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

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ABSTRACT

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

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1.0 Introduction

Corrosion is considered to be the major reason for structural failures. In many instances, the most and perhaps the only effective measure that can be taken for corrosion control is to protect the structure with a coating. Corrosion control by coatings has progressed to a scientific level. An ideal corrosion protection coating or lining system must be environmentally friendly, worker-safe, durable and able to expose little or no substrate surface to the environment. Trenchless technology includes various methods for rehabilitation of pipelines and underground pipelines with minimum disruption of surface and subsurface. There are number of methods available for rehabilitation of water lines. The effectiveness of the method depends on the physical properties of lining, pipe material and the geometry. Several factors must be evaluated before choosing a particular lining method of rehabilitation for an individual project. A lining material should be capable of providing protection against corrosion and guarantee long-term gap spanning ability. For deteriorated pipe, lining should provide structural enhancement in conjunction with the host pipe. Rehabilitation planning should be established based on the evaluation of deterioration degree of pipes. Polyurea, a breakthrough product developed in 1980's is two component elastomeric lining system possessing the characteristics of regenerating the properties of pipe from its application.

Underground infrastructure is a liquid asset which is often taken for granted, because of our mindset "out of sight and out of mind" (Najafi & Gokhale, 2005). This unfortunate mindset is the major factor influencing the deterioration of our underground infrastructure. The effect of deterioration of water lines could result in great detriment and could be costly.

1.1 Objectives and Scope

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

This research work is comprised of evaluating the some mechanical properties at room temperature; Performing trial test with similar setup to determine the appropriate stress value for long-term test; Performing test on the liner material such as long-term tensile and flexural creep and formulate results and predicting long-term properties and design life of polyurea composite.

2.0 Literature Review

2.1 Coatings and Linings

Pipeline coatings have undergone dramatic technological changes over the past two decades. Coatings now must perform at higher in-service operating temperatures, must not be damaged in handling during construction or in operation by soil stress or soil movement, and must provide exceptional corrosion protection. Coatings also must be user friendly and must be able to be applied in a mill or in the field. Coatings are the primary means of corrosion protection for a buried pipeline whether for new construction or for pipeline rehabilitation. Although cathodic protection is applied, it is considered the second line of defense against corrosion. Therefore, today's coatings must provide better protection than their predecessors, continue to function under severe operating conditions, and be applied under less than ideal conditions. The primary materials used for coatings and linings can be categorized into cementitious, polymers, sheet liners and cured-in-place liners (Najafi, & Gokhale, 2005).

2.2 Polymers - Polyurea

Polymers are group of materials made up of long covalently-bonded molecules. Polymers are commonly classified into three groups: thermoplastics, elastomers and thermosets. Figure 1 provides and outline of the various classification of polymers. Thermoplastics are linear or branched polymers that can be molded and shaped when it is heated. Elastomers are cross-linked rubbery polymers which are easily stretchable. Thermosets are those polymers which do not melt when heated.

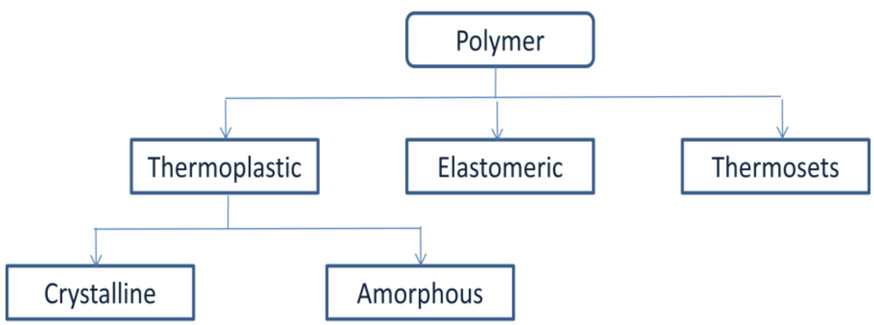

Figure 1 – Classification of Polymer (Young & Lovell, 1991)

Currently there are various polymers available in the market, each of them with distinctive properties and applications. Some of the common polymers used in pipeline industry are polyurethane, polyurea, epoxies, polyester, and vinyl ester

Polyurea linings are one of the latest technologies in the protective coating industry and have shown a great deal of versatility and acceptance from the industrial end application markets. Because of its excellent physical, chemical and mechanical properties, its efficient handling performance and due to environmental reasons polyurea has found an increasing market interest in the last few years. Polyurea is two-component elastomers, with one component being an isocyanate material, and the other polyether polyamine. Polyurea linings are usually sprayed through 1:1 ratio, but might vary depending on the manufacturer's formulation.

2.3 General Properties

Polyurea have some unique and outstanding properties which makes it demanding in coating and trenchless industry. Some of the most distinct features of polyurea are:

1. **100% Solids:** Refers to lack of solvent, which can carry or reduce any of the coating resins. This helps in achieving additional thickness and increase physical and chemical resistance
2. **VOC's:** Polyurea does not contain any Volatile Organic Compounds as per EPA Method 8260
3. **Humidity:** Polyurea is not likely to be affected by moisture and humidity but in reality if there are excessive water puddles remaining in the pipe, some blistering may be present.
4. **Heat and Fire Resistance:** Polyurea coatings have excellent resistance to heat distortion and sagging. Depending on the formulation, some polyureas have a low heat deflection temperature. When exposed to constant flame for 20-30 seconds, polyurea coatings will self-extinguish
5. **Waterproof:** Seamless waterproofing system for concrete, wood, metal, soil, and other substrates
6. **Abrasion Resistance:** Polyurea has excellent resistance to withstand mechanical action such as rubbing, scraping, or erosion, that tends progressively to remove material from its surface
7. **Elasticity:** Polymer being an elastomer has a very linear structure with much less cross-linking which makes it stretchy and elastic.

Table 1.0 presents some of the typical physical properties of polyurea.

Table 1 –Typical Physical Properties of Polyurea

Typical Physical Properties	Description
Tensile Strength	• Test Method : ASTM D-638 • Range: up to 4,000 psi
100% Modulus	• 500 – 1800 psi
Flexural Strength	• Test Method : ASTM D-790 • Range: 3200 – 3,500 psi
Flexural Modulus	• Test Method : ASTM D-790 • 100,000 to 110,000 psi
Elongation	• 20 – 1,000 %
Gel Time	• 2 – 15 seconds
Tear Strength	• 250 – 600 pounds per linear inch
Application Temperature	• - 40^{o} F to 122^{o} F
Initial Curing Time	• 3 – 10 seconds • Autocatalytic

3.0 Installation Procedure of Polyurea Lining

The wide use of polyurea in the current trenchless industry as spray coatings has been made possible through the development of proper installation procedure and application equipment. The main factor governing an efficient lining is proper installation technique and also the sequence of activity followed. The effectiveness of a good lining depends on many other factors such as transportation, temperature changes, resistance to water absorption etc to achieve an effective application at lower cost. When installed by trained professionals, polyurea offers tremendous advantages and durability over older technologies. A properly prepared, primed, and installed polyurea solution provides decades of trouble free use. Figure 2 illustrates the schematic process of polyurea lining.

1. **Site Preparation –** Site preparation includes preparing the pipeline for cutting and cleaning. There are a number of cleaning methods available for cleaning the water pipes, some of which are power boring, drag scraping, abrasive pigging, pressure scraping and pressure jetting.
2. **Locating Hydrants & Valves** – Installation of the polyurea lining material is usually carried from valves to valves from upstream to downstream.
3. **Drying** - Prior to application the main shall be relatively dry and free from standing water. This is achieved by drying with foam swabs, blown through with compressed air.

4. **Pre-lining Inspection** – After the cleaning is done, a visual inspection or a color CCTV inspection of the water main is carried out to check the quality of the cleaning and highlight any potential problems such as: infiltration, dropped joints, structural failures; and standing water.

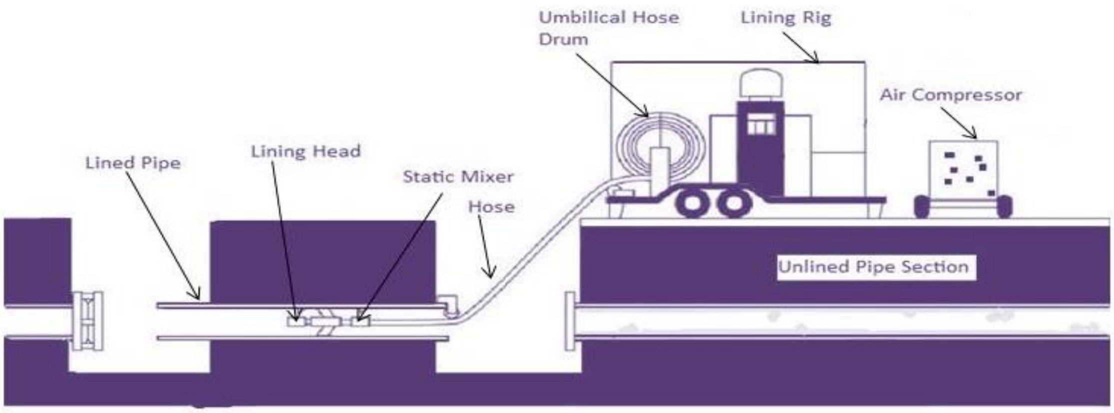

Figure 2 – Schematic Process of Polyurea Lining

5. **Application of Polyurea Lining** – A calibrated static mixer head is used to apply the lining material to achieve its required thickness. Polyurea is fed to the spray head through a system of high-pressure hoses and a uniform thickness liner is applied as the head moves through the existing pipe at a constant speed.
6. **Curing** - Cure time is effected by environmental conditions. Do not force dry. High humidity and/or low temperatures can cause haziness and blushing in the coating. The coating shall be allowed to cure for a minimum period of 10 minutes after completion of lining before next inspection is done.
7. **Post-lining Inspection** - Post lining inspection is carried out to ensure that the lining has been completely and consistently applied, and that the pipe is fully lined, cured and protected.
8. **Close-out** - After the lining is applied, the site is cleared with all pipelines reassembled and waste disposed of.

3.1 Benefits of Polyurea

Polyurea offers a wide range of advantages primarily due to its unique physical, chemical and mechanical properties. Some of the distinct benefits of polyurea are:

- **Easy to Clean:** Polyurea forms an impermeable surface when it cures so it's impossible for dirt, grime, and liquids to bond with the floor which makes it very easy to clean
- **Crack Resistant:** Polyurea is able to elongate at a level of 100%. This makes polyurea able to handle the minute shifting, expanding, and contracting that occurs in all concrete floors
- **Maintenance Free:** Unlike most of the other linings, polyurea does not require periodic maintenance or topcoats thus saving time and cost
- **Fast Reaction Time:** 3 – 10 seconds
- **Attractive:** Polyurea linings are visually appealing with many color options
- **Corrosive Resistant:** Polyurea is much more resistant to corrosion caused by chemical contact. Gasoline, oil and antifreeze are no match for a polyurea coating
- **No Volatile Organic Compounds (VOCs):** All the polyurea linings are VOC free
- **No Odor or Low Odor:** Polyurea linings does not have any odor or during application. Any odor generated by it is at such a low level that it dissipates within two hours
- **Environmentally Friendly:** Along with no VOCs, polyurea creates an extended life cycle for the surface it covers. Repairs and replacements happen less often which is beneficial to the environment
- **Surface Finishing:** Penetrates and seals the surface, leaving a smooth, pinhole and bubble free coating. Displays excellent flexibility and waterproofing properties for use on a variety of substrates
- **Wide Application Temperature Range:** Can be applied at temperatures ranging from -20 to 120°F and in high humidity.

Table 2 gives a detailed comparison between some of the common linings used for renewal of pipelines.

4.0 ANALYSIS OF EXPERIMENTAL DATA

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

Table 2 – Comparison of Polyurea with other Linings

Parameters	Polyurea	Polyurethane	Cement Mortar and Reinforced Shotcrete	Epoxy
Corrosion protection	Effective and corrosion-resistant barrier	Effective and corrosion-resistant barrier	Passive permeable barrier	Di-electric impermeable barrier
History	Has been in use for 10 years	Has been in use for 65 years. Standard AWWA – C222	AWWA Standard since 1955	Introduced in UK water industry in the late 1970s. Standard AWWA C-166-09
Pipe Preparation/Cleaning	Drag scraper, Power boring, jetting	Drag scraper, Power boring, jetting	Scraper method	Rack feed bore
Lining Environment	Dry pipe required	Dry pipe required	Wet or damp pipe: No standing water	Dry pipe required
Typical Lining Thickness	Minimum 1 mm typical 2 – 5 mm	Minimum 1 mm typical 2 – 5 mm	4 – 12 mm diameter pipe	Minimum 1 mm typical 2 – 4 mm
Curing Time before Disinfection	Minimum 1 hr	Minimum 2 hrs	Minimum 24 hrs	Minimum 16 hrs
Mixing Ratio*	1/1	1/1	1 cement/3 sand	1/1
VOC (lbs/gal)	0.00	0.00	0.00	0.30
Application Method	Plural component spray	Plural component spray	Centrifugal, mechanical, pneumatic, hand application	Plural component spray
Application Temperature (^{o}F)	-40 to 150	-40 to 150	35 to 100	40 to 100
Curing Procedure	Not required	Not required	Moist curing or accelerated curing	Maintain Temperature
Color Options	Many colors	Many colors	Not available	Many colors
Odor Generation	No odor	Strong odor during curing	No odor	Strong odor during curing
Bonding to Concrete	Extremely strong	Weak	Good	Strong

***** Ratio might vary depending on the manufacturer's formulation**.**

4.1 Analysis of Tensile Creep Data

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

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

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

Table 4.1 - Load Selection for Various Polyurea Specimens

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

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

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

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

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

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

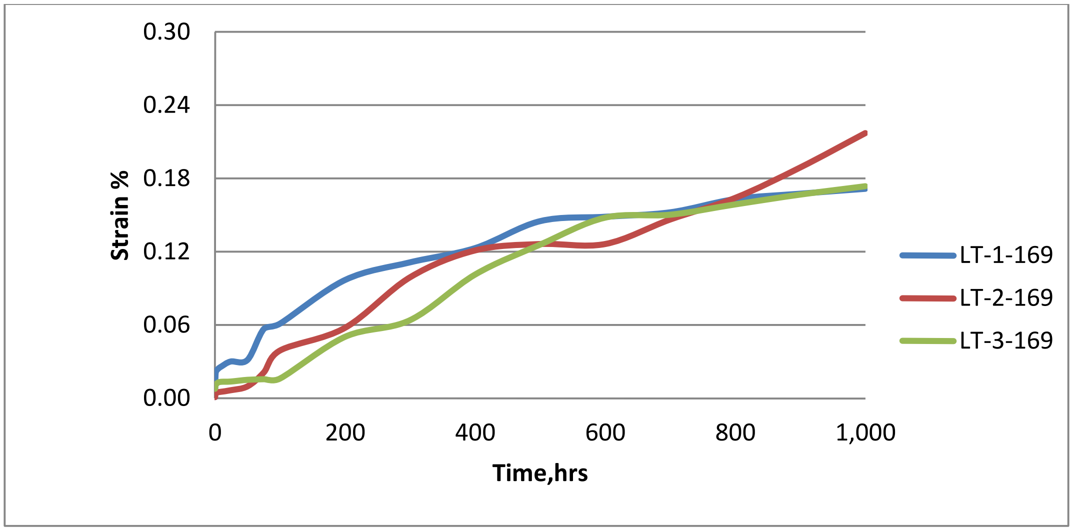

Figure 4.1 - Tensile Creep Strain ε in 169 Polyurea Specimens

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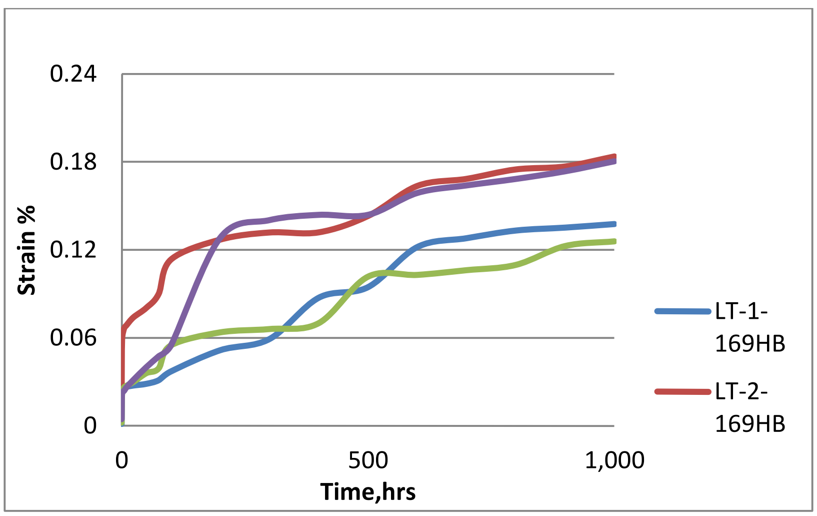

Figure 4.2 - Tensile Creep Strain ε in 169HB Polyurea Specimens

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

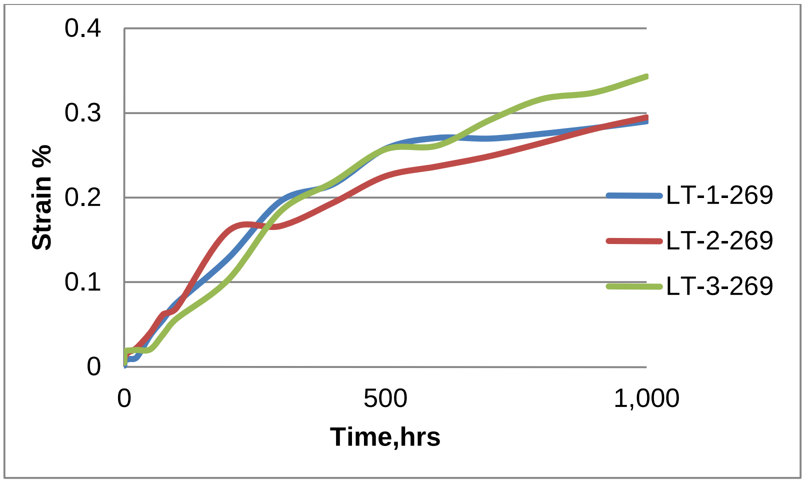

Figure 4.3 - Tensile Creep Strain ε in 269 Polyurea Specimens

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

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

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

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

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

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

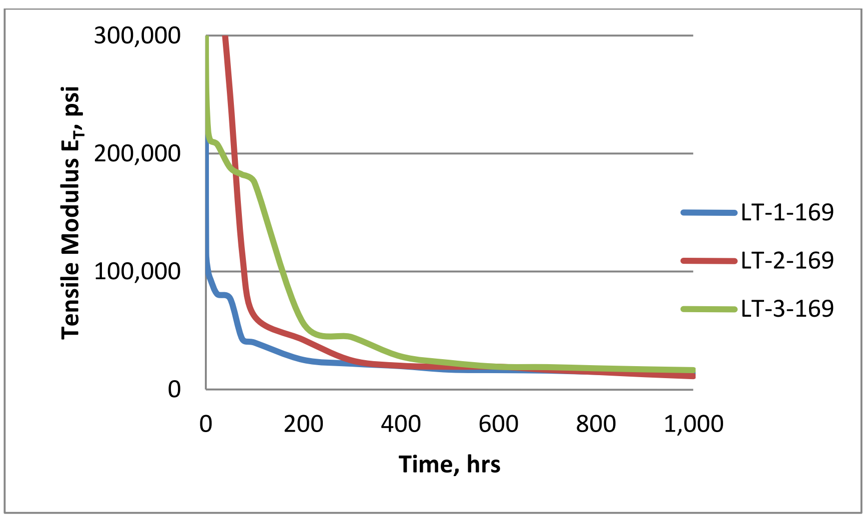

Figure 4.4 - Tensile Creep Modulus E_T versus Time at Various Stress for 169 Specimens

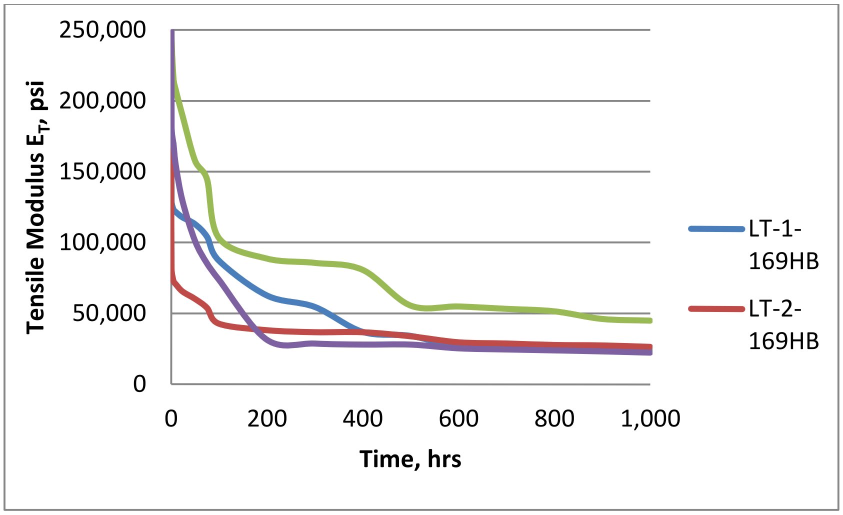

Figure 4.5 - Tensile Creep Modulus E_T versus Time at Various Stress for 169HB Specimens

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

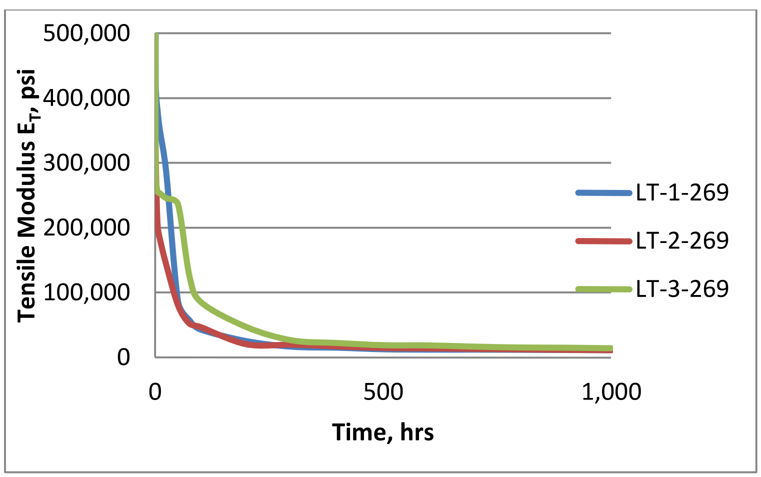

Figure 4.6 - Tensile Creep Modulus E_T versus Time at Various Stress for 269 Specimens

4.2 Tensile Creep Test Results

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

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

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

5.0 Conclusions and Recommendations

5.1 Conclusions

Polyurea spray lining system being one of the latest technologies in the coating industry has shown a good deal of versatility and application usage. Due to its unique physical, chemical and mechanical properties the use of polyurea linings has been increased all over. The rapid reaction and curing time characteristics provides for an extremely good cost and time-effective solution to a variety of coatings and linings applications over conventional technologies. Polyurea linings come in a variety of chemical properties and combinations that would possess a range of mechanical characteristics. The features and benefits provided by advanced polymers cannot be ignored. Polyurea lining has set itself in a different class of lining systems as compared to other conventional linings, like cement mortar and epoxy.

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

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

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

Flexural Creep

Based on the 1,000 hours on polyurea composite specimens at room temperature, we can conclude that 169 and 169HB polyurea specimens performed better in bending when compared to 269 specimens. This is due to more rigidity in case of 169 & 169HB specimen which provided a better stress distribution. There was a 90% reduction in strength for 269 specimens, unlike the other two composites. This concludes 269 polyurea to be more flexible material and 169 and 169HB more rigid. The value of elastic modulus of the materials obtained from long-term test was compared with the values obtained from the short-term tests results.

Tensile Creep

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

<u>Log-Curve Fitting</u>

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

<u>Findley's Power Law</u>

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

5.2 Recommendations for Future Research

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

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

Acknowledgements

I would like to thank 3M/water**,** for giving me an opportunity to work on this interesting project and also for providing the required funding. I also thank Dr. Mohammad Najafi for his guidance and support.

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