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## MATERIAL CHARACTERIZATION OF A COMPOSITE POLYMER LINER FOR REHABILITATION OF PRESSURE PIPELINES

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**ABSTRACT:** Cast in place polymer liners are increasingly being used to repair cast iron pressure water pipes. This liner system is composed of two concentric, tubular, plain-woven polyester jackets, with the inner jacket bonded onto a polyurethane elastomer. The space between the jackets is filled with a proprietary polymeric resin and the liner is cured in the field using pressurized hot water. To date, however, no standards exist for testing this type of liner.

This study is aimed at characterizing the mechanical properties of this liner in the longitudinal and circumferential directions and also developing a method to achieve this goal. A technique has been established in the laboratory to build the liner from its individual components and develop coupons with end tabs. Test results of these coupons agreed with the relative magnitude of moduli and yield stresses of those obtained from coupons cut from a field cured liner exhumed from an actual pipe. As such, the same technique was successfully used to test the liner in the circumferential direction using flat coupons. Individual components of the liner have also been tested and the effect of curing temperature has been examined. The study showed that this liner has a bi-linear stress-strain curve with a curved transition zone followed by strain hardening. Tensile strength and stiffness in the hoop direction were approximately 45% higher than the longitudinal direction. Curing temperature has a pronounced effect on the stress-strain properties of the resin. This is particularly important as the resin substantially controls the initial stiffness of the composite liner.

### 1. INTRODUCTION

Over the years, failure modes such as, wedge splitting, spiral cracking, longitudinal cracking and circumferential breaks have been observed in cast iron pipes used in water distribution systems. Currently, 90% of the repair work performed on water pipes is undertaken by the conventional method of digging an open trench and replacing the damaged pipe segment with a new one (Jeyapalan, 2003). This procedure involves a great deal of work, requires a significant amount of time and is very costly. It can also be disruptive to the public and to traffic, especially in heavily populated urban areas. Moreover, Luk (2001) states that this technique does not provide a permanent solution to the problem since the corrosion process will start over again as soon as a new metal pipe is installed.

Using state-of-the-art trenchless technology, a novel method involving a cured-in-place polymer pipe liner (CIPP) has been developed (Sanexen Environmental Services Inc. brochure, 2004) to structurally rehabilitate damaged cast iron water mains. The Aqua-Pipe™ system (Sanexen Environmental Services Inc. brochure, 2004) is a composite liner composed of two concentric, tubular, plain-woven polyester jackets, with the inner jacket having a bonded layer of polyurethane elastomer at its inner surface. A polymeric resin is injected within the two jackets and the liner is pulled into place through an entry pit using a cable-winch system that is set up at a second access pit further along the section of pipe to be lined. It is then cured in the field using pressurized hot water at approximately 55°C. After curing, the service connections to lateral pipes are re-opened using a remote controlled robot. In addition to providing structural support for the damaged cast iron host pipe, the composite liner protects against further internal corrosion, helps maintain the pipe's hydraulic carrying capacity, and prevents leakage.

## **2. RESEARCH SIGNIFICANCE**

There has been a significant amount of research conducted on the application of cured-in-place pipe liners in gravity flow pipes (e.g. El-Sawy and Moore, 1997; Moore and El-Sawy, 1996); however, there has been little research on applying the CIPP system in pressure pipe applications. Allouche et al (2004) report on a preliminary study, where six potential limit states for pressure pipe liners are identified. However, ASTM F1216-06 only provides a simple calculation of liner thickness to withstand hoop tensions resulting from the internal pressure, and it does not explain how to design for the other potential limit states identified by Allouche et al (2004).

This paper provides a step towards understanding the mechanical behavior of these pressure pipe liners. Specimens of the Aqua-Pipe™ liner system, exhumed from a trial lining project in Hamilton (Ontario) are analyzed experimentally to gain an understanding of the constitutive material characteristics of this composite liner. The components of the liner in their pre-cured state are tested separately in the longitudinal and circumferential directions and a replica version of the cured liner is fabricated in-house and compared to the exhumed cured sample.

Data from this work will be used to develop a finite element model for the Aqua-Pipe™ liner itself as well as composite liners of this type in general, in conjunction with the host pipe system, so that a comprehensive limit states design method can be developed.

## **3. EXPERIMENTAL PROCEDURES**

The following sections provide details of the experimental program in terms of preparation and testing of various types of test specimens. This includes specimens exhumed from the field and those prepared in-house, along with the individual components of the liner. Details of the testing procedures and instrumentations are also given.

### *Specimen Preparation of the Exhumed Aqua-Pipe™ Liner*

Segments of the lined cast iron pipes were received from the field and sections of the Aqua-Pipe™ liner were extracted. The outer diameter of the liner was 155mm and the total thickness was approximately 4.7mm. Rectangular coupons, 25 x 225mm, were cut along the longitudinal axis of the extracted tubular liner. Special tabs were fabricated on both ends and both sides of the coupons to conform to their curved surfaces in the transverse direction. They were attached to facilitate gripping of the coupons in the test machine. The tabs consisted of glass fiber woven fabric, Tyfo SHE-51A, impregnated by Tyfo S Epoxy resin (Fyfe Co LLC brochure). After the epoxy wetted fabric was installed, the assembly was placed between two parallel flat surfaces under a heavy weight and left to cure for 48 hours. Figure 1 shows a picture of a finished coupon with the 50mm long tabs installed at each end and Figure 2 shows a close up view of the coupon's end.

Since no standards exist on testing this type of liner, the procedures used for preparation of fiber reinforced polymer (FRP) flat coupons (ASTM D3039/3039M-00) were adopted. In total, seven coupons were prepared.

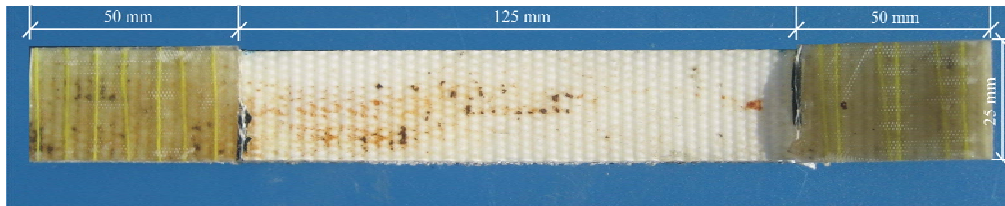


Figure 1. Exhumed liner coupon with gripping tabs attached

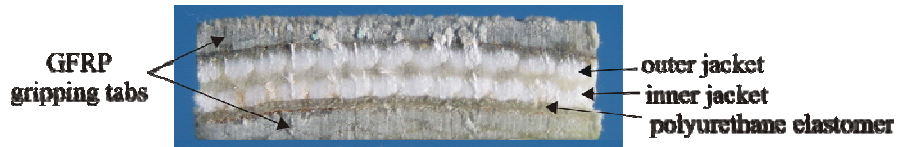


Figure 2. End view of exhumed liner coupon with gripping tabs attached

#### *Specimen Preparation of the Individual Components of the Composite Liner*

The inner and outer jackets of the composite liner are essentially the same; except that the inner jacket has a non-structural polyurethane elastomer layer bonded to its inner surface that is compatible with the transmission of potable water. Sections of the inner and outer jackets were provided in their original form (i.e. woven polyester fiber fabric), as shown in Figures 3a and 3b.

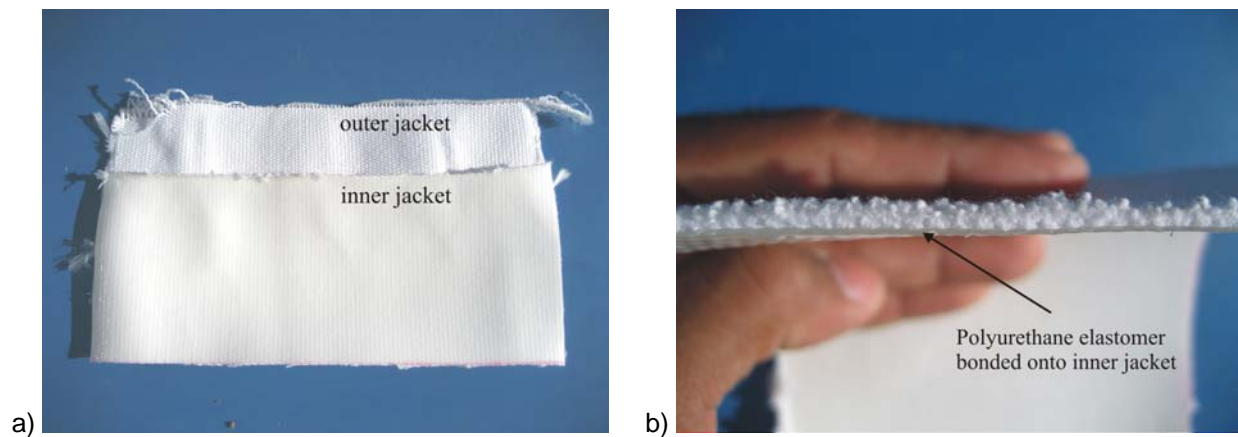


Figure 3. a) Inner and outer jackets of the Aqua-Pipe™ liner b) Close up of the inner jacket

Test coupons of the same dimensions as those prepared earlier, as shown in Figure 1, were prepared from the inner and outer jackets but in both the longitudinal and transverse directions. Additional coupons were made from the outer jacket in the longitudinal directions with the circumferential strands removed from the fabric to examine their contribution and assess the effect of the plain weave. GFRP gripping tabs of the same type as described earlier were fabricated at the ends of these coupons. In total, fourteen and seven coupons were prepared from the outer jacket in the longitudinal and transverse directions, respectively, and seven and seven coupons were prepared from the inner jacket in the longitudinal and transverse directions, respectively.

Coupons of the polymeric resin were made in accordance with ASTM D638-03. Using a type IV dumbbell cutting tool, shown in Figure 4a, a mould was created (Figure 4c) out of a smooth, high quality, high-density polyethylene (GSE HD) geomembrane. This type of material was suitable for the mould since the cured resin did not adhere to the geomembrane and it was capable of retaining its form even at high

curing temperatures. The resin coupons were made using three sheets of GSE HD stacked one on top of the other, with the middle sheet cut to act as the mould. After mixing the epoxy resin and hardener with 100:30 ratio by weight, it was poured into the mould and weights were placed on top of the stack to remove as many air bubbles as possible that might have formed within the coupons. The stack was then placed in a forced air oven and the resin was cured for approximately one hour. The end results were coupons made entirely of the curable polymeric resin shown in Figure 4d. The coupons were cured at 55°C, which is the approximate temperature of the hot water typically used in the field under pressure to inflate and cure the liner. In order to examine the effect of curing temperature, additional resin coupons were prepared and cured at 20°C, 40°C and 70°C temperatures. In total, 5 coupons were prepared for each curing temperature.

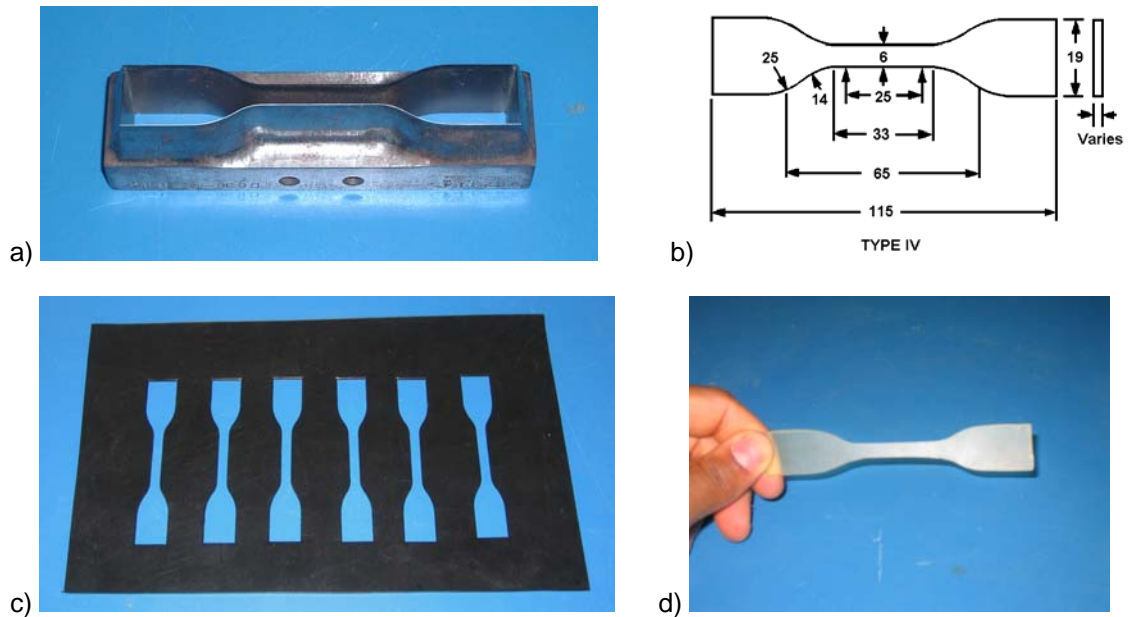


Figure 4. a) Type IV dumbbell cutting tool, b) Dimensions of the type IV dumbbell cutting tool, c) Mould made out of the GSE HD membrane, d) Resin Coupon

#### *Specimen Preparation of the In-house Fabricated Composite Liner*

As the liner is mainly loaded under internal pressure, it is crucial to understand its behavior in the circumferential direction and establish its tensile strength and modulus in this direction. Due to the tubular nature of the exhumed cured liner it is difficult to perform tensile tests in the circumferential direction. Therefore, it was decided that flat and straight coupons would be fabricated from the individual liner components in the circumferential direction. In order to establish confidence in the validity of this technique to represent the circumferential behavior, additional coupons representing the longitudinal direction were also fabricated using the same technique. These were then tested and their behaviour compared to the longitudinal characteristics of coupons cut from the exhumed liner.

A section of the pre-cured liner consisting of the inner and outer jackets was cut into flat sheets as shown in Figure 3a. Resin was injected in between the inner and outer jackets and a rolling pin was used to saturate them with resin. The wet system was then placed in between two sheets of GSE HD and cured at a temperature of 55°C for one hour. Weights were set on top of the GSE HD to imitate the pressure that is applied in the field by the hot water when curing the liner. The fabricated composite liner was then removed from the oven and let sit for a day. Rectangular coupons of the same dimensions as those of the exhumed liner coupons were cut in both the longitudinal and transverse (representing the circumferential) directions. To maintain consistency, GFRP gripping tabs were also fabricated on the ends of the coupons even though they did not possess any curvature. In total, seven and seven coupons were fabricated for the longitudinal and transverse directions, respectively.

### 3. EXPERIMENTAL SETUP AND INSTRUMENTATION

A Zwick/Roell material testing machine (MTM), shown in Figure 5a, was used to perform direct uniaxial tensile tests on all of the coupons.

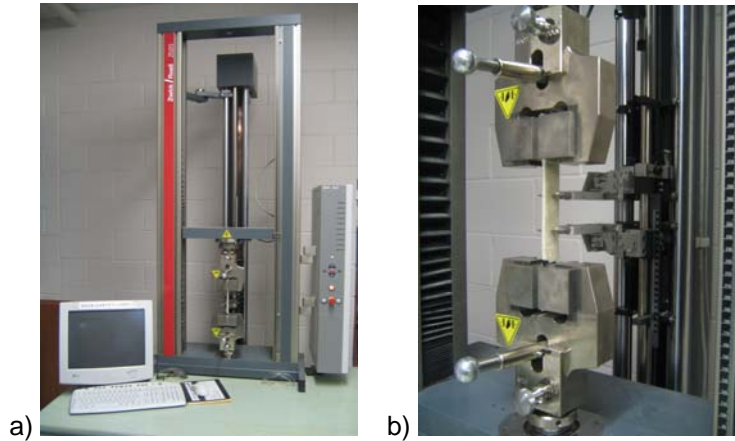


Figure 5. a) Zwick/Roell material testing machine, b) Close up of the built-in extensometer

The MTM is a tabletop test machine with a maximum test load of 20 kN. It is equipped with wedge grips and a longstroke extensometer, shown in Figure 5b, that is accurate up to 5  $\mu\text{m}$ . Although the extensometer has a robust construction and an impact resistant measuring system, its arms were unclamped from the coupons at specified loads prior to failure, except when testing the resin coupons because they did not fail violently. Two coupons of each type were tested without the extensometer to estimate the maximum load that each type of coupon would attain. The extensometer removal loads were then determined accordingly. This was done as a precautionary measure to avoid any damage to the extensometer during the tests. All tests were performed at  $23 \pm 1^\circ\text{C}$  (room temperature) and the rate of loading for each test was 5 mm/min.

### 4. RESULTS OF THE EXPERIMENTAL PROGRAM

The data and graphs presented in this section are based on averaged values of five tests for each type of coupon unless otherwise stated. Table 1 shows the loads at which the extensometer was unclamped from the different types of coupons. It also shows the average maximum load that each group of coupons attained.

Table 1. Extensometer removal loads and average maximum loads.

Coupon Type	Orientation	Extensometer Removal Load (N)	Average Maximum Load (N)	Standard Deviation (N)
<b>Exhumed liner</b>	Longitudinal	6000	7884	87
<b>Fabricated liner</b>	Longitudinal	6000	7627	322
	Circumferential	7750	10170	591
<b>Inner Jacket</b>	Longitudinal	3000	3956	177
	Circumferential	3000	4918	457
<b>Outer Jacket</b>	Longitudinal	2750	3182	197
	Longitudinal Strands	2750	3137	323
	Circumferential	2750	5176	281
<b>Resin</b>	Homogeneous	not removed	See Table 2	

For the graphs presented in this section, the behavior between the removal load of the extensometer and the average maximum load was extrapolated.

### *Behavior of the Individual Liner Components*

#### The Polymeric Resin

The effect of curing temperature on the stress-strain behavior of the resin was investigated by curing the resin at four different temperatures: 20°C, 40°C, 55°C and 70°C. Figure 6 shows the stress-strain curves of the resin at different curing temperatures.

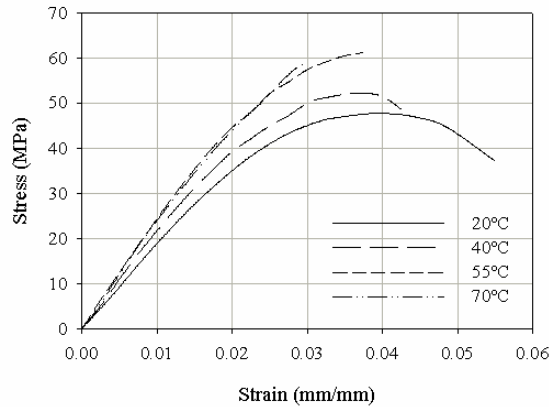


Figure 6. Stress-strain curves for the resin coupons at various curing temperatures.

Using the data from 0% to 2% strain, where the behavior is generally linear, the elastic modulus of each resin coupon was calculated. A mean modulus was then assessed at each curing temperature. Table 2 shows the mean tensile strength and modulus of the coupons at each curing temperature along with their respective standard deviations. Note that there are no values for the tensile strength of the coupons cured at 70°C because they all failed prematurely due to air bubbles; however, these tests all passed the yield point, so data for the tensile modulus was still available.

Table 2 - Effect of curing temperature on the tensile modulus and strength of the resin

Curing Temperature	Tensile Modulus (from 0% to 2% strain)		Tensile Strength	
	Mean (MPa)	Standard Deviation (MPa)	Mean (MPa)	Standard Deviation (MPa)
20°C	1832	162	47.5	0.6
40°C	2076	90	52.7	0.8
55°C	2356	133	60.8	0.6
70°C	2307	117	x	x

It was found that the strength and modulus of the cured resin increased with an increase in curing temperature but only up to a certain temperature (55°C). A 28% increase in the resin’s strength is seen from 20°C to 55°C. However, no increase in mechanical properties is observed beyond this temperature. More tests may need to be conducted at curing temperatures around 55°C to determine the exact temperature at which the strength and modulus of the cured resin cease to increase. These tests confirm that a minimum amount of heat is required to allow the cross-linking reaction to take place during the curing process. Small imperfections caused many of the coupons to fail prematurely before the ultimate tensile strength was reached. This occurred most frequently with coupons that were cured at the higher temperatures and when air bubbles existed. Multiple coupons were tested at each temperature until five were tested past the yield point. These provided the data that is presented.

## The Inner and Outer Jackets

Figures 7a and 7b show the load-strain behavior of the inner and outer woven fabric jackets respectively in the longitudinal and circumferential directions and Table 3 provides the mean values for tensile modulus and ultimate load along with standard deviations. The load is measured in Newton's per millimeter using the width of each specimen. Figures 7a and 7b only show the behavior up to the point of extensometer removal. Therefore, some data is missing especially in the case of the circumferential tests. Another difficulty arose with these coupons, since it was difficult to determine their width accurately. When these fabrics are not impregnated with resin, the coupon width can change as the amount of tension placed on each coupon is varied. This was less severe for the coupons cut from the inner jacket, since the non-structural polyurethane layer of the liner jacket helped to keep the fabric in place. The decision was made to measure the width of each coupon while it was in a relaxed state.

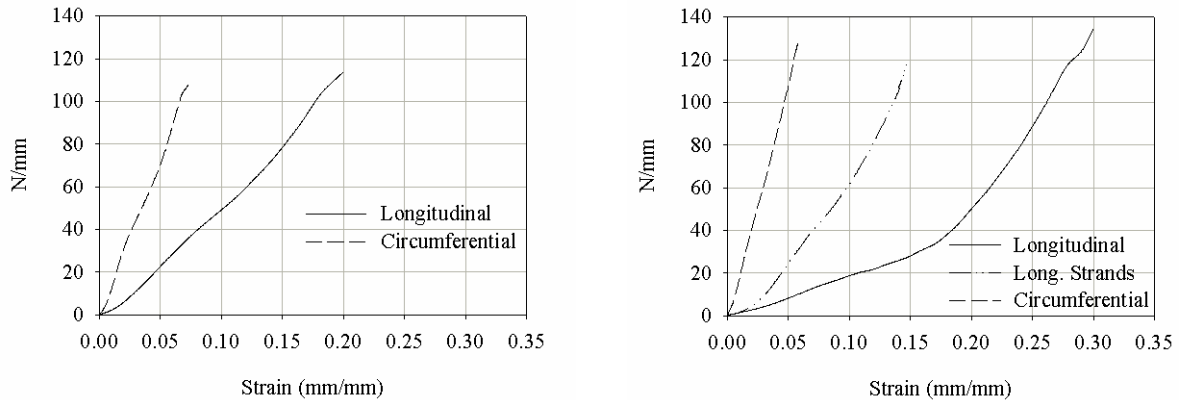


Figure 7. a) Load-strain behavior of the inner jacket, b) Load-strain behavior of the outer jacket.

Table 3 - Tensile modulus and ultimate load of the inner and outer jackets tested separately.

Coupon Type	Orientation	Tensile Modulus		Ultimate Load	
		Mean (N/mm)	Standard Deviation (N/mm)	Mean (N/mm)	Standard Deviation (N/mm)
Inner Jacket	Longitudinal	588	31	154	6
	Circumferential	1530	90	182	11
Outer Jacket	Longitudinal	194; 833	13; 28	161	9
	Longitudinal Strands	982	82	167	13
	Circumferential	2270	56	242	18

Figure 7a shows that the inner jacket behaves linearly in both the longitudinal and circumferential directions, with tensile moduli of approximately 588 N/mm and 1530 N/mm, respectively. The outer jacket behavior on the other hand is slightly different. Figure 7b shows that the coupons cut from the outer jacket in the longitudinal direction follow a bilinear strain hardening curve. The initial modulus is approximately 200 N/mm and the final modulus is approximately 830 N/mm. This effect is caused by the plain-weave of the polyester fibers within the outer jacket, which was not the case for the inner jacket. As the coupon elongates, the longitudinal strands straighten and the axial stiffness of the fabric stiffens. This stiffening is observed between 15% and 20% strain. The final modulus is relatively close in value to the modulus of the longitudinal coupons with the circumferential strands removed, also presented in Figure 7b, because with the circumferential strands removed the tests begin with the strands almost fully elongated. The modulus of the longitudinal strands alone is approximately 980 N/mm, which supports this interpretation. For both the inner and outer jackets, the tests performed in the circumferential direction show higher stiffness (1530 and 2270 N/mm, respectively) than that measured during the tests performed in the longitudinal direction.

## The Exhumed versus Fabricated Composite Liner

The coupons cut in the longitudinal direction from the composite liner fabricated in the laboratory produced very similar stress-strain curves to those cut from the exhumed liner. The data is plotted in Figure 8.

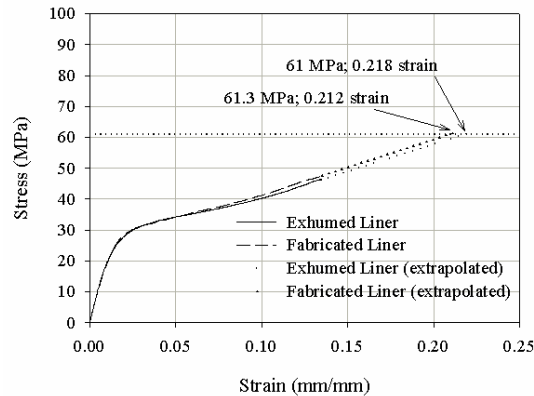


Figure 8. Stress-strain curves for the exhumed and fabricated liners in the longitudinal direction

At first glance, the curves appear to be somewhat bilinear. The liners behave linearly from 0% to 1% strain and again from 4% to 8% strain. However, they go through a stiffening phase at around 8% to 9% strain, after which their moduli remain linear until the extensometer is removed at a load of 6000 N, corresponding to 49 MPa stress. The average ultimate tensile strengths of the exhumed and fabricated liners in the longitudinal direction are 61 MPa and 61.3 MPa, respectively. Extrapolating the curves leads to a maximum strain of roughly 21% for both liners. Table 4 compares the two sets of data.

Table 4 - Comparison of the exhumed liner and the fabricated liner in the longitudinal direction

Liner Type	Modulus (between strain values)			Yield Strain	Yield Strength (0.2% offset)	Ultimate Tensile Strength
	0% to 1%	4% to 8%	9% to 13%			
	(MPa)	(MPa)	(MPa)			
<b>Exhumed</b>	2019	115	180	1.0	23.5	61
<b>Fabricated (longitudinal)</b>	2017	135	190	0.9	24	61.3

The similarity in behavior and strength of the longitudinal coupons prepared in the laboratory versus those exhumed from the field provide credibility to the technique developed to produce test coupons in the laboratory. As such, test results of the laboratory prepared coupons in the transverse direction can be considered well representative of the actual liner behavior in the circumferential direction. Figure 9 shows the average stress-strain curve of these coupons.

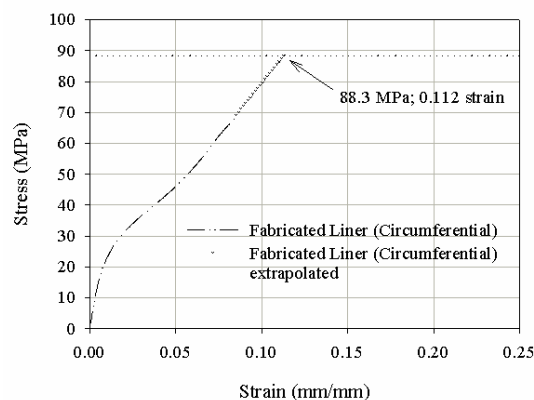


Figure 9. Stress-strain curve for the fabricated liner in the transverse (circumferential) direction

It is clear that the composite liner is much stiffer and stronger in the circumferential direction than the longitudinal direction. The yield strain is approximately half the value of that in the longitudinal direction, but yield strength is similar in both orientations. The ultimate tensile strength in the circumferential direction is approximately 45% higher than in the longitudinal direction. The maximum hoop strain, extrapolated from the curve, is approximately 11%. The overall behavior and shape of the stress-strain curve is similar to that of the longitudinal direction. As summarized in Table 5, the initial modulus is the highest (3.04 GPa), followed by a significant post yield reduction (0.48 GPa) and then a slight increase up to 0.72 GPa to the point where the extensometer is removed at 7750 N (corresponding to a stress of 67 MPa).

Table 5. Data for the fabricated liner in the circumferential direction

Liner Type	Mean Modulus (between strain values)			Yield Strain	Yield Strength (0.2% offset)	Ultimate Tensile Strength
	0% to 0.5%	2% to 5%	6% to 8%			
	(MPa)	(MPa)	(MPa)	%	(MPa)	(MPa)
<b>Fabricated (circumferential)</b>	3040	480	720	0.6	21.5	88.3

## 5. DISCUSSION

By examining the overall behavior of the composite liner, shown in Figures 8 and 9, in relation to the behavior of the individual components (i.e. the resin and inner and outer jackets), shown in Figures 6, 7a and 7b, respectively, the following key aspects of the behavior can be explained.

- Initially, the resin dominates the behavior and essentially contributes most of the stiffness of the system. The behavior eventually becomes nonlinear because of the shape of stress-strain curve of the resin.
- As the resin behavior becomes more nonlinear, load begins to transfer from the resin to the inner and outer jackets, until eventually the resin cracks at a strain of about 0.03 to 0.04. At this point the entire load is carried by the jackets.

The behavior continues to be linear in the second part of the curve but at the substantially reduced stiffness of the jackets. Very little strain hardening occurs. If discrete cracks occur in the resin, it appears that the resin subsequently provides only a small part of the overall stiffness through the intact sections between the cracks.

## 6. SUMMARY AND CONCLUSIONS

The mechanical characteristics of a novel liner material consisting of polyester fiber woven jackets saturated with polymeric resin have been studied. The study objective was to establish the full stress-strain curves of the composite liner in the circumferential and longitudinal directions. It was first necessary to establish the testing methodology and procedures for test specimen preparation, since no specific standard exists for testing this type of material.

Coupons were cut longitudinally from a composite liner exhumed from a pipe repaired in the field. Flat coupons were also fabricated in the laboratory using the individual components of the liner system. Longitudinal tests on these specimens showed excellent agreement between liner samples prepared in the laboratory, and those exhumed from the field. The same laboratory preparation technique was therefore used to establish the characteristics of flat liner specimens cut in the hoop direction; this would otherwise have been difficult since circumferential samples cut from exhumed liner would be curved.

The following conclusions are drawn:

1. The stress-strain behavior of the composite liner is generally bi-linear with a curved transition zone followed by strain hardening behavior. The initial modulus and ultimate tensile strength in the hoop direction are about 45% higher than those measured in the longitudinal direction.
2. The size, shape and end tab preparation techniques of the liner coupons used in this study, which are based on ASTM D3039/D3039M-00 for glass and carbon fiber reinforced polymer material, resulted in successful tests, and therefore appear suitable for this type of pipe liner composite .
3. Laboratory fabrication techniques have been established for assembling flat composite liner sections, from the individual components; these demonstrated behavior almost identical to that obtained from exhumed liners that were cured in the field.
4. The tensile strength of the liner in the hoop direction has been established and can be used in design to calculate the ultimate internal pressure of a circular axisymmetric liner using basic mechanics.
5. Resin curing temperature influenced both strength and stiffness, with higher temperatures leading to higher the strength and stiffness, however, beyond 55°C, the constitutive characteristics became stable.

Additional research is however needed to examine the following issues:

1. Wrinkles develop in the liner when its diameter is larger than that of the host pipe; the effect of these wrinkles on the liner behavior needs to be established.
2. Effect of rate of loading and cyclic loading on liner behavior needs to be studied.
3. Effect of sustained loading and the long term performance of the liner need investigation.

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