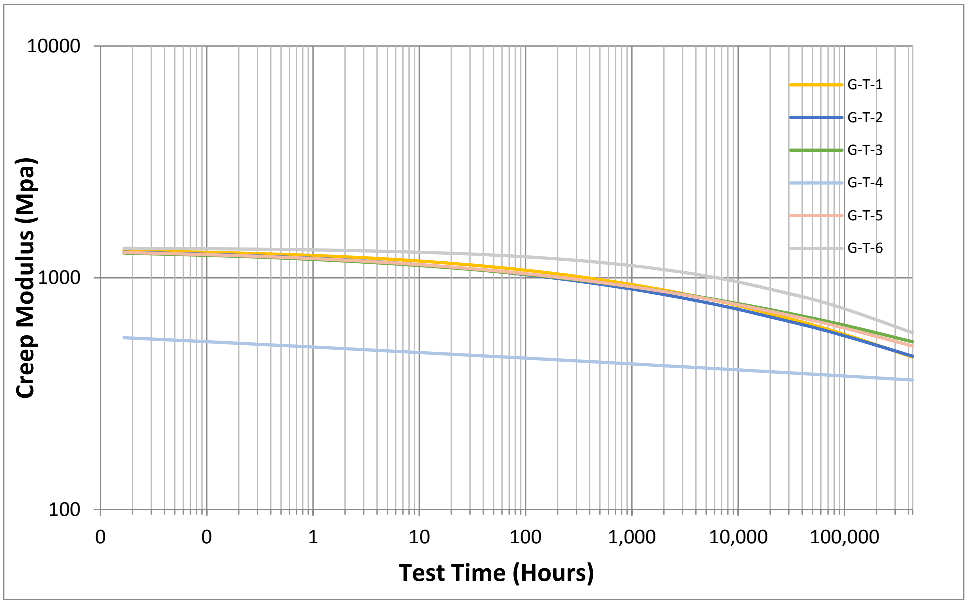

Figure 4.19 - Tensile Modulus Prediction for 50 Years - Findley's Power Law

Table 4.10 shows a comparison between experimental tensile creep strain and calculated strain obtained from Findley's power law.

Table 4.10 – Comparison of Experimental and Theoretical Strain for Tensile Creep Test

Hours / Sample	**Experimental**						**Theoretical**					
	1	**5**	**500**	**2,000**	**5,000**	**10,000**	**1**	**5**	**500**	**2,000**	**5,000**	**10,000**
G-T-1	1.75 E-04	2.18 E-04	4.66 E-04	1.11 E-03	8.12 E-04	1.13 E-03	1.17 E-03	1.25 E-03	1.76 E-03	2.10 E-03	2.33 E-03	2.60 E-03
G-T-2	1.98 E-04	2.18 E-04	3.90 E-04	1.04 E-03	7.23 E-04	1.08 E-03	1.23 E-03	1.33 E-03	1.88 E-03	2.25 E-03	2.48 E-03	2.74 E-03
G-T-3	1.19 E-04	1.43 E-04	3.28 E-04	7.27 E-04	5.06 E-04	8.47 E-04	1.25 E-03	1.35 E-03	1.83 E-03	2.14 E-03	2.32 E-03	2.53 E-03
G-T-4	1.60 E-04	1.86 E-04	6.07 E-04	8.09 E-04	4.77 E-04	8.39 E-04	4.40 E-03	4.68 E-03	5.42 E-03	5.61 E-03	5.75 E-03	5.88 E-03
G-T-5	1.54 E-04	1.91 E-04	3.97 E-04	8.76 E-04	5.51 E-04	8.66 E-04	1.23 E-03	1.33 E-03	1.83 E-03	2.15 E-03	2.35 E-03	2.57 E-03
G-T-6	6.20 E-05	9.80 E-05	4.36 E-04	9.89 E-04	6.79 E-04	1.03 E-03	1.01 E-03	1.08 E-03	1.37 E-03	1.52 E-03	1.66 E-03	1.83 E-03

4.5. Curve Fitting Model

Conic section is a degree two curve that can be obtained as the intersection of a cone (round conical surface) with a plane. Equation 4.6 represents the general equation for all the conic sections. Curve fitting is one of the common methods used to extrapolate the statistical or experimental data.

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

Equation 4.6

For the conducted experiments, both the data collection and design life periods are quite long periods. Therefore, the log-log method is used to extrapolate the data over the 50-year design life of the material. Considering x and y as logs, Equation 4.6 can be written as:

$$[Log(\varepsilon)]^2 = A[Log(t)]^2 + B\log(t) + C \qquad \text{Equation 4.7}$$

where:

X Defined to be [Log (t)]

Y Defined to be [Log (ε)]

ε = Creep strain after (t) hours of loading

A, B, C = Equation parameters (to be calculated based on data collection)

Since strain value (ε) is less than 1, Equation 4.7 can be written as:

$$Log(\varepsilon) = -\sqrt{A[Log(t)]^2 + B\log(t) + C} \qquad \text{Equation 4.8}$$

To calculate the equation’s parameters, three fix points from the data set was selected. Data selection and calculated strain are shown in Sections 4.5.1 and 4.5.2 for flexural and tensile creep test respectively.

4.5.1. Flexural Creep Parameters and Data Extrapolation

By solving simultaneous equations for each sample with three given points shown in Table 4.11, parameters A, B and C are calculated and listed in Table 4.12.

Table 4.11 – Selected Points to Calculate A, B and C for Flexural Creep Test

Hours	1	2,000	10,000
G-F-1	1.67E-06	1.04E-03	0.0011
G-F-2	5.00E-06	5.53E-04	0.0006
G-F-3	1.17E-05	8.40E-04	0.0009
G-F-4	1.00E-05	8.67E-04	0.0009

Table 4.12 – A, B, C Parameters for Equation 4.7

Hours	A	B	C
G-F-1	0.909	-10.419	33.387
G-F-2	0.406	-6.639	28.101
G-F-3	0.326	-5.584	24.335
G-F-4	0.384	-5.999	25.000

Curve parameters calculated in this section were used to compute and predict flexural strain for a 50-years period of time. Predicted strain magnitudes are shown in Table 4.13.

Table 4.13 – Flexural Strain Predicted Using Curve Fitting Model

Flexural Strain Prediction - Curve Fitting Model									
Sample / Hours	1	5	500	2,000	5,000	10,000	50,000	100,000	438,000
G-F-1	0.00000	0.00001	0.00036	0.00104	0.00200	0.00316	0.00757	0.00992	0.01318
G-F-2	0.00000	0.00001	0.00024	0.00055	0.00096	0.00146	0.00378	0.00565	0.01295
G-F-3	0.00001	0.00003	0.00039	0.00084	0.00140	0.00205	0.00497	0.00725	0.01602
G-F-4	0.00001	0.00003	0.00039	0.00087	0.00145	0.00213	0.00504	0.00719	0.01466

Figure 4.20 shows predicted strain for 50-years; data is extrapolated using (Equation 4.8) the curve fitting model.

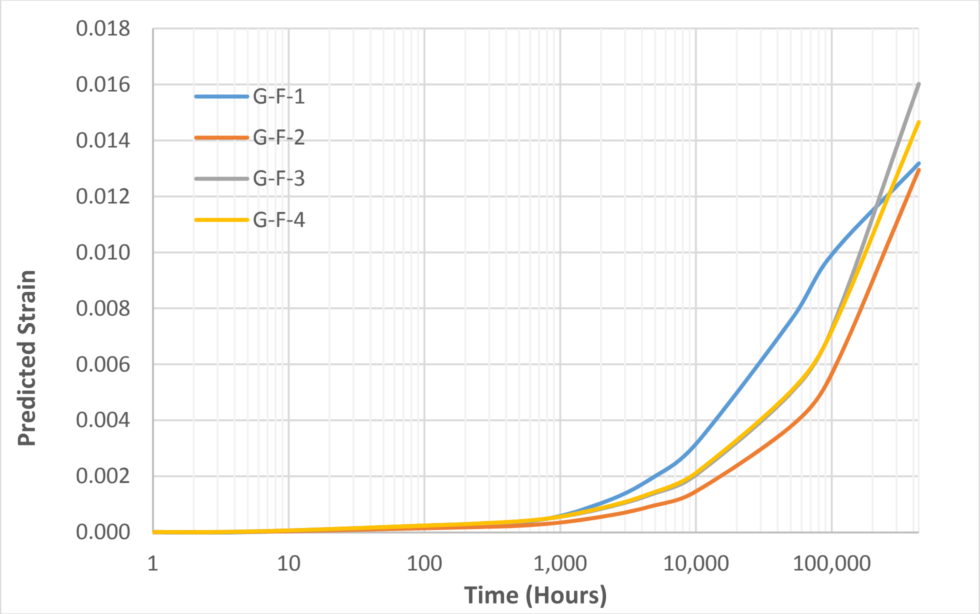

Figure 4.20 - Flexural Strain Prediction for 50 Years - Curve Fitting Model

Table 4.14 shows a comparison between experimental creep strain and calculated strain obtained from the curve fitting model.

Table 4.14 – Comparison of Experimental and Theoretical Strain for Flexural Creep Test

Sample / Hours	**Experimental**						**Theoretical**					
	1	**5**	**500**	**2,000**	**5,000**	**10,000**	**1**	**5**	**500**	**2,000**	**5,000**	**10,000**
G-F-1	1.67 E-06	6.67 E-06	1.20 E-04	1.04 E-03	1.08 E-03	1.09 E-03	1.67 E-06	7.04 E-06	3.57 E-04	1.04 E-03	2.00 E-03	3.16 E-03
G-F-2	5.00 E-06	5.00 E-06	9.33 E-05	5.53 E-04	6.00 E-04	6.07 E-04	5.00 E-06	1.37 E-05	2.37 E-04	5.53 E-04	9.64 E-04	1.46 E-03
G-F-3	1.17 E-05	1.83 E-05	1.00 E-04	8.40 E-04	8.80 E-04	8.93 E-04	1.17 E-05	2.90 E-05	3.87 E-04	8.40 E-04	1.40 E-03	2.05 E-03
G-F-4	1.00 E-05	1.50 E-05	1.07 E-04	8.67 E-04	9.00 E-04	9.00 E-04	1.00 E-05	2.62 E-05	3.92 E-04	8.67 E-04	1.45 E-03	2.13 E-03

Strain level of 0.000872 was observed after 10,000 hours of loading; however, Findley's equation and curve model present 66% and 153% higher values as compared to the actual strain after 10,000 hours.

4.5.2. Tensile Creep Parameters and Data Extrapolation

Following the same procedure to calculate Equation 4.8 parameters, three fix points were picked from the collected data set. These time-strain coordinates and calculated parameters A, B, C are shown in Table 4.15 and 4.16 respectively.

Table 4.15 – Selected Points to Calculate A, B and C for Tensile Creep Test

Sample	1	2,000	10,000
G-T-1	4.00E+00	0.0000	1.13E-03
G-T-2	-8.85E+00	0.0000	1.08E-03
G-T-3	-8.40E+00	0.0000	8.47E-04
G-T-4	-9.61E+00	0.0000	8.39E-04
G-T-5	-9.76E+00	0.0000	8.66E-04
G-T-6	-8.91E+00	0.0000	1.03E-03

Table 4.16 – A, B, C Tensile Parameters for Equation 4.7

Sample	A	B	C
G-T-1	0.0264	-1.7170	14.1148
G-T-2	-0.0133	-1.4143	13.7147
G-T-3	-0.0096	-1.6499	15.4013
G-T-4	-0.1117	-1.1000	14.4087
G-T-5	0.0035	-1.5597	14.5350
G-T-6	0.2460	-3.4401	17.7040

Curve parameters calculated in this section were used to compute and predict tensile strain for a 50-year period of time. Predicted strain magnitudes are shown in Table 4.17.

Table 4.17 – Flexural Strain Predicted Using Curve Fitting Model

Tensile Strain Prediction Curve Fitting Model									
Sample / Hours	**1**	**5**	**500**	**2,000**	**5,000**	**10,000**	**50,000**	**100,000**	**438,000**
G-T-1	0.00018	0.00025	0.00078	0.00111	0.00141	0.00170	0.00266	0.00325	0.00506
G-T-2	0.00020	0.00027	0.00074	0.00104	0.00131	0.00158	0.00250	0.00308	0.00496
G-T-3	0.00012	0.00017	0.00050	0.00073	0.00094	0.00115	0.00188	0.00235	0.00393
G-T-4	0.00016	0.00021	0.00055	0.00081	0.00108	0.00136	0.00250	0.00336	0.00698
G-T-5	0.00015	0.00022	0.00061	0.00085	0.00107	0.00129	0.00200	0.00244	0.00382
G-T-6	0.00006	0.00012	0.00064	0.00099	0.00129	0.00156	0.00229	0.00263	0.00335

Figure 4.21 shows predicted strain for 50-years; data is extrapolated using the curve fitting model (Equation 4.8)

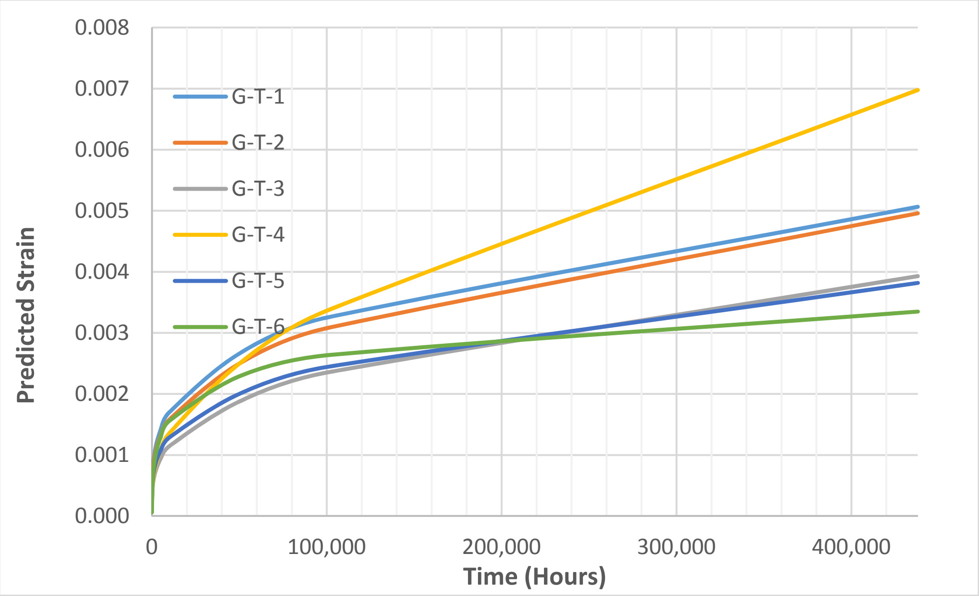

Figure 4.21 - Tensile Strain Prediction for 50 Years - Curve Fitting Model

Table 4.18 shows a comparison between experimental creep strain and calculated strain obtained from the curve fitting model.

Table 4.18 – Comparison of Experimental and Theoretical Strain for Tensile Creep Test

Sample / Hours	**Experimental**						**Theoretical**					
	1	**5**	**500**	**2,000**	**5,000**	**10,000**	**1**	**5**	**500**	**2,000**	**5,000**	**10,000**
G-T-1	1.75 E-04	2.18 E-04	4.66 E-04	1.11 E-03	8.12 E-04	1.13 E-03	1.75 E-04	2.54 E-04	7.76 E-04	1.11 E-03	1.41 E-03	1.70 E-03
G-T-2	1.98 E-04	2.18 E-04	3.90 E-04	1.04 E-03	7.23 E-04	1.08 E-03	1.98 E-04	2.71 E-04	7.40 E-04	1.04 E-03	1.31 E-03	1.58 E-03
G-T-3	1.19 E-04	1.43 E-04	3.28 E-04	7.27 E-04	5.06 E-04	8.47 E-04	1.19 E-04	1.68 E-04	5.03 E-04	7.27 E-04	9.38 E-04	1.15 E-03
G-T-4	1.60 E-04	1.86 E-04	6.07 E-04	8.09 E-04	4.77 E-04	8.39 E-04	1.60 E-04	2.06 E-04	5.50 E-04	8.09 E-04	1.08 E-03	1.36 E-03
G-T-5	1.54 E-04	1.91 E-04	3.97 E-04	8.76 E-04	5.51 E-04	8.66 E-04	1.54 E-04	2.15 E-04	6.06 E-04	8.51 E-04	1.07 E-03	1.29 E-03
G-T-6	6.20 E-05	9.80 E-05	4.36 E-04	9.89 E-04	6.79 E-04	1.03 E-03	6.20 E-05	1.18 E-04	6.38 E-04	9.89 E-04	1.29 E-03	1.56 E-03

4.6. Discussion of Results

As shown in Tables 4.6, 4.9, 4.13 and 4.17, and described in the following sections, predicted strain for 438,000 hours (50 years) using Curve Fitting model showed an average of 34% and 26% higher strains for flexural and tensile tests compared to the results obtained from Findley's model.

4.6.1. Flexural Creep

As described in Chapter 4 and shown in Figure 4.2, flexural creep modulus decreased from E_0=3,620 MPa (525,033 psi) to an average of $E_{10,\ 000}$=2,493 MPa (361,576 psi) over the 10,000 hours of loading. This means a 31% reduction in the magnitude of flexural creep modulus took place over the experiment duration.

Strain level of 0.000872 was observed after 10,000 hours of loading; however, Findley's equation and curve model presented 66% and 152% higher values as compared to the actual strain after 10,000 hours.

Although the calculated strain using Findley's equation and the curve model show relatively higher strain levels at 10,000 hours compared to actual data observation, they both predicted a closer amount of strain to occur after 50 years. Findley's equation shows a strain level of 0.0107 and the curve model presents a flexural strain level of 0.0142 after 50 years. As described previously, the predicted strain level calculated by the curve model is 33% higher than the prediction in Findley's power law.

Figurers 4.22 and 4.23 compare the actual flexural strain recorded during 10,000 hours of experiments with calculated strain over the predicted 50 years according to Findley's power law and the curve fitting model.

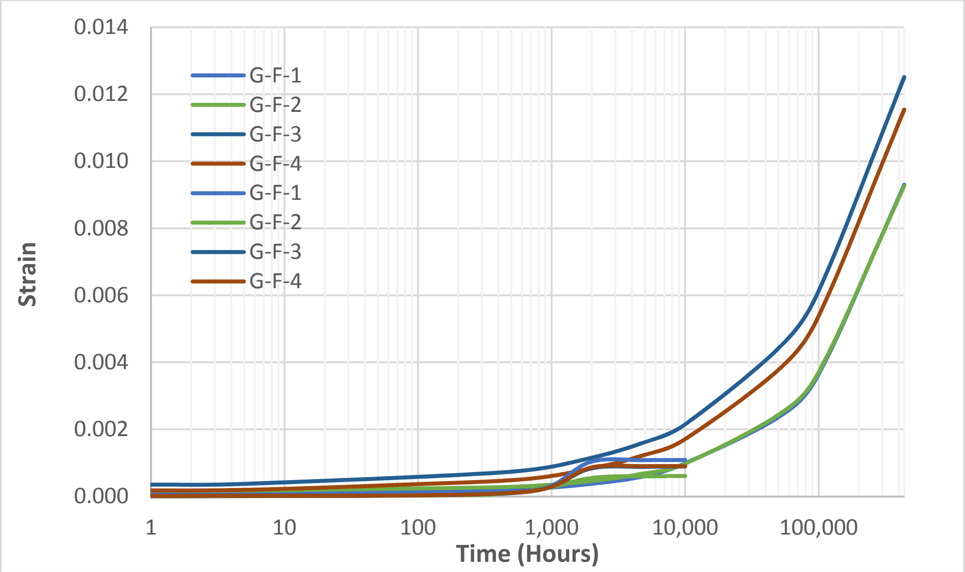

Figure 4.22 – Comparison between Observed Data and Calculated Strain Using Findley's Power Law

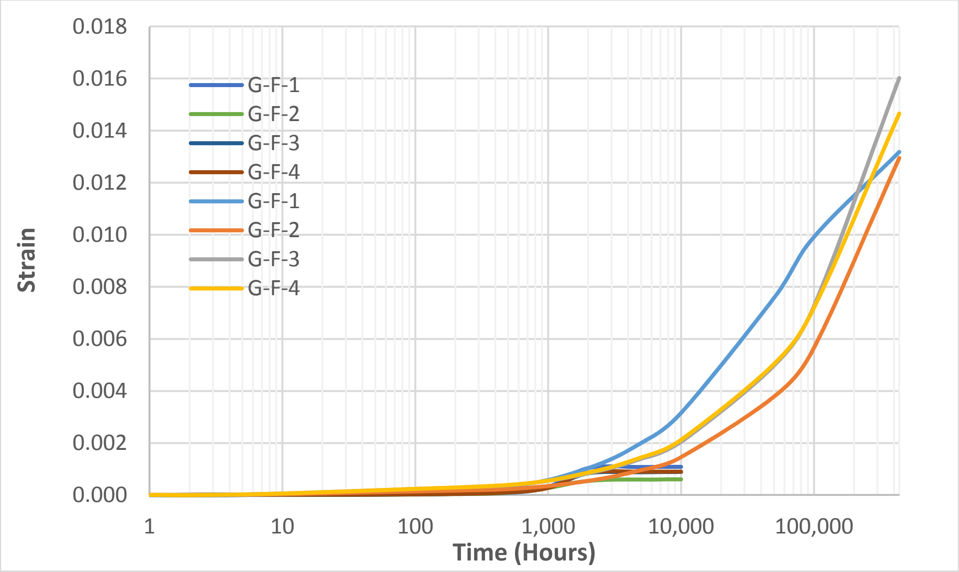

Figure 4.23 – Comparison between Observed Data and Calculated Strain Using Curve Fitting Model

4.6.2. Tensile Creep

Observed data for tensile creep modulus is presented in Table 4.4 and the curve is shown in Figure 4.3. Tensile creep modulus experienced a reduction from E_0=1,349 MPa (195,654 psi) to an average of $E_{10,000}$=731.96 MPa (106,161 psi) over the 10,000 hours of this experiment. This represents a 46% drop in the magnitude of tensile creep modulus.

Strain level of 0.000966 was observed after 10,000 hours of loading. The magnitude of strain calculated by Findley's equation is 150% higher than the recorded data. Curve fitting model calculated a strain level which is 19% higher than the recorded data after 10,000 hours.

The 50-year tensile strain predicted using Fridley's equation shows an average of 0.0048 while the curve model computed a strain with magnitude of 0.00468 for a 50-year design life of material. Findley's results are 3% higher than the predicted strain based on the curve model.

Figurers 4.24 and 4.25 compare the actual tensile strain recorded during 10,000 hours of experiment with calculated strain over the 50 years according to Findley's equation and curve fitting model.

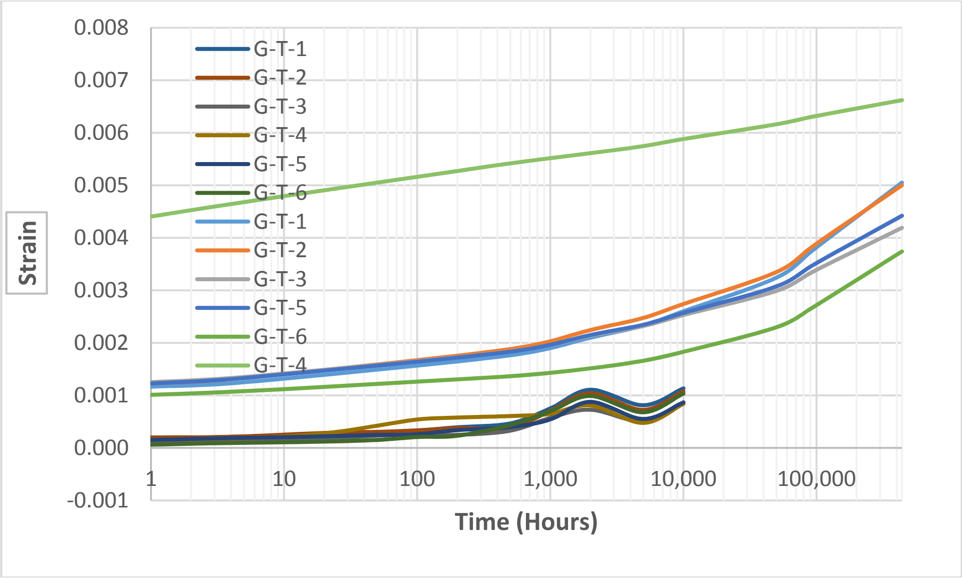

Figure 4.24 – Comparison between Observed Data and Calculated Strain Using Findley's Power Law

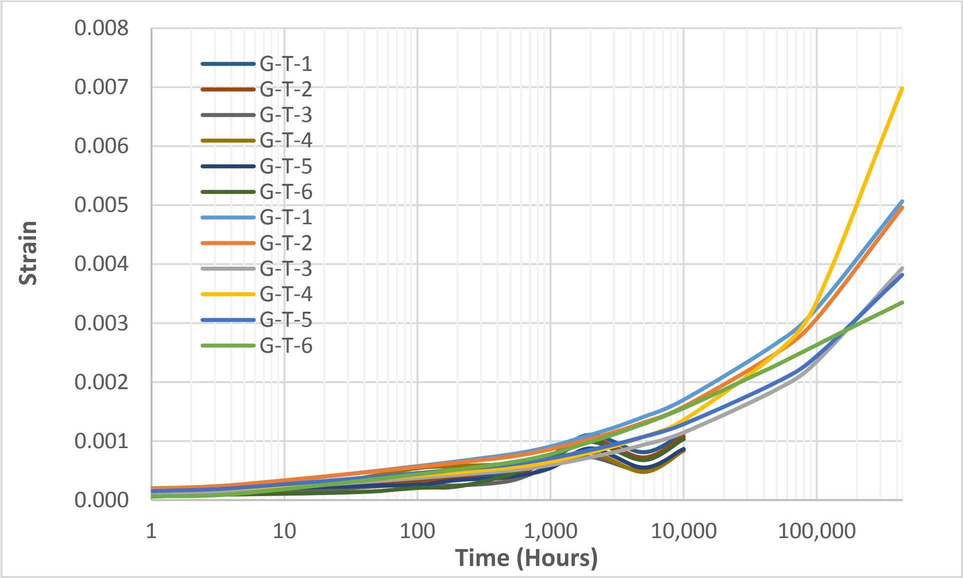

Figure 4.25 – Comparison between Observed Data and Calculated Strain Using Curve Fitting Model

4.7 Chapter Summary

The first three sections of this chapter presented the data-set collected during the flexural and tensile experiments, respectively. As seen in Figures 4.1 and 4.3, both flexural and tensile samples reached a constant, quite steady and ascending trend in their strain-time graphs. After the first 2,000 hours of loading, an average strain level of 0.0825% and 0.0925% were observed for flexural and tensile specimens, respectively, while these strain levels rose by 0.0875% and 0.0966% during the remaining 8,000 hours.

CHAPTER 5

CONCLUSIONS, LIMITATIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

5.1 Conclusions

Based on 10,000 hours of experiments and data collection, the following conclusions can be made:

1- Flexural creep modulus was 69% of its short-term magnitude after 10,000 hours and 20% of the short-term modulus after 50 years.

2- Tensile creep modulus is 54% of its short-term magnitude after 10,000 hours and 36% of the short-term modulus after 50 years.

5.2. Limitations

Limitations on this study were as follows:

3- These tests were carried out in an air-conditioned room. For the long-term creep tests, humidity and temperature need to be maintained more precisely.

4- Total number of samples used for this study was four for the flexural tests and six for the tensile tests. In this experiment, some shape and physical defects caused elimination of some of the specimens.

5.3. Recommendations for Future Research

Recommendations for future research are summarized below:

1- ASTM D2990 recommends the stress level that causes 1% strain after 1,000 hours of loading. Load selection for both tensile and flexural tests was low enough to cause such a high strain rates. This was due to possible loading applications for pipe liners.

2- Investigate the creep behavior of materials under effect of different moistures and temperatures.

3- Investigate the creep behavior of materials under effect of different stress levels.

4- Perform long-term test for more than 10,000 hours and compare the predicted results.

5- Investigate the creep behavior of materials for different polyurea composites.

6- Perform a constant hydrostatic test and compare the results for hoop stress with flexural strain analysis in this experiment.

APPENDIX A

FLEXURAL CREEP DATA

Flexural Strain					
Duration	Hrs	G-F-1	G-F-2	G-F-3	G-F-4
0 min	0	0.00000000	0.00000000	0.00000000	0.00000000
1 min	0	0.00000000	0.00000167	0.00000333	0.00000167
6 min	0	0.00000000	0.00000167	0.00000333	0.00000333
12 min	0	0.00000000	0.00000167	0.00000833	0.00000667
30 min	1	0.00000000	0.00000333	0.00001000	0.00000833
60 min	1	0.00000167	0.00000500	0.00001167	0.00001000
5 hrs	5	0.00000667	0.00000500	0.00001833	0.00001500
20 hrs	20	0.00001333	0.00001167	0.00002000	0.00002167
50 hrs	50	0.00002167	0.00001833	0.00002167	0.00002333
100 hrs	100	0.00003000	0.00002333	0.00002667	0.00002667
200 hrs	200	0.00004667	0.00004000	0.00005000	0.00004667
500 hrs	500	0.00012000	0.00009333	0.00010000	0.00010667
800 hrs	800	0.00026833	0.00023667	0.00024667	0.00022667
1000 hrs	1000	0.00032000	0.00027667	0.00028333	0.00028000
1100 hrs	1100	0.00047333	0.00043333	0.00042667	0.00040667
1600 hrs	1600	0.00103333	0.00054667	0.00083333	0.00086667
1700 hrs	1700	0.00104000	0.00054667	0.00083333	0.00086667
1750 hrs	1750	0.00104000	0.00055333	0.00083333	0.00086667
1870 hrs	1870	0.00104000	0.00055333	0.00083333	0.00086667
2062 hrs	2062	0.00104000	0.00055333	0.00084000	0.00086667
2350 hrs	2350	0.00104667	0.00056667	0.00084667	0.00087333
2710 hrs	2710	0.00104667	0.00057333	0.00086000	0.00088000
3025 hrs	3025	0.00104667	0.00058000	0.00086667	0.00088667
3241 hrs	3241	0.00106667	0.00058667	0.00086667	0.00089333
3409 hrs	3409	0.00106667	0.00058667	0.00086667	0.00089333
3457 hrs	3457	0.00106667	0.00058667	0.00086667	0.00089333
3553 hrs	3553	0.00106667	0.00058667	0.00086667	0.00089333
3625 hrs	3625	0.00106667	0.00058667	0.00086667	0.00089333

Flexural Strain

Duration	Hrs	G-F-1	G-F-2	G-F-3	G-F-4
3697 hrs	3697	0.00107333	0.00059333	0.00087333	0.00089333
3745 hrs	3745	0.00107333	0.00059333	0.00087333	0.00089333
3865 hrs	3865	0.00107333	0.00059333	0.00087333	0.00089333
3961 hrs	3961	0.00107333	0.00059333	0.00087333	0.00089333
4057 hrs	4057	0.00107333	0.00060000	0.00087333	0.00089333
4225 hrs	4225	0.00107333	0.00060000	0.00087333	0.00089333
4369 hrs	4369	0.00107333	0.00060000	0.00088000	0.00090000
4537hrs	4537	0.00108000	0.00060000	0.00088000	0.00090000
4633 hrs	4633	0.00108000	0.00060000	0.00088000	0.00090000
4705 hrs	4705	0.00108000	0.00060000	0.00088000	0.00090000
4873 hrs	4873	0.00108000	0.00060000	0.00088000	0.00090000
5041 hrs	5041	0.00108000	0.00060000	0.00088000	0.00090000
5136 hrs	5136	0.00108000	0.00060000	0.00088000	0.00090000
5304 hrs	5304	0.00108000	0.00060000	0.00088000	0.00090000
5400 hrs	5400	0.00108000	0.00060000	0.00088000	0.00090000
5568 hrs	5568	0.00108000	0.00060000	0.00088000	0.00090000
5736 hrs	5736	0.00108000	0.00060000	0.00088000	0.00090000
5976 hrs	5976	0.00108000	0.00060000	0.00088000	0.00090000
6312 hrs	6312	0.00108000	0.00060000	0.00088000	0.00090000
7224 hrs	7224	0.00108000	0.00060000	0.00088667	0.00090000
7392 hrs	7392	0.00108000	0.00060000	0.00088667	0.00090000
7608 hrs	7608	0.00108667	0.00060667	0.00089333	0.00090000
7776 hrs	7776	0.00108667	0.00060667	0.00089333	0.00090000
7968 hrs	7968	0.00108667	0.00060667	0.00089333	0.00090000
8400 hrs	8400	0.00108667	0.00060667	0.00089333	0.00090000
8592 hrs	8592	0.00108667	0.00060667	0.00089333	0.00090000
10008 hrs	10000	0.00108667	0.00060667	0.00089333	0.00090000

Flexural Modulus Calculations - Findley										
Date	Duration					G-F-1				
	Duration	Years	Hrs	Sec	Log Sec	$\varepsilon-\varepsilon_0$	LOG ($\varepsilon-\varepsilon_0$)	m	n	Modulus Calculations
4/13/2011	0 min	0.00E+00	0.00	0		0.00E+00				
4/13/2011	1 min	1.90E-06	0.02	60	1.78	7.98E-07	-6.10	2.27E-08	6.39E-01	3620
4/13/2011	6 min	1.14E-05	0.10	360	2.56	9.98E-07	-6.00	2.27E-08	6.39E-01	3619
4/13/2011	12 min	2.28E-05	0.20	720	2.86	1.25E-06	-5.90	2.27E-08	6.39E-01	3619
4/13/2011	30 min	5.71E-05	0.50	1800	3.26	1.10E-06	-5.96	2.27E-08	6.39E-01	3618
4/13/2011	60 min	1.14E-04	1	3600	3.56	1.67E-06	-5.78	2.27E-08	6.39E-01	3617
4/13/2011	5 hrs	5.71E-04	5	18000	4.26	6.67E-06	-5.18	2.27E-08	6.39E-01	3611
4/14/2011	20 hrs	2.28E-03	20	72000	4.86	1.33E-05	-4.88	2.27E-08	6.39E-01	3599
4/23/2011	50 hrs	5.71E-03	50	180000	5.26	2.17E-05	-4.66	2.27E-08	6.39E-01	3583
4/25/2011	100 hrs	1.14E-02	100	360000	5.56	3.00E-05	-4.52	2.27E-08	6.39E-01	3562
4/29/2011	200 hrs	2.28E-02	200	720000	5.86	4.67E-05	-4.33	2.27E-08	6.39E-01	3531
5/4/2011	500 hrs	5.71E-02	500	1800000	6.26	1.20E-04	-3.92	2.27E-08	6.39E-01	3463
5/14/2011	800 hrs	9.13E-02	800	2880000	6.46	2.68E-04	-3.57	2.27E-08	6.39E-01	3411
5/22/2011	1000 hrs	1.14E-01	1000	3600000	6.56	3.20E-04	-3.49	2.27E-08	6.39E-01	3381
5/26/2011	1100 hrs	1.26E-01	1100	3960000	6.60	4.73E-04	-3.32	2.27E-08	6.39E-01	3367
6/17/2011	1600 hrs	1.83E-01	1600	5760000	6.76	1.03E-03	-2.99	2.27E-08	6.39E-01	3304
6/21/2011	1700 hrs	1.94E-01	1700	6120000	6.79	1.04E-03	-2.98	2.27E-08	6.39E-01	3293
6/23/2011	1750 hrs	2.00E-01	1750	6300000	6.80	1.04E-03	-2.98	2.27E-08	6.39E-01	3287
6/28/2011	1870 hrs	2.13E-01	1870	6732000	6.83	1.04E-03	-2.98	2.27E-08	6.39E-01	3274
7/6/2011	2062 hrs	2.35E-01	2062	7423200	6.87	1.04E-03	-2.98	2.27E-08	6.39E-01	3254
7/18/2011	2350 hrs	2.68E-01	2350	8460000	6.93	1.05E-03	-2.98	2.27E-08	6.39E-01	3226
8/2/2011	2710 hrs	3.09E-01	2710	9756000	6.99	1.05E-03	-2.98	2.27E-08	6.39E-01	3192
8/15/2011	3025 hrs	3.45E-01	3025	10890000	7.04	1.05E-03	-2.98	2.27E-08	6.39E-01	3165
8/24/2011	3241 hrs	3.70E-01	3241	11667600	7.07	1.07E-03	-2.97	2.27E-08	6.39E-01	3147
8/31/2011	3409 hrs	3.89E-01	3409	12272400	7.09	1.07E-03	-2.97	2.27E-08	6.39E-01	3134
9/2/2011	3457 hrs	3.95E-01	3457	12445200	7.10	1.07E-03	-2.97	2.27E-08	6.39E-01	3130
9/6/2011	3553 hrs	4.06E-01	3553	12790800	7.11	1.07E-03	-2.97	2.27E-08	6.39E-01	3123
9/9/2011	3625 hrs	4.14E-01	3625	13050000	7.12	1.07E-03	-2.97	2.27E-08	6.39E-01	3117
9/12/2011	3697 hrs	4.22E-01	3697	13309200	7.12	1.07E-03	-2.97	2.27E-08	6.39E-01	3112
9/14/2011	3745 hrs	4.28E-01	3745	13482000	7.13	1.07E-03	-2.97	2.27E-08	6.39E-01	3108

Flexural Modulus Calculations - Findley										
Date	Duration					G-F-1				
	Duration	Years	Hrs	Sec	Log Sec	$\varepsilon-\varepsilon_0$	LOG ($\varepsilon-\varepsilon_0$)	m	n	Modulus Calculations
9/19/2011	3865 hrs	4.41E-01	3865.00	13914000	7	1.07E-03	-2.97	2.27E-08	6.39E-01	3099
9/23/2011	3961 hrs	4.52E-01	3961.00	14259600	7.15	1.07E-03	-2.97	2.27E-08	6.39E-01	3092
9/27/2011	4057hrs	4.63E-01	4057.00	14605200	7.16	1.07E-03	-2.97	2.27E-08	6.39E-01	3085
10/4/2011	4225 hrs	4.82E-01	4225.00	15210000	7.18	1.07E-03	-2.97	2.27E-08	6.39E-01	3073
10/10/2011	4369 hrs	4.99E-01	4369.00	15728400	7.20	1.07E-03	-2.97	2.27E-08	6.39E-01	3063
10/17/2011	4537hrs	5.18E-01	4537	16333200	7.21	1.08E-03	-2.97	2.27E-08	6.39E-01	3052
10/21/2011	4633 hrs	5.29E-01	4633	16678800	7.22	1.08E-03	-2.97	2.27E-08	6.39E-01	3045
10/24/2011	4705 hrs	5.37E-01	4705	16938000	7.23	1.08E-03	-2.97	2.27E-08	6.39E-01	3041
10/31/2011	4873 hrs	5.56E-01	4873	17542800	7.24	1.08E-03	-2.97	2.27E-08	6.39E-01	3030
11/7/2011	5041 hrs	5.75E-01	5041	18147600	7.26	1.08E-03	-2.97	2.27E-08	6.39E-01	3019
11/11/2011	5136 hrs	5.86E-01	5136	18489600	7.27	1.08E-03	-2.97	2.27E-08	6.39E-01	3013
11/18/2011	5304 hrs	6.05E-01	5304	19094400	7.28	1.08E-03	-2.97	2.27E-08	6.39E-01	3002
11/22/2011	5400 hrs	6.16E-01	5400	19440000	7.29	1.08E-03	-2.97	2.27E-08	6.39E-01	2997
11/29/2011	5568 hrs	6.36E-01	5568	20044800	7.30	1.08E-03	-2.97	2.27E-08	6.39E-01	2986
12/6/2011	5736 hrs	6.55E-01	5736	20649600	7.31	1.08E-03	-2.97	2.27E-08	6.39E-01	2976
12/16/2011	5976 hrs	6.82E-01	5976	21513600	7.33	1.08E-03	-2.97	2.27E-08	6.39E-01	2962
12/30/2011	6312 hrs	7.21E-01	6312	22723200	7.36	1.08E-03	-2.97	2.27E-08	6.39E-01	2943
2/6/2012	7224 hrs	8.25E-01	7224	26006400	7.42	1.08E-03	-2.97	2.27E-08	6.39E-01	2895
2/13/2012	7392 hrs	8.44E-01	7392	26611200	7.43	1.08E-03	-2.97	2.27E-08	6.39E-01	2886
2/22/2012	7608 hrs	8.68E-01	7608	27388800	7.44	1.09E-03	-2.96	2.27E-08	6.39E-01	2875
2/29/2012	7776 hrs	8.88E-01	7776	27993600	7.45	1.09E-03	-2.96	2.27E-08	6.39E-01	2867
3/8/2012	7968 hrs	9.10E-01	7968	28684800	7.46	1.09E-03	-2.96	2.27E-08	6.39E-01	2858
3/26/2012	8400 hrs	9.59E-01	8400	30240000	7.48	1.09E-03	-2.96	2.27E-08	6.39E-01	2837
4/4/2012	8592 hrs	9.81E-01	8592	30931200	7.49	1.09E-03	-2.96	2.27E-08	6.39E-01	2828
6/3/2012	10008 hrs	1.14E+00	10000	36000000	7.56	1.09E-03	-2.96	2.27E-08	6.39E-01	2767
		5.71E+00	50000	180000000	8.26			2.27E-08	6.39E-01	1943
		1.14E+01	100000	360000000	8.56			2.27E-08	6.39E-01	1545
		5.00E+01	438000	1576800000	9.20			2.27E-08	6.39E-01	813

Flexural Modulus Calculations - Findley										
Date	Duration					G-F-2				
	Duration	Years	Hrs	Sec	Log Sec	$\varepsilon-\varepsilon_0$	LOG ($\varepsilon-\varepsilon_0$)	m	n	Modulus Calculations
4/13/2011	0 min	0.00E+00	0.00	0		0.00E+00				
4/13/2011	1 min	1.90E-06	0.02	60	1.78	1.67E-06	-5.78	2.22E-08	6.40E-01	3620
4/13/2011	6 min	1.14E-05	0.10	360	2.56	1.67E-06	-5.78	2.22E-08	6.40E-01	3619
4/13/2011	12 min	2.28E-05	0.20	720	2.86	1.67E-06	-5.78	2.22E-08	6.40E-01	3619
4/13/2011	30 min	5.71E-05	0.50	1800	3.26	3.33E-06	-5.48	2.22E-08	6.40E-01	3618
4/13/2011	60 min	1.14E-04	1	3600	3.56	5.00E-06	-5.30	2.22E-08	6.40E-01	3617
4/13/2011	5 hrs	5.71E-04	5	18000	4.26	5.00E-06	-5.30	2.22E-08	6.40E-01	3612
4/14/2011	20 hrs	2.28E-03	20	72000	4.86	1.17E-05	-4.93	2.22E-08	6.40E-01	3599
4/23/2011	50 hrs	5.71E-03	50	180000	5.26	1.83E-05	-4.74	2.22E-08	6.40E-01	3583
4/25/2011	100 hrs	1.14E-02	100	360000	5.56	2.33E-05	-4.63	2.22E-08	6.40E-01	3563
4/29/2011	200 hrs	2.28E-02	200	720000	5.86	4.00E-05	-4.40	2.22E-08	6.40E-01	3532
5/4/2011	500 hrs	5.71E-02	500	1800000	6.26	9.33E-05	-4.03	2.22E-08	6.40E-01	3465
5/14/2011	800 hrs	9.13E-02	800	2880000	6.46	2.37E-04	-3.63	2.22E-08	6.40E-01	3413
5/22/2011	1000 hrs	1.14E-01	1000	3600000	6.56	2.77E-04	-3.56	2.22E-08	6.40E-01	3383
5/26/2011	1100 hrs	1.26E-01	1100	3960000	6.60	4.33E-04	-3.36	2.22E-08	6.40E-01	3370
6/17/2011	1600 hrs	1.83E-01	1600	5760000	6.76	5.47E-04	-3.26	2.22E-08	6.40E-01	3307
6/21/2011	1700 hrs	1.94E-01	1700	6120000	6.79	5.47E-04	-3.26	2.22E-08	6.40E-01	3296
6/23/2011	1750 hrs	2.00E-01	1750	6300000	6.80	5.53E-04	-3.26	2.22E-08	6.40E-01	3291
6/28/2011	1870 hrs	2.13E-01	1870	6732000	6.83	5.53E-04	-3.26	2.22E-08	6.40E-01	3278
7/6/2011	2062 hrs	2.35E-01	2062	7423200	6.87	5.53E-04	-3.26	2.22E-08	6.40E-01	3258
7/18/2011	2350 hrs	2.68E-01	2350	8460000	6.93	5.67E-04	-3.25	2.22E-08	6.40E-01	3230
8/2/2011	2710 hrs	3.09E-01	2710	9756000	6.99	5.73E-04	-3.24	2.22E-08	6.40E-01	3197
8/15/2011	3025 hrs	3.45E-01	3025	10890000	7.04	5.80E-04	-3.24	2.22E-08	6.40E-01	3170
8/24/2011	3241 hrs	3.70E-01	3241	11667600	7.07	5.87E-04	-3.23	2.22E-08	6.40E-01	3152
8/31/2011	3409 hrs	3.89E-01	3409	12272400	7.09	5.87E-04	-3.23	2.22E-08	6.40E-01	3139
9/2/2011	3457 hrs	3.95E-01	3457	12445200	7.10	5.87E-04	-3.23	2.22E-08	6.40E-01	3135
9/6/2011	3553 hrs	4.06E-01	3553	12790800	7.11	5.87E-04	-3.23	2.22E-08	6.40E-01	3127
9/9/2011	3625 hrs	4.14E-01	3625	13050000	7.12	5.87E-04	-3.23	2.22E-08	6.40E-01	3122
9/12/2011	3697 hrs	4.22E-01	3697	13309200	7.12	5.93E-04	-3.23	2.22E-08	6.40E-01	3116
9/14/2011	3745 hrs	4.28E-01	3745	13482000	7.13	5.93E-04	-3.23	2.22E-08	6.40E-01	3113

Flexural Modulus Calculations - Findley										
Date	Duration					G-F-2				
	Duration	Years	Hrs	Sec	Log Sec	$\varepsilon-\varepsilon_0$	LOG ($\varepsilon-\varepsilon_0$)	m	n	Modulus Calculations
9/19/2011	3865 hrs	4.41E-01	3865.00	13914000	7	5.93E-04	-3.23	2.22E-08	6.40E-01	3104
9/23/2011	3961 hrs	4.52E-01	3961.00	14259600	7.15	5.93E-04	-3.23	2.22E-08	6.40E-01	3097
9/27/2011	4057hrs	4.63E-01	4057.00	14605200	7.16	6.00E-04	-3.22	2.22E-08	6.40E-01	3090
10/4/2011	4225 hrs	4.82E-01	4225.00	15210000	7.18	6.00E-04	-3.22	2.22E-08	6.40E-01	3078
10/10/2011	4369 hrs	4.99E-01	4369.00	15728400	7.20	6.00E-04	-3.22	2.22E-08	6.40E-01	3068
10/17/2011	4537hrs	5.18E-01	4537	16333200	7.21	6.00E-04	-3.22	2.22E-08	6.40E-01	3057
10/21/2011	4633 hrs	5.29E-01	4633	16678800	7.22	6.00E-04	-3.22	2.22E-08	6.40E-01	3051
10/24/2011	4705 hrs	5.37E-01	4705	16938000	7.23	6.00E-04	-3.22	2.22E-08	6.40E-01	3046
10/31/2011	4873 hrs	5.56E-01	4873	17542800	7.24	6.00E-04	-3.22	2.22E-08	6.40E-01	3035
11/7/2011	5041 hrs	5.75E-01	5041	18147600	7.26	6.00E-04	-3.22	2.22E-08	6.40E-01	3024
11/11/2011	5136 hrs	5.86E-01	5136	18489600	7.27	6.00E-04	-3.22	2.22E-08	6.40E-01	3018
11/18/2011	5304 hrs	6.05E-01	5304	19094400	7.28	6.00E-04	-3.22	2.22E-08	6.40E-01	3008
11/22/2011	5400 hrs	6.16E-01	5400	19440000	7.29	6.00E-04	-3.22	2.22E-08	6.40E-01	3002
11/29/2011	5568 hrs	6.36E-01	5568	20044800	7.30	6.00E-04	-3.22	2.22E-08	6.40E-01	2992
12/6/2011	5736 hrs	6.55E-01	5736	20649600	7.31	6.00E-04	-3.22	2.22E-08	6.40E-01	2982
12/16/2011	5976 hrs	6.82E-01	5976	21513600	7.33	6.00E-04	-3.22	2.22E-08	6.40E-01	2968
12/30/2011	6312 hrs	7.21E-01	6312	22723200	7.36	6.00E-04	-3.22	2.22E-08	6.40E-01	2949
2/6/2012	7224 hrs	8.25E-01	7224	26006400	7.42	6.00E-04	-3.22	2.22E-08	6.40E-01	2900
2/13/2012	7392 hrs	8.44E-01	7392	26611200	7.43	6.00E-04	-3.22	2.22E-08	6.40E-01	2892
2/22/2012	7608 hrs	8.68E-01	7608	27388800	7.44	6.07E-04	-3.22	2.22E-08	6.40E-01	2881
2/29/2012	7776 hrs	8.88E-01	7776	27993600	7.45	6.07E-04	-3.22	2.22E-08	6.40E-01	2873
3/8/2012	7968 hrs	9.10E-01	7968	28684800	7.46	6.07E-04	-3.22	2.22E-08	6.40E-01	2864
3/26/2012	8400 hrs	9.59E-01	8400	30240000	7.48	6.07E-04	-3.22	2.22E-08	6.40E-01	2843
4/4/2012	8592 hrs	9.81E-01	8592	30931200	7.49	6.07E-04	-3.22	2.22E-08	6.40E-01	2834
6/3/2012	10008 hrs	1.14E+00	10000	36000000	7.56	6.07E-04	-3.22	2.22E-08	6.40E-01	2773
		5.71E+00	50000	180000000	8.26			2.22E-08	6.40E-01	1950
		1.14E+01	100000	360000000	8.56			2.22E-08	6.40E-01	1550
		5.00E+01	438000	1576800000	9.20			2.22E-08	6.40E-01	816

Flexural Modulus Calculations - Findley										
Date	Duration					G-F-3				
	Duration	Years	Hrs	Sec	Log Sec	$\varepsilon-\varepsilon_0$	LOG $(\varepsilon-\varepsilon_0)$	m	n	Modulus Calculations
4/13/2011	0 min	0.00E+00	0.00	0		0.00E+00				
4/13/2011	1 min	1.90E-06	0.02	60	1.78	3.33E-06	-5.48	1.76E-07	5.03E-01	3617
4/13/2011	6 min	1.14E-05	0.10	360	2.56	3.33E-06	-5.48	1.76E-07	5.03E-01	3612
4/13/2011	12 min	2.28E-05	0.20	720	2.86	8.33E-06	-5.08	1.76E-07	5.03E-01	3609
4/13/2011	30 min	5.71E-05	0.50	1800	3.26	1.00E-05	-5.00	1.76E-07	5.03E-01	3603
4/13/2011	60 min	1.14E-04	1	3600	3.56	1.17E-05	-4.93	1.76E-07	5.03E-01	3596
4/13/2011	5 hrs	5.71E-04	5	18000	4.26	1.83E-05	-4.74	1.76E-07	5.03E-01	3567
4/14/2011	20 hrs	2.28E-03	20	72000	4.86	2.00E-05	-4.70	1.76E-07	5.03E-01	3514
4/23/2011	50 hrs	5.71E-03	50	180000	5.26	2.17E-05	-4.66	1.76E-07	5.03E-01	3455
4/25/2011	100 hrs	1.14E-02	100	360000	5.56	2.67E-05	-4.57	1.76E-07	5.03E-01	3391
4/29/2011	200 hrs	2.28E-02	200	720000	5.86	5.00E-05	-4.30	1.76E-07	5.03E-01	3303
5/4/2011	500 hrs	5.71E-02	500	1800000	6.26	1.00E-04	-4.00	1.76E-07	5.03E-01	3142
5/14/2011	800 hrs	9.13E-02	800	2880000	6.46	2.47E-04	-3.61	1.76E-07	5.03E-01	3035
5/22/2011	1000 hrs	1.14E-01	1000	3600000	6.56	2.83E-04	-3.55	1.76E-07	5.03E-01	2978
5/26/2011	1100 hrs	1.26E-01	1100	3960000	6.60	4.27E-04	-3.37	1.76E-07	5.03E-01	2952
6/17/2011	1600 hrs	1.83E-01	1600	5760000	6.76	8.33E-04	-3.08	1.76E-07	5.03E-01	2843
6/21/2011	1700 hrs	1.94E-01	1700	6120000	6.79	8.33E-04	-3.08	1.76E-07	5.03E-01	2825
6/23/2011	1750 hrs	2.00E-01	1750	6300000	6.80	8.33E-04	-3.08	1.76E-07	5.03E-01	2816
6/28/2011	1870 hrs	2.13E-01	1870	6732000	6.83	8.33E-04	-3.08	1.76E-07	5.03E-01	2795
7/6/2011	2062 hrs	2.35E-01	2062	7423200	6.87	8.40E-04	-3.08	1.76E-07	5.03E-01	2763
7/18/2011	2350 hrs	2.68E-01	2350	8460000	6.93	8.47E-04	-3.07	1.76E-07	5.03E-01	2719
8/2/2011	2710 hrs	3.09E-01	2710	9756000	6.99	8.60E-04	-3.07	1.76E-07	5.03E-01	2670
8/15/2011	3025 hrs	3.45E-01	3025	10890000	7.04	8.67E-04	-3.06	1.76E-07	5.03E-01	2630
8/24/2011	3241 hrs	3.70E-01	3241	11667600	7.07	8.67E-04	-3.06	1.76E-07	5.03E-01	2605
8/31/2011	3409 hrs	3.89E-01	3409	12272400	7.09	8.67E-04	-3.06	1.76E-07	5.03E-01	2586
9/2/2011	3457 hrs	3.95E-01	3457	12445200	7.10	8.67E-04	-3.06	1.76E-07	5.03E-01	2581
9/6/2011	3553 hrs	4.06E-01	3553	12790800	7.11	8.67E-04	-3.06	1.76E-07	5.03E-01	2571
9/9/2011	3625 hrs	4.14E-01	3625	13050000	7.12	8.67E-04	-3.06	1.76E-07	5.03E-01	2563
9/12/2011	3697 hrs	4.22E-01	3697	13309200	7.12	8.73E-04	-3.06	1.76E-07	5.03E-01	2556
9/14/2011	3745 hrs	4.28E-01	3745	13482000	7.13	8.73E-04	-3.06	1.76E-07	5.03E-01	2551

Flexural Modulus Calculations - Findley										
Date	Duration					G-F-3				
	Duration	Years	Hrs	Sec	Log Sec	$\varepsilon - \varepsilon_0$	LOG ($\varepsilon - \varepsilon_0$)	m	n	Modulus Calculations
9/19/2011	3865 hrs	4.41E-01	3865.00	13914000	7	8.73E-04	-3.06	1.76E-07	5.03E-01	2539
9/23/2011	3961 hrs	4.52E-01	3961.00	14259600	7.15	8.73E-04	-3.06	1.76E-07	5.03E-01	2530
9/27/2011	4057hrs	4.63E-01	4057.00	14605200	7.16	8.73E-04	-3.06	1.76E-07	5.03E-01	2521
10/4/2011	4225 hrs	4.82E-01	4225.00	15210000	7.18	8.73E-04	-3.06	1.76E-07	5.03E-01	2505
10/10/2011	4369 hrs	4.99E-01	4369.00	15728400	7.20	8.80E-04	-3.06	1.76E-07	5.03E-01	2492
10/17/2011	4537hrs	5.18E-01	4537	16333200	7.21	8.80E-04	-3.06	1.76E-07	5.03E-01	2477
10/21/2011	4633 hrs	5.29E-01	4633	16678800	7.22	8.80E-04	-3.06	1.76E-07	5.03E-01	2469
10/24/2011	4705 hrs	5.37E-01	4705	16938000	7.23	8.80E-04	-3.06	1.76E-07	5.03E-01	2463
10/31/2011	4873 hrs	5.56E-01	4873	17542800	7.24	8.80E-04	-3.06	1.76E-07	5.03E-01	2449
11/7/2011	5041 hrs	5.75E-01	5041	18147600	7.26	8.80E-04	-3.06	1.76E-07	5.03E-01	2435
11/11/2011	5136 hrs	5.86E-01	5136	18489600	7.27	8.80E-04	-3.06	1.76E-07	5.03E-01	2428
11/18/2011	5304 hrs	6.05E-01	5304	19094400	7.28	8.80E-04	-3.06	1.76E-07	5.03E-01	2415
11/22/2011	5400 hrs	6.16E-01	5400	19440000	7.29	8.80E-04	-3.06	1.76E-07	5.03E-01	2407
11/29/2011	5568 hrs	6.36E-01	5568	20044800	7.30	8.80E-04	-3.06	1.76E-07	5.03E-01	2395
12/6/2011	5736 hrs	6.55E-01	5736	20649600	7.31	8.80E-04	-3.06	1.76E-07	5.03E-01	2383
12/16/2011	5976 hrs	6.82E-01	5976	21513600	7.33	8.80E-04	-3.06	1.76E-07	5.03E-01	2366
12/30/2011	6312 hrs	7.21E-01	6312	22723200	7.36	8.80E-04	-3.06	1.76E-07	5.03E-01	2343
2/6/2012	7224 hrs	8.25E-01	7224	26006400	7.42	8.87E-04	-3.05	1.76E-07	5.03E-01	2287
2/13/2012	7392 hrs	8.44E-01	7392	26611200	7.43	8.87E-04	-3.05	1.76E-07	5.03E-01	2277
2/22/2012	7608 hrs	8.68E-01	7608	27388800	7.44	8.93E-04	-3.05	1.76E-07	5.03E-01	2265
2/29/2012	7776 hrs	8.88E-01	7776	27993600	7.45	8.93E-04	-3.05	1.76E-07	5.03E-01	2255
3/8/2012	7968 hrs	9.10E-01	7968	28684800	7.46	8.93E-04	-3.05	1.76E-07	5.03E-01	2245
3/26/2012	8400 hrs	9.59E-01	8400	30240000	7.48	8.93E-04	-3.05	1.76E-07	5.03E-01	2222
4/4/2012	8592 hrs	9.81E-01	8592	30931200	7.49	8.93E-04	-3.05	1.76E-07	5.03E-01	2212
6/3/2012	10008 hrs	1.14E+00	10000	36000000	7.56	8.93E-04	-3.05	1.76E-07	5.03E-01	2146
		5.71E+00	50000	180000000	8.26			1.76E-07	5.03E-01	1423
		1.14E+01	100000	360000000	8.56			1.76E-07	5.03E-01	1135
		5.00E+01	438000	1576800000	9.20			1.76E-07	5.03E-01	646

Flexural Modulus Calculations - Findley

Date	Duration					G-F-4				
	Duration	Years	Hrs	Sec	Log Sec	$\varepsilon-\varepsilon_0$	LOG ($\varepsilon-\varepsilon_0$)	m	n	Modulus Calculations
4/13/2011	0 min	0.00E+00	0.00	0		0.00E+00				
4/13/2011	1 min	1.90E-06	0.02	60	1.78	1.67E-06	-5.78	1.18E-07	5.29E-01	3618
4/13/2011	6 min	1.14E-05	0.10	360	2.56	3.33E-06	-5.48	1.18E-07	5.29E-01	3615
4/13/2011	12 min	2.28E-05	0.20	720	2.86	6.67E-06	-5.18	1.18E-07	5.29E-01	3613
4/13/2011	30 min	5.71E-05	0.50	1800	3.26	8.33E-06	-5.08	1.18E-07	5.29E-01	3609
4/13/2011	60 min	1.14E-04	1	3600	3.56	1.00E-05	-5.00	1.18E-07	5.29E-01	3604
4/13/2011	5 hrs	5.71E-04	5	18000	4.26	1.50E-05	-4.82	1.18E-07	5.29E-01	3583
4/14/2011	20 hrs	2.28E-03	20	72000	4.86	2.17E-05	-4.66	1.18E-07	5.29E-01	3543
4/23/2011	50 hrs	5.71E-03	50	180000	5.26	2.33E-05	-4.63	1.18E-07	5.29E-01	3496
4/25/2011	100 hrs	1.14E-02	100	360000	5.56	2.67E-05	-4.57	1.18E-07	5.29E-01	3444
4/29/2011	200 hrs	2.28E-02	200	720000	5.86	4.67E-05	-4.33	1.18E-07	5.29E-01	3372
5/4/2011	500 hrs	5.71E-02	500	1800000	6.26	1.07E-04	-3.97	1.18E-07	5.29E-01	3234
5/14/2011	800 hrs	9.13E-02	800	2880000	6.46	2.27E-04	-3.64	1.18E-07	5.29E-01	3139
5/22/2011	1000 hrs	1.14E-01	1000	3600000	6.56	2.80E-04	-3.55	1.18E-07	5.29E-01	3088
5/26/2011	1100 hrs	1.26E-01	1100	3960000	6.60	4.07E-04	-3.39	1.18E-07	5.29E-01	3065
6/17/2011	1600 hrs	1.83E-01	1600	5760000	6.76	8.67E-04	-3.06	1.18E-07	5.29E-01	2965
6/21/2011	1700 hrs	1.94E-01	1700	6120000	6.79	8.67E-04	-3.06	1.18E-07	5.29E-01	2947
6/23/2011	1750 hrs	2.00E-01	1750	6300000	6.80	8.67E-04	-3.06	1.18E-07	5.29E-01	2939
6/28/2011	1870 hrs	2.13E-01	1870	6732000	6.83	8.67E-04	-3.06	1.18E-07	5.29E-01	2919
7/6/2011	2062 hrs	2.35E-01	2062	7423200	6.87	8.67E-04	-3.06	1.18E-07	5.29E-01	2890
7/18/2011	2350 hrs	2.68E-01	2350	8460000	6.93	8.73E-04	-3.06	1.18E-07	5.29E-01	2849
8/2/2011	2710 hrs	3.09E-01	2710	9756000	6.99	8.80E-04	-3.06	1.18E-07	5.29E-01	2802
8/15/2011	3025 hrs	3.45E-01	3025	10890000	7.04	8.87E-04	-3.05	1.18E-07	5.29E-01	2764
8/24/2011	3241 hrs	3.70E-01	3241	11667600	7.07	8.93E-04	-3.05	1.18E-07	5.29E-01	2740
8/31/2011	3409 hrs	3.89E-01	3409	12272400	7.09	8.93E-04	-3.05	1.18E-07	5.29E-01	2722
9/2/2011	3457 hrs	3.95E-01	3457	12445200	7.10	8.93E-04	-3.05	1.18E-07	5.29E-01	2717
9/6/2011	3553 hrs	4.06E-01	3553	12790800	7.11	8.93E-04	-3.05	1.18E-07	5.29E-01	2708
9/9/2011	3625 hrs	4.14E-01	3625	13050000	7.12	8.93E-04	-3.05	1.18E-07	5.29E-01	2700
9/12/2011	3697 hrs	4.22E-01	3697	13309200	7.12	8.93E-04	-3.05	1.18E-07	5.29E-01	2693
9/14/2011	3745 hrs	4.28E-01	3745	13482000	7.13	8.93E-04	-3.05	1.18E-07	5.29E-01	2688

Flexural Modulus Calculations - Findley										
Date	Duration					G-F-4				
	Duration	Years	Hrs	Sec	Log Sec	$\varepsilon-\varepsilon_0$	LOG ($\varepsilon-\varepsilon_0$)	m	n	Modulus Calculations
9/19/2011	3865 hrs	4.41E-01	3865.00	13914000	7	8.93E-04	-3.05	1.18E-07	5.29E-01	2677
9/23/2011	3961 hrs	4.52E-01	3961.00	14259600	7.15	8.93E-04	-3.05	1.18E-07	5.29E-01	2668
9/27/2011	4057hrs	4.63E-01	4057.00	14605200	7.16	8.93E-04	-3.05	1.18E-07	5.29E-01	2659
10/4/2011	4225 hrs	4.82E-01	4225.00	15210000	7.18	8.93E-04	-3.05	1.18E-07	5.29E-01	2644
10/10/2011	4369 hrs	4.99E-01	4369.00	15728400	7.20	9.00E-04	-3.05	1.18E-07	5.29E-01	2631
10/17/2011	4537hrs	5.18E-01	4537	16333200	7.21	9.00E-04	-3.05	1.18E-07	5.29E-01	2617
10/21/2011	4633 hrs	5.29E-01	4633	16678800	7.22	9.00E-04	-3.05	1.18E-07	5.29E-01	2609
10/24/2011	4705 hrs	5.37E-01	4705	16938000	7.23	9.00E-04	-3.05	1.18E-07	5.29E-01	2603
10/31/2011	4873 hrs	5.56E-01	4873	17542800	7.24	9.00E-04	-3.05	1.18E-07	5.29E-01	2589
11/7/2011	5041 hrs	5.75E-01	5041	18147600	7.26	9.00E-04	-3.05	1.18E-07	5.29E-01	2576
11/11/2011	5136 hrs	5.86E-01	5136	18489600	7.27	9.00E-04	-3.05	1.18E-07	5.29E-01	2568
11/18/2011	5304 hrs	6.05E-01	5304	19094400	7.28	9.00E-04	-3.05	1.18E-07	5.29E-01	2556
11/22/2011	5400 hrs	6.16E-01	5400	19440000	7.29	9.00E-04	-3.05	1.18E-07	5.29E-01	2548
11/29/2011	5568 hrs	6.36E-01	5568	20044800	7.30	9.00E-04	-3.05	1.18E-07	5.29E-01	2536
12/6/2011	5736 hrs	6.55E-01	5736	20649600	7.31	9.00E-04	-3.05	1.18E-07	5.29E-01	2524
12/16/2011	5976 hrs	6.82E-01	5976	21513600	7.33	9.00E-04	-3.05	1.18E-07	5.29E-01	2508
12/30/2011	6312 hrs	7.21E-01	6312	22723200	7.36	9.00E-04	-3.05	1.18E-07	5.29E-01	2485
2/6/2012	7224 hrs	8.25E-01	7224	26006400	7.42	9.00E-04	-3.05	1.18E-07	5.29E-01	2429
2/13/2012	7392 hrs	8.44E-01	7392	26611200	7.43	9.00E-04	-3.05	1.18E-07	5.29E-01	2419
2/22/2012	7608 hrs	8.68E-01	7608	27388800	7.44	9.00E-04	-3.05	1.18E-07	5.29E-01	2407
2/29/2012	7776 hrs	8.88E-01	7776	27993600	7.45	9.00E-04	-3.05	1.18E-07	5.29E-01	2397
3/8/2012	7968 hrs	9.10E-01	7968	28684800	7.46	9.00E-04	-3.05	1.18E-07	5.29E-01	2387
3/26/2012	8400 hrs	9.59E-01	8400	30240000	7.48	9.00E-04	-3.05	1.18E-07	5.29E-01	2364
4/4/2012	8592 hrs	9.81E-01	8592	30931200	7.49	9.00E-04	-3.05	1.18E-07	5.29E-01	2354
6/3/2012	10008 hrs	1.14E+00	10000	36000000	7.56	9.00E-04	-3.05	1.18E-07	5.29E-01	2288
		5.71E+00	50000	180000000	8.26			1.18E-07	5.29E-01	1531
		1.14E+01	100000	360000000	8.56			1.18E-07	5.29E-01	1219
		5.00E+01	438000	1576800000	9.20			1.18E-07	5.29E-01	683

APPENDIX B

TENSILE CREEP DATA

Tensile Strain							
Duration	Hours	G-T-1	G-T-2	G-T-3	G-T-4	G-T-5	G-T-6
0 min	0.00	0.000547	-0.001009	-0.000444	0.000234	-0.000951	0.000089
1 min	0.02	0.000002	0.000003	0.000003	0.000005	0.000005	0.000002
6 min	0.10	0.000008	0.000012	0.000004	0.000007	0.000014	0.000016
12 min	0.20	0.000028	0.000038	0.000033	0.000037	0.000042	0.000022
30 min	0.50	0.000074	0.000147	0.000042	0.000087	0.000079	0.000038
60 min	1	0.000175	0.000198	0.000119	0.000160	0.000154	0.000062
5 hrs	5	0.000218	0.000218	0.000143	0.000186	0.000191	0.000098
20 hrs	20	0.000245	0.000287	0.000174	0.000275	0.000220	0.000119
50 hrs	50	0.000254	0.000306	0.000234	0.000423	0.000247	0.000152
100 hrs	100	0.000325	0.000334	0.000259	0.000541	0.000259	0.000208
200 hrs	200	0.000393	0.000379	0.000249	0.000578	0.000339	0.000231
300 hrs	300	0.000451	0.000397	0.000292	0.000605	0.000346	0.000229
600 hrs	600	0.000466	0.000390	0.000328	0.000607	0.000397	0.000436
800 hrs	800	0.000701	0.000655	0.000549	0.000634	0.000466	0.000622
900 hrs	900	0.000751	0.000708	0.000573	0.000648	0.000543	0.000698
1400 hrs	1400	0.000880	0.000781	0.000672	0.000656	0.000692	0.000791
1500 hrs	1500	0.000894	0.000844	0.000672	0.000558	0.000699	0.000806
1550 hrs	1550	0.000876	0.000823	0.000667	0.000412	0.000707	0.000782
1670 hrs	1670	0.000947	0.000874	0.000724	0.000690	0.000743	0.000887
1862 hrs	1862	0.001057	0.000855	0.000788	0.000783	0.000813	0.000936
2150 hrs	2150	0.001108	0.001039	0.000727	0.000809	0.000876	0.000989
2510 hrs	2510	0.001081	0.000991	0.000727	0.000752	0.000813	0.000952
2825 hrs	2825	0.001123	0.001009	0.000817	0.000783	0.000804	0.000990
3041 hrs	3041	0.001171	0.001007	0.000822	0.000801	0.000892	0.001031
3209 hrs	3209	0.001148	0.001055	0.000805	0.000793	0.000860	0.000997
3257 hrs	3257	0.001124	0.001064	0.000802	0.000807	0.000799	0.000997
3353 hrs	3353	0.001278	0.001184	0.000944	0.000944	0.001041	0.000958
3425 hrs	3425	0.001031	0.000938	0.000676	0.000696	0.000769	0.000917

Tensile Strain							
Duration	Hours	G-T-1	G-T-2	G-T-3	G-T-4	G-T-5	G-T-6
3497 hrs	3497	0.001054	0.000970	0.000692	0.000720	0.000792	0.000921
3545 hrs	3545	0.001022	0.000958	0.000677	0.000696	0.000758	0.000939
3665 hrs	3665	0.001035	0.000969	0.000722	0.000762	0.000831	0.000955
3761 hrs	3761	0.001005	0.000942	0.000653	0.000674	0.000720	0.000875
3857 hrs	3857	0.001099	0.000946	0.000708	0.000763	0.000827	0.000964
4025 hrs	4025	0.001027	0.000913	0.000664	0.000693	0.000746	0.000895
4169 hrs	4169	0.001159	0.000849	0.000588	0.000621	0.000595	0.000812
4337 hrs	4337	0.001062	0.000991	0.000727	0.000729	0.000808	0.000932
4433 hrs	4433	0.000969	0.000960	0.000655	0.000702	0.000776	0.000916
4505 hrs	4505	0.000966	0.000902	0.000557	0.000673	0.000741	0.000868
4673 hrs	4673	0.000948	0.000863	0.000564	0.000621	0.000688	0.000815
4841 hrs	4841	0.001004	0.000919	0.000528	0.000678	0.000750	0.000858
4937 hrs	4937	0.000819	0.000784	0.000493	0.000442	0.000554	0.000690
5105 hrs	5105	0.000777	0.000674	0.000473	0.000422	0.000530	0.000671
5201 hrs	5206	0.000949	0.000733	0.000579	0.000481	0.000709	0.000811
5369 hrs	5369	0.000812	0.000723	0.000506	0.000477	0.000551	0.000679
5513 hrs	5513	0.000920	0.000693	0.000551	0.000315	0.000655	0.000779
5777 hrs	5777	0.000927	0.000684	0.000556	0.000457	0.000659	0.000765
6113 hrs	6113	0.000903	0.000803	0.000563	0.000488	0.000638	0.000751
7025 hrs	7025	0.000843	0.000758	0.000472	0.000529	0.000561	0.000682
7073 hrs	7073	0.000817	0.000732	0.000469	0.000502	0.000562	0.000671
7121 hrs	7121	0.000815	0.000732	0.000470	0.000520	0.000575	0.000695
7193 hrs	7193	0.000689	0.000603	0.000376	0.000351	0.000445	0.000545
7241 hrs	7241	0.000838	0.000742	0.000451	0.000610	0.000562	0.000706
7409 hrs	7409	0.000905	0.000836	0.000588	0.000549	0.000706	0.000779
7577 hrs	7577	0.000965	0.000836	0.000627	0.000633	0.000567	0.000926
7769 hrs	7769	0.000939	0.000953	0.000609	0.000608	0.000640	0.000853
8081 hrs	8081	0.001147	0.001071	0.000868	0.000853	0.000932	0.001035
10008 hrs	10008	0.001133	0.001077	0.000847	0.000839	0.000866	0.001034

Tensile Modulus Calculations										
Date	Duration					G-T-1				
	Duration	Years	Hrs	Sec	Log Sec	$\varepsilon-\varepsilon_0$	LOG ($\varepsilon-\varepsilon_0$)	m	n	Modulus Calculations
4/20/2011	0 min	0.00E+00	0.00	0		5.47E-04				
4/20/2011	1 min	1.90E-06	0.02	60	1.78	2.00E-06	-5.70	1.67E-05	2.45E-01	1310
4/20/2011	6 min	1.14E-05	0.10	360	2.56	8.00E-06	-5.10	1.67E-05	2.45E-01	1290
4/20/2011	12 min	2.28E-05	0.20	720	2.86	2.80E-05	-4.55	1.67E-05	2.45E-01	1279
4/20/2011	30 min	5.71E-05	0.50	1800	3.26	7.40E-05	-4.13	1.67E-05	2.45E-01	1263
4/20/2011	60 min	1.14E-04	1	3600	3.56	1.75E-04	-3.76	1.67E-05	2.45E-01	1248
4/20/2011	5 hrs	5.71E-04	5	18000	4.26	2.18E-04	-3.66	1.67E-05	2.45E-01	1204
4/21/2011	20 hrs	2.28E-03	20	72000	4.86	2.45E-04	-3.61	1.67E-05	2.45E-01	1154
4/23/2011	50 hrs	5.71E-03	50	180000	5.26	2.54E-04	-3.60	1.67E-05	2.45E-01	1113
4/25/2011	100 hrs	1.14E-02	100	360000	5.56	3.25E-04	-3.49	1.67E-05	2.45E-01	1078
4/29/2011	200 hrs	2.28E-02	200	720000	5.86	3.93E-04	-3.41	1.67E-05	2.45E-01	1040
5/2/2011	300 hrs	3.42E-02	300	1080000	6.03	4.51E-04	-3.35	1.67E-05	2.45E-01	1015
5/14/2011	600 hrs	6.85E-02	600	2160000	6.33	4.66E-04	-3.33	1.67E-05	2.45E-01	971
5/22/2011	800 hrs	9.13E-02	800	2880000	6.46	7.01E-04	-3.15	1.67E-05	2.45E-01	951
5/26/2011	900 hrs	1.03E-01	900	3240000	6.51	7.51E-04	-3.12	1.67E-05	2.45E-01	943
6/17/2011	1400 hrs	1.60E-01	1400	5040000	6.70	8.80E-04	-3.06	1.67E-05	2.45E-01	912
6/21/2011	1500 hrs	1.71E-01	1500	5400000	6.73	8.94E-04	-3.05	1.67E-05	2.45E-01	907
6/23/2011	1550 hrs	1.77E-01	1550	5580000	6.75	8.76E-04	-3.06	1.67E-05	2.45E-01	904
6/28/2011	1670 hrs	1.91E-01	1670	6012000	6.78	9.47E-04	-3.02	1.67E-05	2.45E-01	899
7/6/2011	1862 hrs	2.13E-01	1862	6703200	6.83	1.06E-03	-2.98	1.67E-05	2.45E-01	891
7/18/2011	2150 hrs	2.45E-01	2150	7740000	6.89	1.11E-03	-2.96	1.67E-05	2.45E-01	880
8/2/2011	2510 hrs	2.87E-01	2510	9036000	6.96	1.08E-03	-2.97	1.67E-05	2.45E-01	868
8/15/2011	2825 hrs	3.22E-01	2825	10170000	7.01	1.12E-03	-2.95	1.67E-05	2.45E-01	859
8/24/2011	3041 hrs	3.47E-01	3041	10947600	7.04	1.17E-03	-2.93	1.67E-05	2.45E-01	854
8/31/2011	3209 hrs	3.66E-01	3209	11552400	7.06	1.15E-03	-2.94	1.67E-05	2.45E-01	850
9/2/2011	3257 hrs	3.72E-01	3257	11725200	7.07	1.12E-03	-2.95	1.67E-05	2.45E-01	848
9/6/2011	3353 hrs	3.83E-01	3353	12070800	7.08	1.28E-03	-2.89	1.67E-05	2.45E-01	846
9/9/2011	3425 hrs	3.91E-01	3425	12330000	7.09	1.03E-03	-2.99	1.67E-05	2.45E-01	845
9/12/2011	3497 hrs	3.99E-01	3497	12589200	7.10	1.05E-03	-2.98	1.67E-05	2.45E-01	843
9/14/2011	3545 hrs	4.05E-01	3545	12762000	7.11	1.02E-03	-2.99	1.67E-05	2.45E-01	842

Tensile Modulus Calculations										
Date	Duration					G-T-1				
	Duration	Years	Hrs	Sec	Log Sec	ε-ε0	LOG (ε-ε0)	m	n	Modulus Calculations
9/19/2011	3665 hrs	4.18E-01	3665.00	13194000	7	1.04E-03	-2.99	1.67E-05	2.45E-01	839
9/23/2011	3761 hrs	4.29E-01	3761.00	13539600	7.13	1.01E-03	-3.00	1.67E-05	2.45E-01	837
9/27/2011	3857 hrs	4.40E-01	3857.00	13885200	7.14	1.10E-03	-2.96	1.67E-05	2.45E-01	835
10/4/2011	4025 hrs	4.59E-01	4025.00	14490000	7.16	1.03E-03	-2.99	1.67E-05	2.45E-01	832
10/10/2011	4169 hrs	4.76E-01	4169.00	15008400	7.18	1.16E-03	-2.94	1.67E-05	2.45E-01	829
10/17/2011	4337 hrs	4.95E-01	4337	15613200	7.19	1.06E-03	-2.97	1.67E-05	2.45E-01	826
10/21/2011	4433 hrs	5.06E-01	4433	15958800	7.20	9.69E-04	-3.01	1.67E-05	2.45E-01	824
10/24/2011	4505 hrs	5.14E-01	4505	16218000	7.21	9.66E-04	-3.02	1.67E-05	2.45E-01	823
10/31/2011	4673 hrs	5.33E-01	4673	16822800	7.23	9.48E-04	-3.02	1.67E-05	2.45E-01	820
11/7/2011	4841 hrs	5.53E-01	4841	17427600	7.24	1.00E-03	-3.00	1.67E-05	2.45E-01	818
11/11/2011	4937 hrs	5.64E-01	4937	17773200	7.25	8.19E-04	-3.09	1.67E-05	2.45E-01	816
11/18/2011	5105 hrs	5.83E-01	5105	18378000	7.26	7.77E-04	-3.11	1.67E-05	2.45E-01	813
11/22/2011	5201 hrs	5.94E-01	5206	18741600	7.27	9.49E-04	-3.02	1.67E-05	2.45E-01	812
11/29/2011	5369 hrs	6.13E-01	5369	19328400	7.29	8.12E-04	-3.09	1.67E-05	2.45E-01	809
12/5/2011	5513 hrs	6.29E-01	5513	19846800	7.30	9.20E-04	-3.04	1.67E-05	2.45E-01	807
12/16/2011	5777 hrs	6.59E-01	5777	20797200	7.32	9.27E-04	-3.03	1.67E-05	2.45E-01	803
12/30/2011	6113 hrs	6.98E-01	6113	22006800	7.34	9.03E-04	-3.04	1.67E-05	2.45E-01	799
2/6/2012	7025 hrs	8.02E-01	7025	25290000	7.40	8.43E-04	-3.07	1.67E-05	2.45E-01	788
2/8/2012	7073 hrs	8.07E-01	7073	25462800	7.41	1.00E+00	0.00	1.67E-05	2.45E-01	787
2/10/2012	7121 hrs	8.13E-01	7121	25635600	7.41	2.00E+00	0.30	1.67E-05	2.45E-01	787
2/13/2012	7193 hrs	8.21E-01	7193	25894800	7.41	3.00E+00	0.48	1.67E-05	2.45E-01	786
2/15/2012	7241 hrs	8.27E-01	7241	26067600	7.42	4.00E+00	0.60	1.67E-05	2.45E-01	785
2/22/2012	7409 hrs	8.46E-01	7409	26672400	7.43	5.00E+00	0.70	1.67E-05	2.45E-01	784
2/29/2012	7577 hrs	8.65E-01	7577	27277200	7.44	6.00E+00	0.78	1.67E-05	2.45E-01	782
3/8/2012	7769 hrs	8.87E-01	7769	27968400	7.45	7.00E+00	0.85	1.67E-05	2.45E-01	780
3/21/2012	8081 hrs	9.22E-01	8081	29091600	7.46	8.00E+00	0.90	1.67E-05	2.45E-01	777
6/10/2012	10008 hrs	1.14E+00	10008	36028800	7.56	9.00E+00	0.95	1.67E-05	2.45E-01	759
		5.71E+00	50000					1.67E-05	2.45E-01	627
		1.14E+01	100000					1.67E-05	2.45E-01	570
		5.00E+01	438000					1.67E-05	2.45E-01	455

Tensile Modulus Calculations										
Date	Duration					G-T-2				
	Duration	Years	Hrs	Sec	Log Sec	$\varepsilon-\varepsilon_0$	LOG $(\varepsilon-\varepsilon_0)$	m	n	Modulus Calculations
4/20/2011	0 min	0.00E+00	0.00	0		-1.01E-03				
4/20/2011	1 min	1.90E-06	0.02	60	1.78	3.00E-06	-5.52	2.30E-05	2.20E-01	1290
4/20/2011	6 min	1.14E-05	0.10	360	2.56	1.20E-05	-4.92	2.30E-05	2.20E-01	1264
4/20/2011	12 min	2.28E-05	0.20	720	2.86	3.80E-05	-4.42	2.30E-05	2.20E-01	1251
4/20/2011	30 min	5.71E-05	0.50	1800	3.26	1.47E-04	-3.83	2.30E-05	2.20E-01	1231
4/20/2011	60 min	1.14E-04	1	3600	3.56	1.98E-04	-3.70	2.30E-05	2.20E-01	1214
4/20/2011	5 hrs	5.71E-04	5	18000	4.26	2.18E-04	-3.66	2.30E-05	2.20E-01	1164
4/21/2011	20 hrs	2.28E-03	20	72000	4.86	2.87E-04	-3.54	2.30E-05	2.20E-01	1110
4/23/2011	50 hrs	5.71E-03	50	180000	5.26	3.06E-04	-3.51	2.30E-05	2.20E-01	1068
4/25/2011	100 hrs	1.14E-02	100	360000	5.56	3.34E-04	-3.48	2.30E-05	2.20E-01	1032
4/29/2011	200 hrs	2.28E-02	200	720000	5.86	3.79E-04	-3.42	2.30E-05	2.20E-01	994
5/2/2011	300 hrs	3.42E-02	300	1080000	6.03	3.97E-04	-3.40	2.30E-05	2.20E-01	970
5/14/2011	600 hrs	6.85E-02	600	2160000	6.33	3.90E-04	-3.41	2.30E-05	2.20E-01	927
5/22/2011	800 hrs	9.13E-02	800	2880000	6.46	6.55E-04	-3.18	2.30E-05	2.20E-01	908
5/26/2011	900 hrs	1.03E-01	900	3240000	6.51	7.08E-04	-3.15	2.30E-05	2.20E-01	901
6/17/2011	1400 hrs	1.60E-01	1400	5040000	6.70	7.81E-04	-3.11	2.30E-05	2.20E-01	871
6/21/2011	1500 hrs	1.71E-01	1500	5400000	6.73	8.44E-04	-3.07	2.30E-05	2.20E-01	867
6/23/2011	1550 hrs	1.77E-01	1550	5580000	6.75	8.23E-04	-3.08	2.30E-05	2.20E-01	864
6/28/2011	1670 hrs	1.91E-01	1670	6012000	6.78	8.74E-04	-3.06	2.30E-05	2.20E-01	859
7/6/2011	1862 hrs	2.13E-01	1862	6703200	6.83	8.55E-04	-3.07	2.30E-05	2.20E-01	852
7/18/2011	2150 hrs	2.45E-01	2150	7740000	6.89	1.04E-03	-2.98	2.30E-05	2.20E-01	842
8/2/2011	2510 hrs	2.87E-01	2510	9036000	6.96	9.91E-04	-3.00	2.30E-05	2.20E-01	831
8/15/2011	2825 hrs	3.22E-01	2825	10170000	7.01	1.01E-03	-3.00	2.30E-05	2.20E-01	823
8/24/2011	3041 hrs	3.47E-01	3041	10947600	7.04	1.01E-03	-3.00	2.30E-05	2.20E-01	817
8/31/2011	3209 hrs	3.66E-01	3209	11552400	7.06	1.06E-03	-2.98	2.30E-05	2.20E-01	814
9/2/2011	3257 hrs	3.72E-01	3257	11725200	7.07	1.06E-03	-2.97	2.30E-05	2.20E-01	813
9/6/2011	3353 hrs	3.83E-01	3353	12070800	7.08	1.18E-03	-2.93	2.30E-05	2.20E-01	810
9/9/2011	3425 hrs	3.91E-01	3425	12330000	7.09	9.38E-04	-3.03	2.30E-05	2.20E-01	809
9/12/2011	3497 hrs	3.99E-01	3497	12589200	7.10	9.70E-04	-3.01	2.30E-05	2.20E-01	807
9/14/2011	3545 hrs	4.05E-01	3545	12762000	7.11	9.58E-04	-3.02	2.30E-05	2.20E-01	807

Tensile Modulus Calculations										
Date	Duration					G-T-2				
	Duration	Years	Hrs	Sec	Log Sec	$\varepsilon-\varepsilon_0$	LOG ($\varepsilon-\varepsilon_0$)	m	n	Modulus Calculations
9/19/2011	3665 hrs	4.18E-01	3665.00	13194000	7	9.69E-04	-3.01	2.30E-05	2.20E-01	804
9/23/2011	3761 hrs	4.29E-01	3761.00	13539600	7.13	9.42E-04	-3.03	2.30E-05	2.20E-01	802
9/27/2011	3857 hrs	4.40E-01	3857.00	13885200	7.14	9.46E-04	-3.02	2.30E-05	2.20E-01	800
10/4/2011	4025 hrs	4.59E-01	4025.00	14490000	7.16	9.13E-04	-3.04	2.30E-05	2.20E-01	797
10/10/2011	4169 hrs	4.76E-01	4169.00	15008400	7.18	8.49E-04	-3.07	2.30E-05	2.20E-01	795
10/17/2011	4337 hrs	4.95E-01	4337	15613200	7.19	9.91E-04	-3.00	2.30E-05	2.20E-01	792
10/21/2011	4433 hrs	5.06E-01	4433	15958800	7.20	9.60E-04	-3.02	2.30E-05	2.20E-01	791
10/24/2011	4505 hrs	5.14E-01	4505	16218000	7.21	9.02E-04	-3.04	2.30E-05	2.20E-01	789
10/31/2011	4673 hrs	5.33E-01	4673	16822800	7.23	8.63E-04	-3.06	2.30E-05	2.20E-01	787
11/7/2011	4841 hrs	5.53E-01	4841	17427600	7.24	9.19E-04	-3.04	2.30E-05	2.20E-01	784
11/11/2011	4937 hrs	5.64E-01	4937	17773200	7.25	7.84E-04	-3.11	2.30E-05	2.20E-01	783
11/18/2011	5105 hrs	5.83E-01	5105	18378000	7.26	6.74E-04	-3.17	2.30E-05	2.20E-01	780
11/22/2011	5201 hrs	5.94E-01	5206	18741600	7.27	7.33E-04	-3.13	2.30E-05	2.20E-01	779
11/29/2011	5369 hrs	6.13E-01	5369	19328400	7.29	7.23E-04	-3.14	2.30E-05	2.20E-01	777
12/5/2011	5513 hrs	6.29E-01	5513	19846800	7.30	6.93E-04	-3.16	2.30E-05	2.20E-01	775
12/16/2011	5777 hrs	6.59E-01	5777	20797200	7.32	6.84E-04	-3.16	2.30E-05	2.20E-01	771
12/30/2011	6113 hrs	6.98E-01	6113	22006800	7.34	8.03E-04	-3.10	2.30E-05	2.20E-01	767
2/6/2012	7025 hrs	8.02E-01	7025	25290000	7.40	7.58E-04	-3.12	2.30E-05	2.20E-01	757
2/8/2012	7073 hrs	8.07E-01	7073	25462800	7.41	1.00E+00	0.00	2.30E-05	2.20E-01	757
2/10/2012	7121 hrs	8.13E-01	7121	25635600	7.41	2.00E+00	0.30	2.30E-05	2.20E-01	756
2/13/2012	7193 hrs	8.21E-01	7193	25894800	7.41	3.00E+00	0.48	2.30E-05	2.20E-01	755
2/15/2012	7241 hrs	8.27E-01	7241	26067600	7.42	4.00E+00	0.60	2.30E-05	2.20E-01	755
2/22/2012	7409 hrs	8.46E-01	7409	26672400	7.43	5.00E+00	0.70	2.30E-05	2.20E-01	753
2/29/2012	7577 hrs	8.65E-01	7577	27277200	7.44	6.00E+00	0.78	2.30E-05	2.20E-01	752
3/8/2012	7769 hrs	8.87E-01	7769	27968400	7.45	7.00E+00	0.85	2.30E-05	2.20E-01	750
3/21/2012	8081 hrs	9.22E-01	8081	29091600	7.46	8.00E+00	0.90	2.30E-05	2.20E-01	747
6/10/2012	10008 hrs	1.14E+00	10008	36028800	7.56	9.00E+00	0.95	2.30E-05	2.20E-01	731
		5.71E+00	50000					2.30E-05	2.20E-01	612
		1.14E+01	100000					2.30E-05	2.20E-01	562
		5.00E+01	438000					2.30E-05	2.20E-01	459

Tensile Modulus Calculations

Date	Duration					G-T-3				
	Duration	Years	Hrs	Sec	Log Sec	ε-ε_0	LOG (ε-ε_0)	m	n	Modulus Calculations
4/20/2011	0 min	0.00E+00	0.00	0		-4.44E-04				
4/20/2011	1 min	1.90E-06	0.02	60	1.78	3.00E-06	-5.52	2.55E-05	1.94E-01	1278
4/20/2011	6 min	1.14E-05	0.10	360	2.56	4.00E-06	-5.40	2.55E-05	1.94E-01	1250
4/20/2011	12 min	2.28E-05	0.20	720	2.86	3.30E-05	-4.48	2.55E-05	1.94E-01	1237
4/20/2011	30 min	5.71E-05	0.50	1800	3.26	4.20E-05	-4.38	2.55E-05	1.94E-01	1217
4/20/2011	60 min	1.14E-04	1	3600	3.56	1.19E-04	-3.92	2.55E-05	1.94E-01	1200
4/20/2011	5 hrs	5.71E-04	5	18000	4.26	1.43E-04	-3.84	2.55E-05	1.94E-01	1154
4/21/2011	20 hrs	2.28E-03	20	72000	4.86	1.74E-04	-3.76	2.55E-05	1.94E-01	1104
4/23/2011	50 hrs	5.71E-03	50	180000	5.26	2.34E-04	-3.63	2.55E-05	1.94E-01	1066
4/25/2011	100 hrs	1.14E-02	100	360000	5.56	2.59E-04	-3.59	2.55E-05	1.94E-01	1035
4/29/2011	200 hrs	2.28E-02	200	720000	5.86	2.49E-04	-3.60	2.55E-05	1.94E-01	1002
5/2/2011	300 hrs	3.42E-02	300	1080000	6.03	2.92E-04	-3.53	2.55E-05	1.94E-01	981
5/14/2011	600 hrs	6.85E-02	600	2160000	6.33	3.28E-04	-3.48	2.55E-05	1.94E-01	944
5/22/2011	800 hrs	9.13E-02	800	2880000	6.46	5.49E-04	-3.26	2.55E-05	1.94E-01	928
5/26/2011	900 hrs	1.03E-01	900	3240000	6.51	5.73E-04	-3.24	2.55E-05	1.94E-01	921
6/17/2011	1400 hrs	1.60E-01	1400	5040000	6.70	6.72E-04	-3.17	2.55E-05	1.94E-01	896
6/21/2011	1500 hrs	1.71E-01	1500	5400000	6.73	6.72E-04	-3.17	2.55E-05	1.94E-01	891
6/23/2011	1550 hrs	1.77E-01	1550	5580000	6.75	6.67E-04	-3.18	2.55E-05	1.94E-01	890
6/28/2011	1670 hrs	1.91E-01	1670	6012000	6.78	7.24E-04	-3.14	2.55E-05	1.94E-01	885
7/6/2011	1862 hrs	2.13E-01	1862	6703200	6.83	7.88E-04	-3.10	2.55E-05	1.94E-01	879
7/18/2011	2150 hrs	2.45E-01	2150	7740000	6.89	7.27E-04	-3.14	2.55E-05	1.94E-01	870
8/2/2011	2510 hrs	2.87E-01	2510	9036000	6.96	7.27E-04	-3.14	2.55E-05	1.94E-01	861
8/15/2011	2825 hrs	3.22E-01	2825	10170000	7.01	8.17E-04	-3.09	2.55E-05	1.94E-01	854
8/24/2011	3041 hrs	3.47E-01	3041	10947600	7.04	8.22E-04	-3.09	2.55E-05	1.94E-01	849
8/31/2011	3209 hrs	3.66E-01	3209	11552400	7.06	8.05E-04	-3.09	2.55E-05	1.94E-01	846
9/2/2011	3257 hrs	3.72E-01	3257	11725200	7.07	8.02E-04	-3.10	2.55E-05	1.94E-01	845
9/6/2011	3353 hrs	3.83E-01	3353	12070800	7.08	9.44E-04	-3.03	2.55E-05	1.94E-01	843
9/9/2011	3425 hrs	3.91E-01	3425	12330000	7.09	6.76E-04	-3.17	2.55E-05	1.94E-01	842
9/12/2011	3497 hrs	3.99E-01	3497	12589200	7.10	6.92E-04	-3.16	2.55E-05	1.94E-01	840
9/14/2011	3545 hrs	4.05E-01	3545	12762000	7.11	6.77E-04	-3.17	2.55E-05	1.94E-01	840

Tensile Modulus Calculations										
Date	Duration					G-T-3				
	Duration	Years	Hrs	Sec	Log Sec	ε-ε0	LOG (ε-ε0)	m	n	Modulus Calculations
9/19/2011	3665 hrs	4.18E-01	3665.00	13194000	7	7.22E-04	-3.14	2.55E-05	1.94E-01	838
9/23/2011	3761 hrs	4.29E-01	3761.00	13539600	7.13	6.53E-04	-3.19	2.55E-05	1.94E-01	836
9/27/2011	3857 hrs	4.40E-01	3857.00	13885200	7.14	7.08E-04	-3.15	2.55E-05	1.94E-01	834
10/4/2011	4025 hrs	4.59E-01	4025.00	14490000	7.16	6.64E-04	-3.18	2.55E-05	1.94E-01	832
10/10/2011	4169 hrs	4.76E-01	4169.00	15008400	7.18	5.88E-04	-3.23	2.55E-05	1.94E-01	830
10/17/2011	4337 hrs	4.95E-01	4337	15613200	7.19	7.27E-04	-3.14	2.55E-05	1.94E-01	827
10/21/2011	4433 hrs	5.06E-01	4433	15958800	7.20	6.55E-04	-3.18	2.55E-05	1.94E-01	826
10/24/2011	4505 hrs	5.14E-01	4505	16218000	7.21	5.57E-04	-3.25	2.55E-05	1.94E-01	825
10/31/2011	4673 hrs	5.33E-01	4673	16822800	7.23	5.64E-04	-3.25	2.55E-05	1.94E-01	823
11/7/2011	4841 hrs	5.53E-01	4841	17427600	7.24	5.28E-04	-3.28	2.55E-05	1.94E-01	820
11/11/2011	4937 hrs	5.64E-01	4937	17773200	7.25	4.93E-04	-3.31	2.55E-05	1.94E-01	819
11/18/2011	5105 hrs	5.83E-01	5105	18378000	7.26	4.73E-04	-3.33	2.55E-05	1.94E-01	817
11/22/2011	5201 hrs	5.94E-01	5206	18741600	7.27	5.79E-04	-3.24	2.55E-05	1.94E-01	816
11/29/2011	5369 hrs	6.13E-01	5369	19328400	7.29	5.06E-04	-3.30	2.55E-05	1.94E-01	814
12/5/2011	5513 hrs	6.29E-01	5513	19846800	7.30	5.51E-04	-3.26	2.55E-05	1.94E-01	812
12/16/2011	5777 hrs	6.59E-01	5777	20797200	7.32	5.56E-04	-3.25	2.55E-05	1.94E-01	809
12/30/2011	6113 hrs	6.98E-01	6113	22006800	7.34	5.63E-04	-3.25	2.55E-05	1.94E-01	806
2/6/2012	7025 hrs	8.02E-01	7025	25290000	7.40	4.72E-04	-3.33	2.55E-05	1.94E-01	797
2/8/2012	7073 hrs	8.07E-01	7073	25462800	7.41	1.00E+00	0.00	2.55E-05	1.94E-01	796
2/10/2012	7121 hrs	8.13E-01	7121	25635600	7.41	2.00E+00	0.30	2.55E-05	1.94E-01	796
2/13/2012	7193 hrs	8.21E-01	7193	25894800	7.41	3.00E+00	0.48	2.55E-05	1.94E-01	795
2/15/2012	7241 hrs	8.27E-01	7241	26067600	7.42	4.00E+00	0.60	2.55E-05	1.94E-01	795
2/22/2012	7409 hrs	8.46E-01	7409	26672400	7.43	5.00E+00	0.70	2.55E-05	1.94E-01	793
2/29/2012	7577 hrs	8.65E-01	7577	27277200	7.44	6.00E+00	0.78	2.55E-05	1.94E-01	792
3/8/2012	7769 hrs	8.87E-01	7769	27968400	7.45	7.00E+00	0.85	2.55E-05	1.94E-01	790
3/21/2012	8081 hrs	9.22E-01	8081	29091600	7.46	8.00E+00	0.90	2.55E-05	1.94E-01	788
6/10/2012	10008 hrs	1.14E+00	10008	36028800	7.56	9.00E+00	0.95	2.55E-05	1.94E-01	774
		5.71E+00	50000					2.55E-05	1.94E-01	670
		1.14E+01	100000					2.55E-05	1.94E-01	624
		5.00E+01	438000					2.55E-05	1.94E-01	530

Tensile Modulus Calculations										
Date	Duration					G-T-4				
	Duration	Years	Hrs	Sec	Log Sec	$\varepsilon-\varepsilon_0$	LOG ($\varepsilon-\varepsilon_0$)	m	n	Modulus Calculations
4/20/2011	0 min	0.00E+00	0.00	0		2.34E-04				
4/20/2011	1 min	1.90E-06	0.02	60	1.78	5.00E-06	-5.30	3.47E-04	3.71E-02	551
4/20/2011	6 min	1.14E-05	0.10	360	2.56	7.00E-06	-5.15	3.47E-04	3.71E-02	530
4/20/2011	12 min	2.28E-05	0.20	720	2.86	3.70E-05	-4.43	3.47E-04	3.71E-02	522
4/20/2011	30 min	5.71E-05	0.50	1800	3.26	8.70E-05	-4.06	3.47E-04	3.71E-02	511
4/20/2011	60 min	1.14E-04	1	3600	3.56	1.60E-04	-3.80	3.47E-04	3.71E-02	503
4/20/2011	5 hrs	5.71E-04	5	18000	4.26	1.86E-04	-3.73	3.47E-04	3.71E-02	484
4/21/2011	20 hrs	2.28E-03	20	72000	4.86	2.75E-04	-3.56	3.47E-04	3.71E-02	468
4/23/2011	50 hrs	5.71E-03	50	180000	5.26	4.23E-04	-3.37	3.47E-04	3.71E-02	458
4/25/2011	100 hrs	1.14E-02	100	360000	5.56	5.41E-04	-3.27	3.47E-04	3.71E-02	450
4/29/2011	200 hrs	2.28E-02	200	720000	5.86	5.78E-04	-3.24	3.47E-04	3.71E-02	442
5/2/2011	300 hrs	3.42E-02	300	1080000	6.03	6.05E-04	-3.22	3.47E-04	3.71E-02	438
5/14/2011	600 hrs	6.85E-02	600	2160000	6.33	6.07E-04	-3.22	3.47E-04	3.71E-02	430
5/22/2011	800 hrs	9.13E-02	800	2880000	6.46	6.34E-04	-3.20	3.47E-04	3.71E-02	427
5/26/2011	900 hrs	1.03E-01	900	3240000	6.51	6.48E-04	-3.19	3.47E-04	3.71E-02	426
6/17/2011	1400 hrs	1.60E-01	1400	5040000	6.70	6.56E-04	-3.18	3.47E-04	3.71E-02	421
6/21/2011	1500 hrs	1.71E-01	1500	5400000	6.73	5.58E-04	-3.25	3.47E-04	3.71E-02	421
6/23/2011	1550 hrs	1.77E-01	1550	5580000	6.75	4.12E-04	-3.39	3.47E-04	3.71E-02	420
6/28/2011	1670 hrs	1.91E-01	1670	6012000	6.78	6.90E-04	-3.16	3.47E-04	3.71E-02	419
7/6/2011	1862 hrs	2.13E-01	1862	6703200	6.83	7.83E-04	-3.11	3.47E-04	3.71E-02	418
7/18/2011	2150 hrs	2.45E-01	2150	7740000	6.89	8.09E-04	-3.09	3.47E-04	3.71E-02	417
8/2/2011	2510 hrs	2.87E-01	2510	9036000	6.96	7.52E-04	-3.12	3.47E-04	3.71E-02	415
8/15/2011	2825 hrs	3.22E-01	2825	10170000	7.01	7.83E-04	-3.11	3.47E-04	3.71E-02	414
8/24/2011	3041 hrs	3.47E-01	3041	10947600	7.04	8.01E-04	-3.10	3.47E-04	3.71E-02	413
8/31/2011	3209 hrs	3.66E-01	3209	11552400	7.06	7.93E-04	-3.10	3.47E-04	3.71E-02	412
9/2/2011	3257 hrs	3.72E-01	3257	11725200	7.07	8.07E-04	-3.09	3.47E-04	3.71E-02	412
9/6/2011	3353 hrs	3.83E-01	3353	12070800	7.08	9.44E-04	-3.03	3.47E-04	3.71E-02	412
9/9/2011	3425 hrs	3.91E-01	3425	12330000	7.09	6.96E-04	-3.16	3.47E-04	3.71E-02	412
9/12/2011	3497 hrs	3.99E-01	3497	12589200	7.10	7.20E-04	-3.14	3.47E-04	3.71E-02	412
9/14/2011	3545 hrs	4.05E-01	3545	12762000	7.11	6.96E-04	-3.16	3.47E-04	3.71E-02	411

Tensile Modulus Calculations										
Date	Duration					G-T-4				
	Duration	Years	Hrs	Sec	Log Sec	ε-ε0	LOG (ε-ε0)	m	n	Modulus Calculations
9/19/2011	3665 hrs	4.18E-01	3665.00	13194000	7	7.62E-04	-3.12	3.47E-04	3.71E-02	411
9/23/2011	3761 hrs	4.29E-01	3761.00	13539600	7.13	6.74E-04	-3.17	3.47E-04	3.71E-02	411
9/27/2011	3857 hrs	4.40E-01	3857.00	13885200	7.14	7.63E-04	-3.12	3.47E-04	3.71E-02	410
10/4/2011	4025 hrs	4.59E-01	4025.00	14490000	7.16	6.93E-04	-3.16	3.47E-04	3.71E-02	410
10/10/2011	4169 hrs	4.76E-01	4169.00	15008400	7.18	6.21E-04	-3.21	3.47E-04	3.71E-02	410
10/17/2011	4337 hrs	4.95E-01	4337	15613200	7.19	7.29E-04	-3.14	3.47E-04	3.71E-02	409
10/21/2011	4433 hrs	5.06E-01	4433	15958800	7.20	7.02E-04	-3.15	3.47E-04	3.71E-02	409
10/24/2011	4505 hrs	5.14E-01	4505	16218000	7.21	6.73E-04	-3.17	3.47E-04	3.71E-02	409
10/31/2011	4673 hrs	5.33E-01	4673	16822800	7.23	6.21E-04	-3.21	3.47E-04	3.71E-02	408
11/7/2011	4841 hrs	5.53E-01	4841	17427600	7.24	6.78E-04	-3.17	3.47E-04	3.71E-02	408
11/11/2011	4937 hrs	5.64E-01	4937	17773200	7.25	4.42E-04	-3.35	3.47E-04	3.71E-02	408
11/18/2011	5105 hrs	5.83E-01	5105	18378000	7.26	4.22E-04	-3.37	3.47E-04	3.71E-02	408
11/22/2011	5201 hrs	5.94E-01	5206	18741600	7.27	4.81E-04	-3.32	3.47E-04	3.71E-02	407
11/29/2011	5369 hrs	6.13E-01	5369	19328400	7.29	4.77E-04	-3.32	3.47E-04	3.71E-02	407
12/5/2011	5513 hrs	6.29E-01	5513	19846800	7.30	3.15E-04	-3.50	3.47E-04	3.71E-02	407
12/16/2011	5777 hrs	6.59E-01	5777	20797200	7.32	4.57E-04	-3.34	3.47E-04	3.71E-02	406
12/30/2011	6113 hrs	6.98E-01	6113	22006800	7.34	4.88E-04	-3.31	3.47E-04	3.71E-02	406
2/6/2012	7025 hrs	8.02E-01	7025	25290000	7.40	5.29E-04	-3.28	3.47E-04	3.71E-02	404
2/8/2012	7073 hrs	8.07E-01	7073	25462800	7.41	1.00E+00	0.00	3.47E-04	3.71E-02	404
2/10/2012	7121 hrs	8.13E-01	7121	25635600	7.41	2.00E+00	0.30	3.47E-04	3.71E-02	404
2/13/2012	7193 hrs	8.21E-01	7193	25894800	7.41	3.00E+00	0.48	3.47E-04	3.71E-02	404
2/15/2012	7241 hrs	8.27E-01	7241	26067600	7.42	4.00E+00	0.60	3.47E-04	3.71E-02	404
2/22/2012	7409 hrs	8.46E-01	7409	26672400	7.43	5.00E+00	0.70	3.47E-04	3.71E-02	404
2/29/2012	7577 hrs	8.65E-01	7577	27277200	7.44	6.00E+00	0.78	3.47E-04	3.71E-02	403
3/8/2012	7769 hrs	8.87E-01	7769	27968400	7.45	7.00E+00	0.85	3.47E-04	3.71E-02	403
3/21/2012	8081 hrs	9.22E-01	8081	29091600	7.46	8.00E+00	0.90	3.47E-04	3.71E-02	403
6/10/2012	10008 hrs	1.14E+00	10008	36028800	7.56	9.00E+00	0.95	3.47E-04	3.71E-02	400
		5.71E+00	50000					3.47E-04	3.71E-02	384
		1.14E+01	100000					3.47E-04	3.71E-02	377
		5.00E+01	438000					3.47E-04	3.71E-02	362

Tensile Modulus Calculations										
Date	Duration					G-T-5				
	Duration	Years	Hrs	Sec	Log Sec	$\varepsilon-\varepsilon_0$	LOG ($\varepsilon-\varepsilon_0$)	m	n	Modulus Calculations
4/20/2011	0 min	0.00E+00	0.00	0		-9.51E-04				
4/20/2011	1 min	1.90E-06	0.02	60	1.78	5.00E-06	-5.30	2.35E-05	2.06E-01	1286
4/20/2011	6 min	1.14E-05	0.10	360	2.56	1.40E-05	-4.85	2.35E-05	2.06E-01	1259
4/20/2011	12 min	2.28E-05	0.20	720	2.86	4.20E-05	-4.38	2.35E-05	2.06E-01	1247
4/20/2011	30 min	5.71E-05	0.50	1800	3.26	7.90E-05	-4.10	2.35E-05	2.06E-01	1227
4/20/2011	60 min	1.14E-04	1	3600	3.56	1.54E-04	-3.81	2.35E-05	2.06E-01	1211
4/20/2011	5 hrs	5.71E-04	5	18000	4.26	1.91E-04	-3.72	2.35E-05	2.06E-01	1164
4/21/2011	20 hrs	2.28E-03	20	72000	4.86	2.20E-04	-3.66	2.35E-05	2.06E-01	1113
4/23/2011	50 hrs	5.71E-03	50	180000	5.26	2.47E-04	-3.61	2.35E-05	2.06E-01	1074
4/25/2011	100 hrs	1.14E-02	100	360000	5.56	2.59E-04	-3.59	2.35E-05	2.06E-01	1042
4/29/2011	200 hrs	2.28E-02	200	720000	5.86	3.39E-04	-3.47	2.35E-05	2.06E-01	1007
5/2/2011	300 hrs	3.42E-02	300	1080000	6.03	3.46E-04	-3.46	2.35E-05	2.06E-01	985
5/14/2011	600 hrs	6.85E-02	600	2160000	6.33	3.97E-04	-3.40	2.35E-05	2.06E-01	946
5/22/2011	800 hrs	9.13E-02	800	2880000	6.46	4.66E-04	-3.33	2.35E-05	2.06E-01	929
5/26/2011	900 hrs	1.03E-01	900	3240000	6.51	5.43E-04	-3.27	2.35E-05	2.06E-01	922
6/17/2011	1400 hrs	1.60E-01	1400	5040000	6.70	6.92E-04	-3.16	2.35E-05	2.06E-01	895
6/21/2011	1500 hrs	1.71E-01	1500	5400000	6.73	6.99E-04	-3.16	2.35E-05	2.06E-01	890
6/23/2011	1550 hrs	1.77E-01	1550	5580000	6.75	7.07E-04	-3.15	2.35E-05	2.06E-01	888
6/28/2011	1670 hrs	1.91E-01	1670	6012000	6.78	7.43E-04	-3.13	2.35E-05	2.06E-01	884
7/6/2011	1862 hrs	2.13E-01	1862	6703200	6.83	8.13E-04	-3.09	2.35E-05	2.06E-01	877
7/18/2011	2150 hrs	2.45E-01	2150	7740000	6.89	8.76E-04	-3.06	2.35E-05	2.06E-01	868
8/2/2011	2510 hrs	2.87E-01	2510	9036000	6.96	8.13E-04	-3.09	2.35E-05	2.06E-01	858
8/15/2011	2825 hrs	3.22E-01	2825	10170000	7.01	8.04E-04	-3.09	2.35E-05	2.06E-01	850
8/24/2011	3041 hrs	3.47E-01	3041	10947600	7.04	8.92E-04	-3.05	2.35E-05	2.06E-01	845
8/31/2011	3209 hrs	3.66E-01	3209	11552400	7.06	8.60E-04	-3.07	2.35E-05	2.06E-01	842
9/2/2011	3257 hrs	3.72E-01	3257	11725200	7.07	7.99E-04	-3.10	2.35E-05	2.06E-01	841
9/6/2011	3353 hrs	3.83E-01	3353	12070800	7.08	1.04E-03	-2.98	2.35E-05	2.06E-01	839
9/9/2011	3425 hrs	3.91E-01	3425	12330000	7.09	7.69E-04	-3.11	2.35E-05	2.06E-01	838
9/12/2011	3497 hrs	3.99E-01	3497	12589200	7.10	7.92E-04	-3.10	2.35E-05	2.06E-01	836
9/14/2011	3545 hrs	4.05E-01	3545	12762000	7.11	7.58E-04	-3.12	2.35E-05	2.06E-01	835

Tensile Modulus Calculations										
Date	Duration					G-T-5				
	Duration	Years	Hrs	Sec	Log Sec	$\varepsilon-\varepsilon_0$	LOG ($\varepsilon-\varepsilon_0$)	m	n	Modulus Calculations
9/19/2011	3665 hrs	4.18E-01	3665.00	13194000	7	8.31E-04	-3.08	2.35E-05	2.06E-01	833
9/23/2011	3761 hrs	4.29E-01	3761.00	13539600	7.13	7.20E-04	-3.14	2.35E-05	2.06E-01	832
9/27/2011	3857 hrs	4.40E-01	3857.00	13885200	7.14	8.27E-04	-3.08	2.35E-05	2.06E-01	830
10/4/2011	4025 hrs	4.59E-01	4025.00	14490000	7.16	7.46E-04	-3.13	2.35E-05	2.06E-01	827
10/10/2011	4169 hrs	4.76E-01	4169.00	15008400	7.18	5.95E-04	-3.23	2.35E-05	2.06E-01	825
10/17/2011	4337 hrs	4.95E-01	4337	15613200	7.19	8.08E-04	-3.09	2.35E-05	2.06E-01	822
10/21/2011	4433 hrs	5.06E-01	4433	15958800	7.20	7.76E-04	-3.11	2.35E-05	2.06E-01	821
10/24/2011	4505 hrs	5.14E-01	4505	16218000	7.21	7.41E-04	-3.13	2.35E-05	2.06E-01	820
10/31/2011	4673 hrs	5.33E-01	4673	16822800	7.23	6.88E-04	-3.16	2.35E-05	2.06E-01	817
11/7/2011	4841 hrs	5.53E-01	4841	17427600	7.24	7.50E-04	-3.12	2.35E-05	2.06E-01	815
11/11/2011	4937 hrs	5.64E-01	4937	17773200	7.25	5.54E-04	-3.26	2.35E-05	2.06E-01	814
11/18/2011	5105 hrs	5.83E-01	5105	18378000	7.26	5.30E-04	-3.28	2.35E-05	2.06E-01	811
11/22/2011	5201 hrs	5.94E-01	5206	18741600	7.27	7.09E-04	-3.15	2.35E-05	2.06E-01	810
11/29/2011	5369 hrs	6.13E-01	5369	19328400	7.29	5.51E-04	-3.26	2.35E-05	2.06E-01	808
12/5/2011	5513 hrs	6.29E-01	5513	19846800	7.30	6.55E-04	-3.18	2.35E-05	2.06E-01	806
12/16/2011	5777 hrs	6.59E-01	5777	20797200	7.32	6.59E-04	-3.18	2.35E-05	2.06E-01	803
12/30/2011	6113 hrs	6.98E-01	6113	22006800	7.34	6.38E-04	-3.20	2.35E-05	2.06E-01	799
2/6/2012	7025 hrs	8.02E-01	7025	25290000	7.40	5.61E-04	-3.25	2.35E-05	2.06E-01	790
2/8/2012	7073 hrs	8.07E-01	7073	25462800	7.41	1.00E+00	0.00	2.35E-05	2.06E-01	790
2/10/2012	7121 hrs	8.13E-01	7121	25635600	7.41	2.00E+00	0.30	2.35E-05	2.06E-01	789
2/13/2012	7193 hrs	8.21E-01	7193	25894800	7.41	3.00E+00	0.48	2.35E-05	2.06E-01	788
2/15/2012	7241 hrs	8.27E-01	7241	26067600	7.42	4.00E+00	0.60	2.35E-05	2.06E-01	788
2/22/2012	7409 hrs	8.46E-01	7409	26672400	7.43	5.00E+00	0.70	2.35E-05	2.06E-01	786
2/29/2012	7577 hrs	8.65E-01	7577	27277200	7.44	6.00E+00	0.78	2.35E-05	2.06E-01	785
3/8/2012	7769 hrs	8.87E-01	7769	27968400	7.45	7.00E+00	0.85	2.35E-05	2.06E-01	783
3/21/2012	8081 hrs	9.22E-01	8081	29091600	7.46	8.00E+00	0.90	2.35E-05	2.06E-01	781
6/10/2012	10008 hrs	1.14E+00	10008	36028800	7.56	9.00E+00	0.95	2.35E-05	2.06E-01	766
		5.71E+00	50000					2.35E-05	2.06E-01	655
		1.14E+01	100000					2.35E-05	2.06E-01	607
		5.00E+01	438000					2.35E-05	2.06E-01	508

Tensile Modulus Calculations

Date	Duration					G-T-6				
	Duration	Years	Hrs	Sec	Log Sec	ε-ε_0	LOG (ε-ε_0)	m	n	Modulus Calculations
4/20/2011	0 min	0.00E+00	0.00	0		8.90E-05				
4/20/2011	1 min	1.90E-06	0.02	60	1.78	2.00E-06	-5.70	4.60E-06	3.14E-01	1341
4/20/2011	6 min	1.14E-05	0.10	360	2.56	1.60E-05	-4.80	4.60E-06	3.14E-01	1335
4/20/2011	12 min	2.28E-05	0.20	720	2.86	2.20E-05	-4.66	4.60E-06	3.14E-01	1331
4/20/2011	30 min	5.71E-05	0.50	1800	3.26	3.80E-05	-4.42	4.60E-06	3.14E-01	1325
4/20/2011	60 min	1.14E-04	1	3600	3.56	6.20E-05	-4.21	4.60E-06	3.14E-01	1320
4/20/2011	5 hrs	5.71E-04	5	18000	4.26	9.80E-05	-4.01	4.60E-06	3.14E-01	1301
4/21/2011	20 hrs	2.28E-03	20	72000	4.86	1.19E-04	-3.92	4.60E-06	3.14E-01	1276
4/23/2011	50 hrs	5.71E-03	50	180000	5.26	1.52E-04	-3.82	4.60E-06	3.14E-01	1253
4/25/2011	100 hrs	1.14E-02	100	360000	5.56	2.08E-04	-3.68	4.60E-06	3.14E-01	1232
4/29/2011	200 hrs	2.28E-02	200	720000	5.86	2.31E-04	-3.64	4.60E-06	3.14E-01	1206
5/2/2011	300 hrs	3.42E-02	300	1080000	6.03	2.29E-04	-3.64	4.60E-06	3.14E-01	1189
5/14/2011	600 hrs	6.85E-02	600	2160000	6.33	4.36E-04	-3.36	4.60E-06	3.14E-01	1156
5/22/2011	800 hrs	9.13E-02	800	2880000	6.46	6.22E-04	-3.21	4.60E-06	3.14E-01	1141
5/26/2011	900 hrs	1.03E-01	900	3240000	6.51	6.98E-04	-3.16	4.60E-06	3.14E-01	1134
6/17/2011	1400 hrs	1.60E-01	1400	5040000	6.70	7.91E-04	-3.10	4.60E-06	3.14E-01	1108
6/21/2011	1500 hrs	1.71E-01	1500	5400000	6.73	8.06E-04	-3.09	4.60E-06	3.14E-01	1103
6/23/2011	1550 hrs	1.77E-01	1550	5580000	6.75	7.82E-04	-3.11	4.60E-06	3.14E-01	1101
6/28/2011	1670 hrs	1.91E-01	1670	6012000	6.78	8.87E-04	-3.05	4.60E-06	3.14E-01	1096
7/6/2011	1862 hrs	2.13E-01	1862	6703200	6.83	9.36E-04	-3.03	4.60E-06	3.14E-01	1089
7/18/2011	2150 hrs	2.45E-01	2150	7740000	6.89	9.89E-04	-3.00	4.60E-06	3.14E-01	1080
8/2/2011	2510 hrs	2.87E-01	2510	9036000	6.96	9.52E-04	-3.02	4.60E-06	3.14E-01	1069
8/15/2011	2825 hrs	3.22E-01	2825	10170000	7.01	9.90E-04	-3.00	4.60E-06	3.14E-01	1061
8/24/2011	3041 hrs	3.47E-01	3041	10947600	7.04	1.03E-03	-2.99	4.60E-06	3.14E-01	1055
8/31/2011	3209 hrs	3.66E-01	3209	11552400	7.06	9.97E-04	-3.00	4.60E-06	3.14E-01	1051
9/2/2011	3257 hrs	3.72E-01	3257	11725200	7.07	9.97E-04	-3.00	4.60E-06	3.14E-01	1050
9/6/2011	3353 hrs	3.83E-01	3353	12070800	7.08	9.58E-04	-3.02	4.60E-06	3.14E-01	1048
9/9/2011	3425 hrs	3.91E-01	3425	12330000	7.09	9.17E-04	-3.04	4.60E-06	3.14E-01	1047
9/12/2011	3497 hrs	3.99E-01	3497	12589200	7.10	9.21E-04	-3.04	4.60E-06	3.14E-01	1045
9/14/2011	3545 hrs	4.05E-01	3545	12762000	7.11	9.39E-04	-3.03	4.60E-06	3.14E-01	1044

Tensile Modulus Calculations

Date	Duration					G-T-6				
	Duration	Years	Hrs	Sec	Log Sec	$\varepsilon-\varepsilon_0$	LOG ($\varepsilon-\varepsilon_0$)	m	n	Modulus Calculations
9/19/2011	3665 hrs	4.18E-01	3665.00	13194000	7	9.55E-04	-3.02	4.60E-06	3.14E-01	1042
9/23/2011	3761 hrs	4.29E-01	3761.00	13539600	7.13	8.75E-04	-3.06	4.60E-06	3.14E-01	1040
9/27/2011	3857 hrs	4.40E-01	3857.00	13885200	7.14	9.64E-04	-3.02	4.60E-06	3.14E-01	1038
10/4/2011	4025 hrs	4.59E-01	4025.00	14490000	7.16	8.95E-04	-3.05	4.60E-06	3.14E-01	1035
10/10/2011	4169 hrs	4.76E-01	4169.00	15008400	7.18	8.12E-04	-3.09	4.60E-06	3.14E-01	1032
10/17/2011	4337 hrs	4.95E-01	4337	15613200	7.19	9.32E-04	-3.03	4.60E-06	3.14E-01	1029
10/21/2011	4433 hrs	5.06E-01	4433	15958800	7.20	9.16E-04	-3.04	4.60E-06	3.14E-01	1027
10/24/2011	4505 hrs	5.14E-01	4505	16218000	7.21	8.68E-04	-3.06	4.60E-06	3.14E-01	1026
10/31/2011	4673 hrs	5.33E-01	4673	16822800	7.23	8.15E-04	-3.09	4.60E-06	3.14E-01	1023
11/7/2011	4841 hrs	5.53E-01	4841	17427600	7.24	8.58E-04	-3.07	4.60E-06	3.14E-01	1020
11/11/2011	4937 hrs	5.64E-01	4937	17773200	7.25	6.90E-04	-3.16	4.60E-06	3.14E-01	1019
11/18/2011	5105 hrs	5.83E-01	5105	18378000	7.26	6.71E-04	-3.17	4.60E-06	3.14E-01	1016
11/22/2011	5201 hrs	5.94E-01	5206	18741600	7.27	8.11E-04	-3.09	4.60E-06	3.14E-01	1015
11/29/2011	5369 hrs	6.13E-01	5369	19328400	7.29	6.79E-04	-3.17	4.60E-06	3.14E-01	1012
12/5/2011	5513 hrs	6.29E-01	5513	19846800	7.30	7.79E-04	-3.11	4.60E-06	3.14E-01	1010
12/16/2011	5777 hrs	6.59E-01	5777	20797200	7.32	7.65E-04	-3.12	4.60E-06	3.14E-01	1006
12/30/2011	6113 hrs	6.98E-01	6113	22006800	7.34	7.51E-04	-3.12	4.60E-06	3.14E-01	1002
2/6/2012	7025 hrs	8.02E-01	7025	25290000	7.40	6.82E-04	-3.17	4.60E-06	3.14E-01	990
2/8/2012	7073 hrs	8.07E-01	7073	25462800	7.41	1.00E+00	0.00	4.60E-06	3.14E-01	990
2/10/2012	7121 hrs	8.13E-01	7121	25635600	7.41	2.00E+00	0.30	4.60E-06	3.14E-01	989
2/13/2012	7193 hrs	8.21E-01	7193	25894800	7.41	3.00E+00	0.48	4.60E-06	3.14E-01	988
2/15/2012	7241 hrs	8.27E-01	7241	26067600	7.42	4.00E+00	0.60	4.60E-06	3.14E-01	988
2/22/2012	7409 hrs	8.46E-01	7409	26672400	7.43	5.00E+00	0.70	4.60E-06	3.14E-01	986
2/29/2012	7577 hrs	8.65E-01	7577	27277200	7.44	6.00E+00	0.78	4.60E-06	3.14E-01	984
3/8/2012	7769 hrs	8.87E-01	7769	27968400	7.45	7.00E+00	0.85	4.60E-06	3.14E-01	982
3/21/2012	8081 hrs	9.22E-01	8081	29091600	7.46	8.00E+00	0.90	4.60E-06	3.14E-01	979
6/10/2012	10008 hrs	1.14E+00	10008	36028800	7.56	9.00E+00	0.95	4.60E-06	3.14E-01	960
		5.71E+00	50000					4.60E-06	3.14E-01	807
		1.14E+01	100000					4.60E-06	3.14E-01	735
		5.00E+01	438000					4.60E-06	3.14E-01	579

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BIOGRAPHICAL INFORMATION

Siavash G. Motlagh was born in 1981 in Tehran, Iran. He received his Bachelor's Degree in Civil Engineering from Iran University of Science and Technology (IUST) in 2004. He then worked as a project engineer and project manager for seven years before joining the University of Texas at Arlington (UTA) in 2011. While pursuing his Master of Science degree in UTA, he was involved in different research projects in trenchless technology as a graduate research assistant under Dr. Mohammad Najafi's supervision. Siavash has presented at No-Dig show in Nashville, Tennessee in 2012, and at the annual ASCE International Pipeline 2013 Conference in Fort Worth, Texas. Starting in July 2013, he started to work as an intern in San Francisco Central Subway project and he plans to continue gaining first-hand experiences in different areas of Civil Engineering.