Testing of Innovative Pipe Renewal Liners for Renovation of Potable Water Distribution Pipelines

by

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Author's Declaration

This thesis consists of material all of which I co-authored: see Statement of Contributions included in the thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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

Statement of Contribution

Chapter 2 of this thesis consist of a paper that will be submitted for publication. The paper is co-authored by myself, Dr. Mark Knight, my supervisor, Dr. Rizwan Younis, a research associate, and Mr. Ahmed Abdel-aal, a MASc student. Dr. Mark Knight advised on data collection and research methodology, I developed the test methods and documented the findings. Mr. Ahmed Abdel-aal implemented the method using excel spreadsheets and assisted with about 30% of the first draft preparation. Dr. Rizwan Younis documented the field investigation activities and assisted with compilation of results for the study.

Chapter 3 of this thesis also consist of a paper that will be submitted for publication. The paper is co-authored by myself, my supervisor, Dr. Mark Knight, Dr. Rizwan Younis, and Mr. Ahmed Abdel-aal. Dr. Mark Knight and Dr. Rizwan Younis documented the research methodology, I carried out the lab experiments, collected and analyzed the experimental data, while Mr. Ahmed Abdel-aal assisted with about 20% of the writing. Dr. Mark Knight assisted with the synthesis of the main conclusions.

Finally, Chapter 4 of this thesis consist of a paper that will be submitted for publication. Most parts of this paper is written by me, with about 45% guidance from my supervisor, Dr. Mark Knight.

Abstract

Trenchless renovation has been in operation since the 1970's in North America and the United Kingdom. However, it has not been widely accepted due to cost-effectiveness concerns. In many Canadian cities faced with the problems of aging and deteriorating water distribution network, various polymer-based products such as Cured-in Place Pipe (CIPP) lining have been widely employed in structural water main rehabilitation applications. In contrast, only few technologies deal with non-structural and semi-structural lining systems, usually meant to serve as barrier coatings, and there are currently no documented test methodologies or protocols to properly test these lining products.

This thesis presents the results of a laboratory testing program designed to investigate the effectiveness of renewal of potable water mains via the use of polyurea and epoxy-polyurethane lining products in two separate locations in Ontario. The primary objectives for this research include: 1) evaluation of the two lining products, which are installed using new technologies, and 2) development of testing protocol to address construction Quality Assurance/Quality Control (QA/QC) concerns for the new lining technologies. Two trial sites are studied to gather field data related to the primary objectives described above. The sites are located on Albert Street, Waterloo, and at the 3M Oxford street facility, located in London, Canada. Innovative lining technologies for non-structural and semi-structural systems are demonstrated in field conditions and measured against defined sets of performance criteria. To this end, a series of experimental tests are carried out to assess pipe surface preparation, bond strength, thickness, material properties, chemical resistance, hole and gap spanning capabilities.

Results indicated that the non-structural liner with thickness value below 1 mm, can exhibit zero discontinuity/pinhole, have good adherence to host pipe up to 13.79 MPa, no pinholes and be chemically resistant. In addition, semi-structural liners require tensile and flexural strain values above 2% to prevent lining cracks. Finally, experimental results obtained have been used to document performance QA/QC requirements to provide utility decision makers with the information needed for field validation of new lining technologies.

Acknowledgements

I would like to thank my supervisor, Dr. Mark Knight, for his guidance throughout this research project. I had a remarkable experience working with him during these two years.

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This research would not have been possible without the help, co-operation and expertise of CATT's Technical director, Dr. Rizwan Younis. I am also grateful to Dr. Dami Adedapo for his kindly guidance at the start of this research, Ahmed Abdel-aal and Saad Ibrahim for their help in different aspects towards completing this project.

I would also like to thank Faculty and Staff for their help and support throughout my terms as a graduate student.

Finally, the support from my family was needed throughout my study. Thank you for believing in me and cheering me up while working on this research.

Dedication

To my adorable wife,

Demmy,

you propelled me to obtain this Master's degree

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Chapter 1
General Introduction

1.1 Background and Motivation

The underground drinking water infrastructure in many Canadian cities have been in service longer than their intended design life, with little to no maintenance resulting in a state of serious deterioration. The Canadian Infrastructure Report Card (CIRC) states that 29% of Canada's potable water infrastructure is in very poor, poor or fair condition. As the existing potable water and wastewater systems continue to age, potentially beyond their service life, the condition of the system components will continue to deteriorate. This increases the backlog, and therefore cost, for renewal and replacement of water systems (CIRC, 2016). These utility networks are mostly faced with problem of deteriorating water distribution network - pipe breaks, leakage, and/or aesthetic water quality problems due to tuberculation; scale buildup, flow capacity reduction, and water quality problems.

Water main pipelines are divided into transmission lines and distribution lines. Transmission lines bring water from the source to the distribution lines, which then distributes the water to the consumers. In comparison with sewers, it is difficult to rehabilitate the water main distribution system. This is because they are mostly smaller diameter pipes (less than 300 mm), flow full and are pressurized systems. Also, potable water supply cannot be interrupted, so temporary bypass has to be provided. However, this has potential water contamination issues.

Failure to address the renewal of aging infrastructure will result in a significant loss of service, which would threaten public health. For years, municipalities have resorted to the traditional open-cut pipe replacement method, which is considered cost effective and provides uninterrupted service to customers as the old main is kept in service until a new main is in place and ready for connection. However, open-cut methods cause considerable inconveniences to customers, businesses, residences, and traffic in the area.

As a result, over the past 15 to 20 years trenchless technologies have attracted the attention of the water industry as an alternative to open-cut methods. This in-situ trenchless water pipe cleaning and lining technologies promises an economically viable and environmentally friendly alternative to pipeline replacement. Different lining materials (i.e. epoxy, polyurea and polyurethane) can be applied to the interior of the host pipe to prevent these issues. These internal linings may be non-structural, semi-structural or fully structural, providing corrosion resistant barrier between the inner wall of the pipe and its content, inhibit further deterioration, and adds structural integrity to the host pipeline.

1.2 Problem Definition

The most common method for the rehabilitation of deteriorated water mains in use today is Cured-in Place Pipe (CIPP), which are used for fully structural applications (replacement pipe). This method has established design, installation, and testing standards.

There are innovative non-structural and semi-structural liners emerging in the market. These liners are capable of providing support to the operation of pipelines that are not due to be replaced, offering useful life extension for the host pipes as it is classified as partially deteriorated. However, there are no documented test methodologies or protocols to properly test these new lining products.

There also exist concerns about the success of a rehabilitation project, which largely depends on proper installation, inspection and assessment of activities in the field. The level of the qualification testing and Quality Assurance/Quality Control (QA/QC) requirements vary from technology to technology. Again, there is no clear industry quality standard in this case for non-structural and semi-structural liners. To properly understand and address these issues, a holistic study on these new liners is needed to evaluate pipes in water distribution networks.

1.3 General Research Objectives

The primary goal of this thesis is to investigate lining performance properties and verify design specifications for new internal pipe linings. This is accomplished by performing series of experiments on samples obtained from field demonstrations.

A QA/QC testing protocol is also developed, which does not only record the use of new lining technologies but provides a documented case study of the application.

The general objectives of this study are as follows:

1) To evaluate quality of pipe cleaning before lining;
2) To make sure lining products applied in the field are "as designed";
3) To assess the lining process, in the field, and carry out pertinent laboratory tests for various physical and mechanical characteristics of the liner; and
4) To develop a construction QA/QC testing program based on results from evaluation of field samples.

1.4 Thesis Organization

This thesis has been written in a "manuscript-based" style, arranged into five chapters, starting with a general introduction followed by the main body from Chapter 2 to 4 organized in an integrated article format. Then, the last chapter presents a general conclusion for the study.

Chapter 1: General Introduction – This chapter provides a background of the study, which is a review of the state of the art in trenchless pipe lining technology. This chapter also defines the problem intended to be solved and highlights the research objectives for all articles in this thesis.

Chapter 2: Manuscript 1 – The title of the first technical paper is "Evaluation of an Innovative Vacuum Applied Liner (VAL) for Water Main Rehabilitation". This paper states findings from a field study conducted to evaluate cleaning and lining process for sections of pipes, then lining product is tested to validate their performance requirements.

Chapter 3: Manuscript 2 – The title of the second technical paper is "Evaluation of Spray Applied Liner for Renovation of Potable Water Distribution Pipelines". This paper presents findings from a City of London pilot project. Results from tests carried out on some pipe samples are used to discuss physical and material properties of the lining product.

Chapter 4: Manuscript 3 – The title of the third technical paper is "Quality Assurance and Quality Control Protocol for Non-Structural and Semi-Structural Pipe Renewal Liners used for Water Mains". This paper provides a proper construction testing protocol that governs effective pipe lining and guides to follow during and after field installation of non-structural and semi-structural lining products.

Chapter 5: Conclusions and Recommendations for Future Work – This chapter provides a summary of findings, contributions to the state of knowledge and recommendations for future work.

Chapter 2

Evaluation of an Innovative Vacuum Applied Liner (VAL) for Water Main Rehabilitation

2.1 Overview

As many water utilities are seeking innovative rehabilitation technologies to extend the life of their water distribution systems, information on the capabilities and applicability of new technologies is not always readily available from an independent source. The purpose of the demonstration program is to evaluate a non-structural lining rehabilitation technology that have the potential to increase the effectiveness of the operation, maintenance, and renewal of aging water distribution and wastewater conveyance systems. This study provides an assessment of the effectiveness of a Vacuum Applied Liner (VAL) product conducted in the City of Waterloo. Following the completion of the in-field pilot study, field samples were obtained for laboratory analysis. Testing on the liners included: thickness, pull-off adhesion, pinholes, immersion, and blistering evaluation. Results from this study shows that 1) waterless pipe cleaning can provide an internal surface finish better than the generally accepted SSPC-SP6/NACE No. 3 minimum, 2) non-structural liner with thickness value below 1 mm, can exhibit chemical resistance, and have zero discontinuities/pinholes, and 3) with an average tensile pull-off strength values between 10.34 and 13.79 MPa, sufficient liner-host pipe bond is achieved to withstand peeling and blistering. Overall, a benchmark testing protocol is developed to quantify quality of a new vacuum-applied non-structural liner.

2.2 Introduction

Water main pipelines are divided into transmission lines and distribution lines. Transmission lines brings water from the source to the distribution lines, which then supplies water to the consumers. According to Knight (2017), most water main networks consist of 90% distribution pipes, which are typically 100mm to 300mm and 10% consist of transmission lines, which are typically 300mm to 600mm.

Based on the Canadian infrastructure report, municipalities serving 18.5 million Canadians, which represents 51.6% of the population of Canada reported that they own a total of 68,646 km of water main pipes (CIRC, 2016). However, many of these underground utility networks have been in service longer than their intended design life (50 to 100 years), with little to no maintenance resulting in a state of serious deterioration. In comparison with sewers, it is difficult to rehabilitate the water main distribution system. This is because they are mostly smaller diameter pipes (less than 300 mm), flow full, and are pressurized systems. Also, potable water supply cannot be interrupted, so temporary bypass is provided. However, this has potential water contamination issues.

The current replacement or installation rate is not impressive. For example, in North America, the current pace of replacement is less than 1 percent per year with very low installation of new pipes. Although, many pipes have been known to operate longer than their design life (50 to 100 years), the frequency of failures increases annually with age. This means that unless a more aggressive rehabilitation program is adopted, communities are going to be hit with substantially increasing repair costs in the future (USEPA, 2009). Traditionally, open-cut method has been employed in rehabilitating old distribution pipes, which causes environmental and social disruptions. However, in-situ trenchless water pipe cleaning and lining technologies promise an economically viable and environmentally friendly alternative.

A new trenchless rehabilitation techniques is Vacuum Applied Liner (VAL). The VAL process involves cleaning pipes with an airborne stream of abrasive grit, then the pipe is lined with a specially-formulated liquid lining product to provide a corrosion/abrasion barrier against further pipeline deterioration. This new lining process is an adaptation of the blown-epoxy methodology used in the plumbing industry, which has been comprehensively discussed in Cooper and Adedapo (2006).

A Canadian engineering company called Envirologics Engineering, Inc., is developing a novel approach to applying the VAL technology in distribution pipelines. In this process, the pipe is cleaned using a variety of abrasives (predominantly stone) in a high-volume air stream.

Then, a lining product is aerodynamically distributed around the entire pipe's internal surface. The system used to apply this approach has been patented under the name "Tomahawk™".

This study presents findings from a field study conducted to evaluate the liner installed using the Tomahawk™ system for pipe rehabilitation.

2.3 Novel Pipe Cleaning and Lining Approach

To evaluate potential of the Tomahawk™ system to serve as an effective rehabilitation method for water main pipeline, a case study is presented. This pilot project was conducted in July 2015 on Albert Street, Waterloo, Ontario. The pipe is cleaned using the new waterless Tomahawk cleaning technology, then cleaning effectiveness is verified. After cleaning, pipe wall assessment is conducted using Pipeline Inspection and Condition Analysis (PICA) I-Pit tool, to provide information about the remaining pipe wall. Finally, lined pipe sections are tested to quantify the performance of the lining product for construction.

2.4 Field Study

A pilot project was conducted on an abandoned 90 m long pipe section located on Albert Street in Waterloo, Ontario. This was a 150 mm diameter cast iron pipe. Figure 2.1 shows the two segments of abandoned pipe, which was divided into two sections having five access pits.

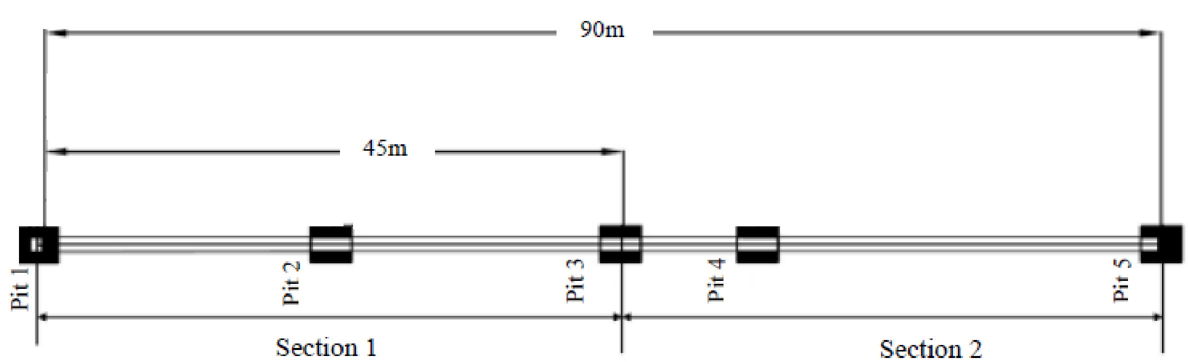


Figure 2.1: Test pipe divided into two sections.

Pipes were sampled from the five access pits. These samples were cut to 0.5 m lengths and quartered, then they were labeled with respect to their parent pipes and access pit. The assigned labels were of the form "Pit-End-Section-Quarter", as in "1A11" for pit 1, section A1, quarter 1 is from 12 to 3 o'clock. Following ASTM F2831, a minimum of six samples were prepared for each substrate type for benchmark testing (i.e. adhesion, liner thickness etc.).

2.4.1 Pipe Cleaning

A Tomahawk system truck and standard vacuum truck are attached on opposite sides of the inlet and outlet of the water pipe by quick-connect couplers. Abrasive materials (crushed Ontario stones) are loaded into the Tomahawk system truck through a hopper, which are then pulled through the pipe by the vacuum truck. As the abrasives travel through the pipe, the pipeline is cleared of any build-up, left completely dry, clean and ready to accept any kind of liner. Figure 2.2 shows the Tomahawk cleaning setup.

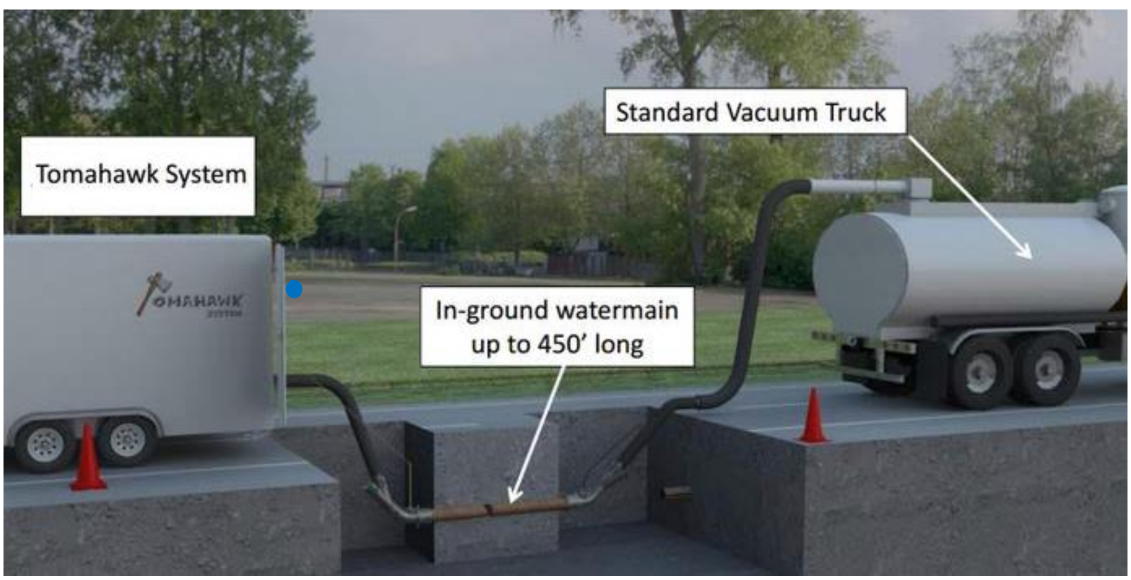


Figure 2.2: Diagram of Tomahawk Pipe Cleaning System. (Tomahawk, 2017)

The Tomahawk Scout™ performs concurrent cleaning, drying and inspection. It is an airstream driven device that has an integrated CCTV camera and an abrasive deflector to increase the effectiveness of the abrasive materials. After initial cleaning, the scout is deployed to allow target cleaning process along the pipe, at joints and around service connections. Also, the scout helps the cleaning process by drawing water and debris from joints, crevices and service connections. Figure 2.3 shows an image of the Tomahawk scout and how it assists pipe cleaning.

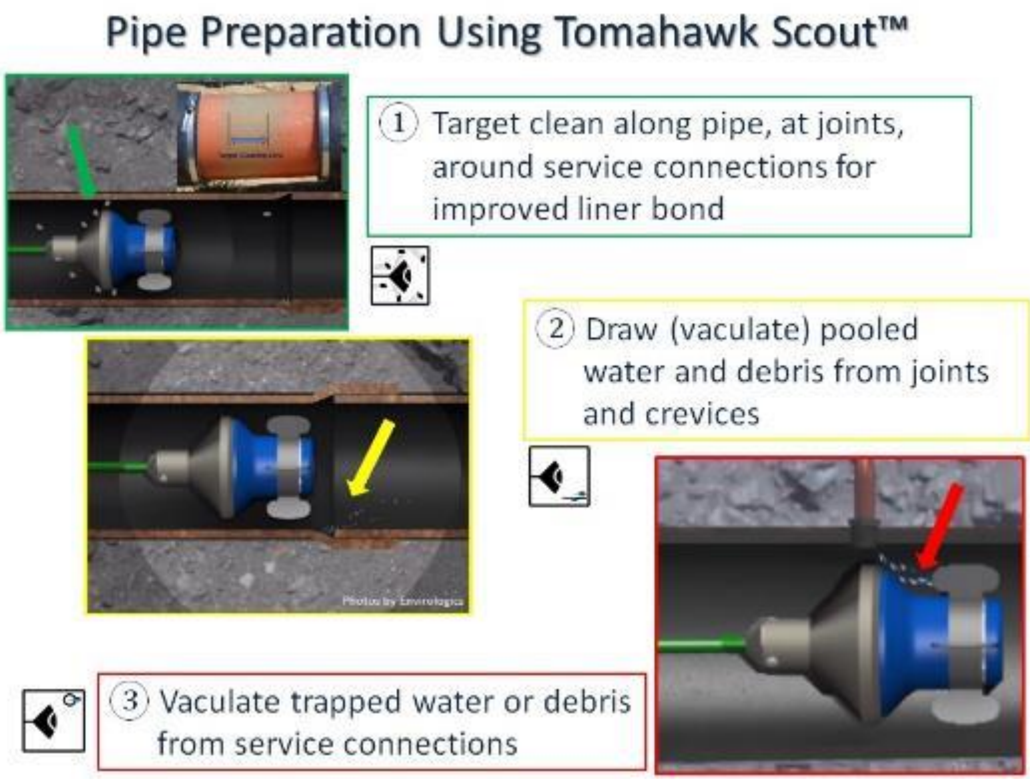
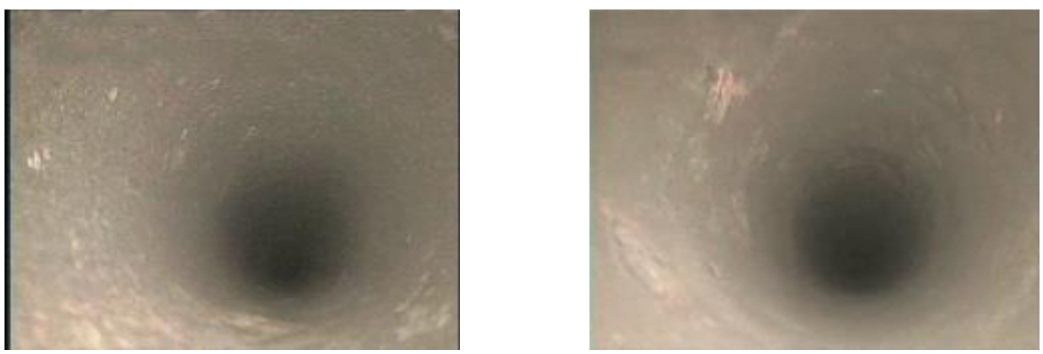


Figure 2.3: Image showing the Tomahawk Scout™ and its function for pipe cleaning. (Tomahawk, 2017)

Figure 2.4 shows the initial condition of the pipe before cleaning and how it looked after cleaning using the Tomahawk™ cleaning System. Unlike other cleaning methods, this is a waterless cleaning technology, which allows linings to be applied to a dry pipe. The resulting pipe surface finish is seen to surpass ASTM F2831 specified minimum requirement of SSPC-SP6/NACE. No. 3, as it is categorized to be near-white metal finish (SSPC-SP10/NACE. No. 2).

(a) Albert Street pipe before cleaning.



(b) Albert Street pipe after cleaning.

Figure 2.4: Test pipe on Albert Street before and after cleaning.

2.4.2 Pipe Wall Condition Assessment

After cleaning, pipe wall assessment was conducted using Pipeline Inspection and Condition Analysis (PICA) I-Pit tool. PICA provides direct condition assessment of the pipelines through the use of in-line inspection (ILI) tools. Accurate measurements of remaining wall thickness in cast-iron pipeline were made available as the current travelled through liners, scale and tubercles to detect graphitization, pitting, corrosion and cracks (PICA, 2016).

After lining, samples were exhumed from pit 1 and 2 for this assessment. Figure 2.5 below shows the results from the PICA test. For the samples taken from pit 1, none of them experienced high volumetric loss in pipe wall thickness. However, there were two instances of high volumetric loss in pit 2. Figure 2.6 shows the corresponding pipe samples where we can readily observe the high volumetric loss in pipe wall thickness.

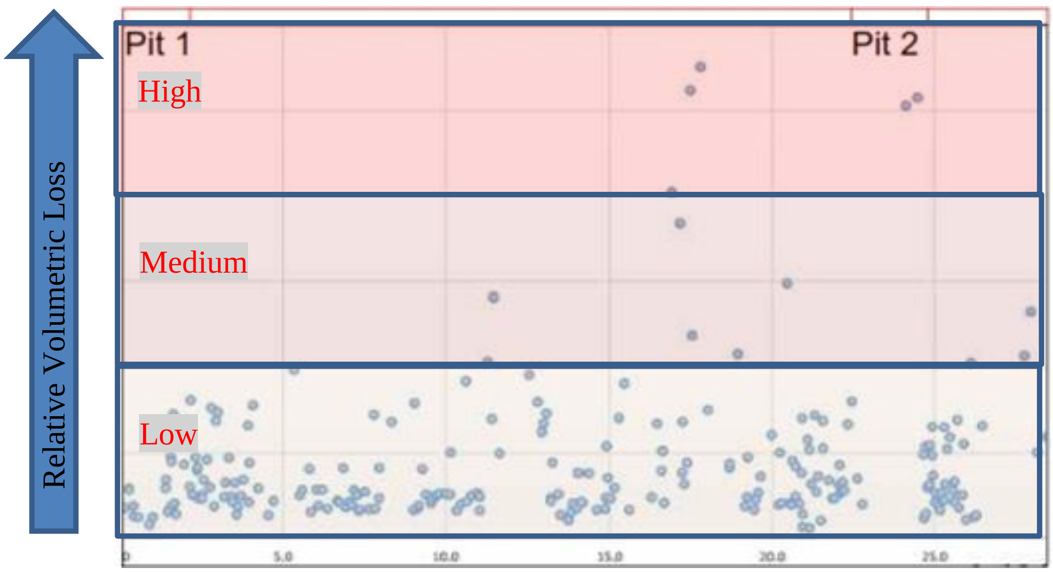
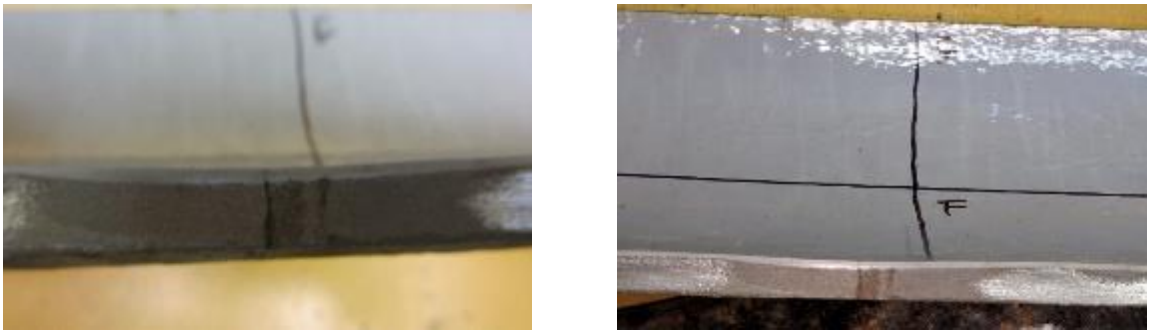
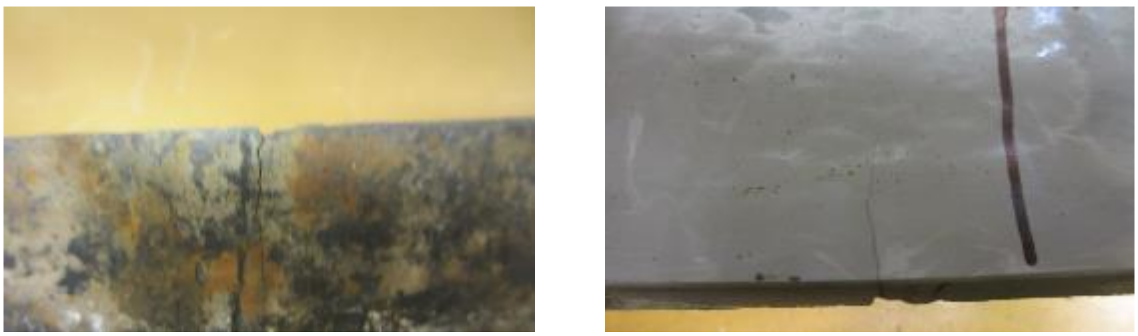


Figure 2.5: Pipe Wall Assessment using PICA I-Pit Tool.



(a) Pipe wall appearance for Pit 2 sample.



(b) Exterior and Interior appearance of Pit 2 sample.

Figure 2.6: Pit samples showing cracks due to high volumetric loss in pipe wall thickness.

2.4.3 Pipe Lining

Tomahawk pipe lining process includes the following elements: inserting a distributive body into the pipe section, adding liquid product to the airstream, and completely curing the lining product. For this case study, the lining material is a two component, high gloss, slow setting epoxy-polyurethane hybrid product named MG-120. As per Madison Chemical Industries Inc., MG-120 is used for infrastructural applications of all types (Madison, 2012). The initial set time for the MG-120 is 5 hours and the ultimate cure time is 7 days.

The MG-120 was mixed on site, then poured into the cleaned pipe. A spreading Distributive Body (DB) placed inside the pipe at the moment of the application of the lining product was pulled through the pipe to distribute the lining product around the pipe. The DB used for this pilot project has a front flex plate diameter of 12.2 cm and rear diameter of 12.7 cm. Linear travel speed of DB inbound and outbound is about 10.7 m/min. A winch controls the speed of the DB travel through the pipe. The DB travelled elevated, off the bottom of the pipe by about 8 mm, to allow air to flow around the full circumference of the DB, which helped substantially to improve lining consistency. Figure 2.7 shows an image of the DB used.

Figure 2.7: Distributive Body used for Albert Street Pilot Project.

During the lining of the pipe segment of Pit 4, heat was applied to decrease the curing time of the liner, however noticeable and undesirable blisters and bubbles were observed. Thus, heat was not applied to the rest of the pipe. Figure 2.8 below shows examples of the pipe at after lining using the Tomahawk™ lining System.

Figure 2.8: Albert Street pipe after Lining.

2.5 Benchmark Testing

Standard performance tests have been used to evaluate the lining, for both pilot field trials, the tests conducted are as follows:

2.5.1 Thickness Measurements

Liner thickness has been measured on selected panels and compared to the minimum thickness required by some relevant standards shown in Table 2.1. A Positector 6000 electronic magnetic gauge (see Figure 2.9) was used to take DFT readings along the length and across the circumference of the pipe sample, this was done to verify uniformity criterion throughout the entire pipe as differences in thickness can result in different permeability and strength of liner.

Figure 2.9: Thickness measurements using a Positector 6000 device.

Table 2.1: Different minimum thickness values presented by relevant standards.

Standard	Title	Min. value (mm)
ASTM F2831-12	Standard Practice for Internal Non Structural Epoxy Barrier Coating Material Used In Rehabilitation of Metallic Pressurized Piping Systems	0.2454
ASTM F3182-16	Standard Practice for the Application of Spray-Applied Polymeric Liners Inside Pipelines for Potable Water	1
AWWA C210	Liquid-Epoxy Coating Systems for the Interior and Exterior of Steel Water Pipelines	0.406
AWWA C222	Polyurethane Coatings for the Interior and Exterior of Steel Water Pipe and Fittings	0.5
SSPC-PA2	Industrial Coating and Lining Application Specialist Qualification and Certification	0.4064

Figure 2.10 and Table 2.2 below show that all the samples satisfied the minimum thickness requirements for ASTM F2831 except for a small section of Pit 4. The excepted section has a minimum thickness of 0.19 mm, which is below 0.2454 mm. None of the average thickness values for the samples satisfied the minimum required value of 1 mm specified by ASTM F3182.

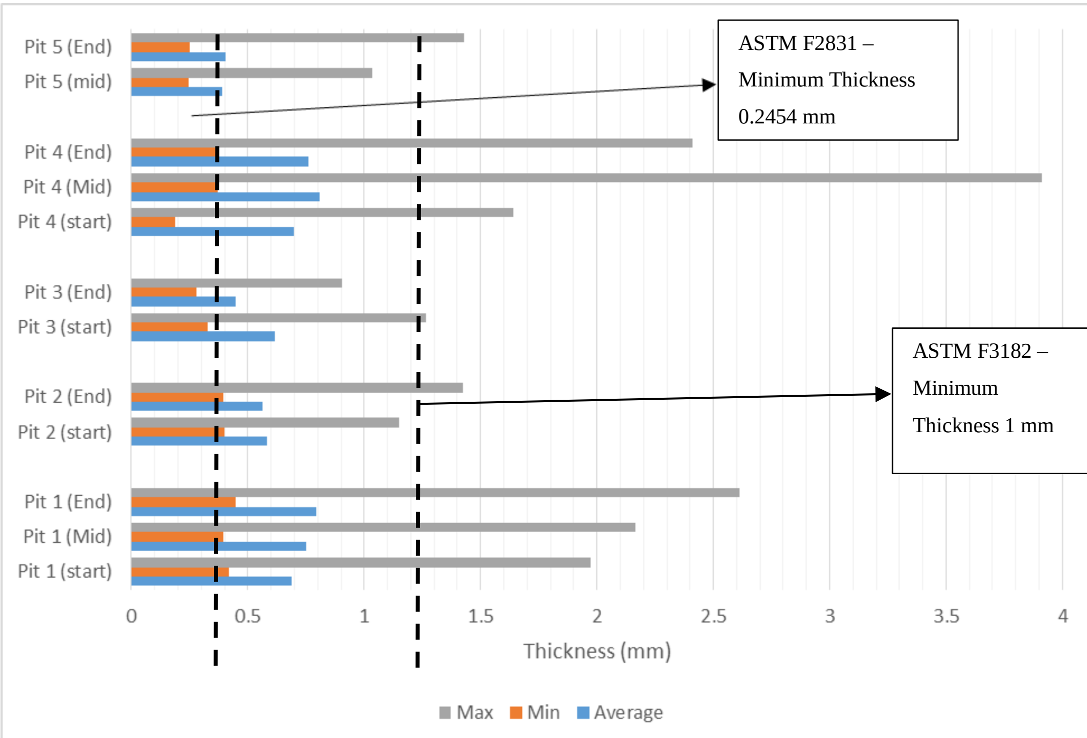


Figure 2.10: Longitudinal lining thickness for samples removed from all the five pits.

Table 2.2: Summary of thickness readings from all access pits

Pit Number	**Maximum (mm)**	**Minimum (mm)**	**Standard deviation**	**Average (mm)**	**ASTM F2831 minimum (mm)**	**ASTM F3182 minimum (mm)**
1	2.61	0.39	0.485	0.77	0.2454	1
2	1.42	0.39	0.211	0.58	0.2454	1
3	1.26	0.28	0.229	0.56	0.2454	1
4	3.91	0.19	0.442	0.76	0.2454	1
5	1.43	0.25	0.196	0.41	0.2454	1

The thickness measurements were also taken to observe the liner at the clock positions. This has been done in order to evaluate if the VAL was uniform throughout the pipe circumference. Figure 2.11 shows the observed thickness values at different clock positions on the pipe. For the MG-120 liner, thickness measurements shows that the maximum values occur at the 6 o'clock position (i.e. bottom of the pipe). Consequently, minimum thickness values are observed at the top section of the pipe. Hence, the lining product is seen to slump as the top sections are thinner. This is acceptable for non-structural application as long as the minimum thickness observed at the top can still serve as barrier coating to the host pipe.

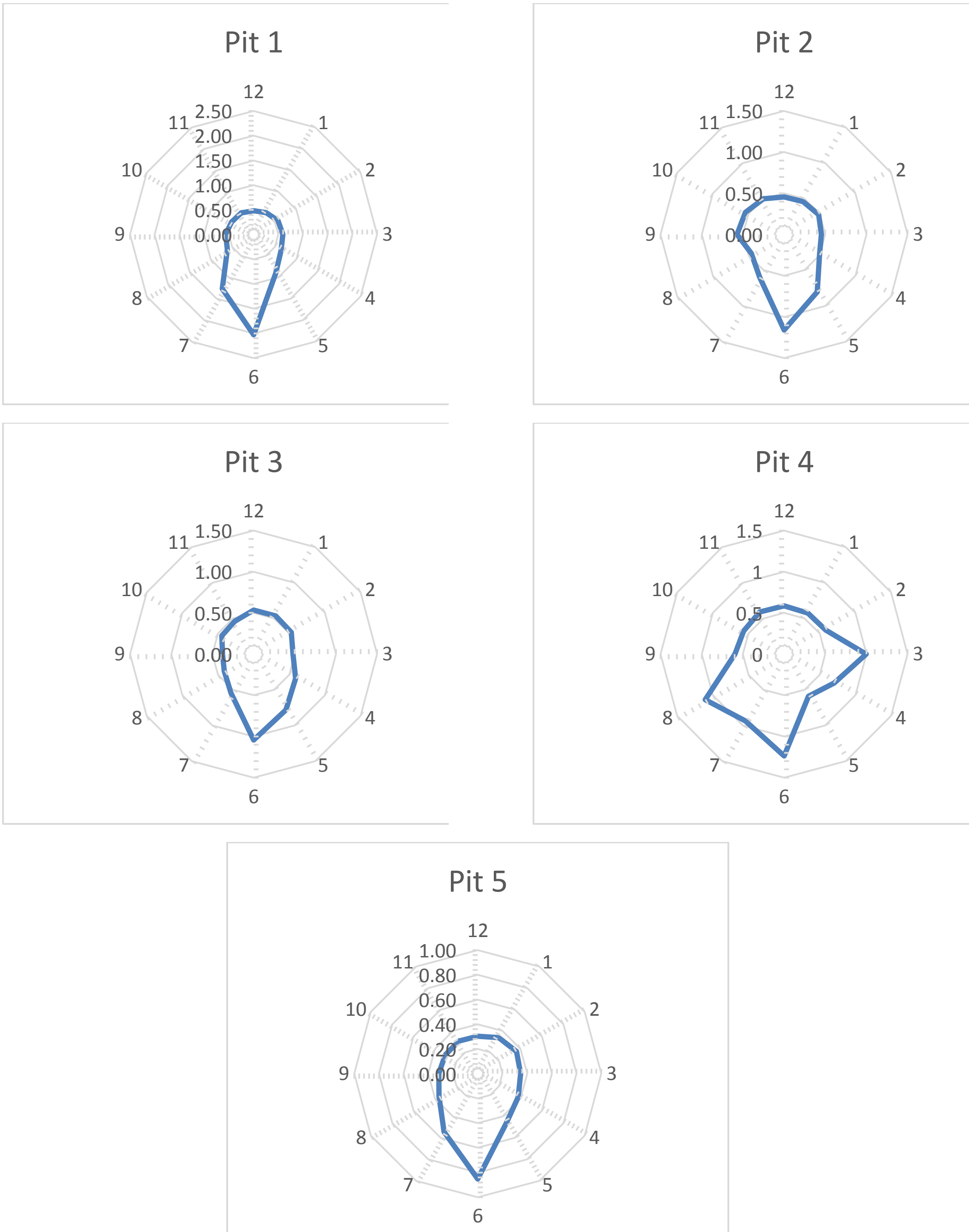


Figure 2.11: Circumferential lining thickness for samples removed from all the five pits.

2.5.2 Pull-Off Adhesion

One major factor that affect the longevity of linings is the degree of adhesion to the host pipe. This is particularly true for liners installed only to serve as internal corrosion barrier. The adhesion test evaluates the pull-off strength of a lining by determining the greatest tensile force that linings can bear before detaching from the substrate. Adhesion testing (tensile pull-off) is described in ASTM D4541, "Standard Method for Pull-Off Strength of Coatings using Portable Adhesion Testers" (ASTM D4541, 2009). A pull-off adhesion tester was used to test the VAL in this study. Adhesion tests results were then evaluated against the standards noted in Table 2.3

Table 2.3: Different standards for minimum pull-off values.

Standard	Title	Min. value (MPa)
ASTM F2831-12	Standard Practice for Internal Non Structural Epoxy Barrier Coating Material Used In Rehabilitation of Metallic Pressurized Piping Systems	17.32
ASTM F3182-16	Standard Practice for the Application of Spray-Applied Polymeric Liners Inside Pipelines for Potable Water	1.72
AWWA C210-13	Liquid-Epoxy Coating Systems for the Interior and Exterior of Steel Water Pipelines	5.52
AWWA C222-08	Polyurethane Coatings for the Interior and Exterior of Steel Water Pipe and Fittings	10.34

Aluminum loading fixtures called "dollies" were bonded to the lined surface by a 2-component epoxy adhesive glue, the lining was lightly sanded and wiped with solvent prior to application of the glue to aid the adhesion. The edges of the dolly were made discontinuous by cutting around it through to the substrate. This was done by using a tool supplied by the manufacturer of the pull-off adhesion tester.

A PosiTest AT Pull-Off Adhesion Tester is used to measure the force required to pull a specified test diameter of lining away from its substrate using hydraulic pressure applied on the dollies. Upon completion of the pull-off test, the dolly and coated surface is examined to determine the nature of fracture. If separation occurred within the liner layer or within substrate-liner interface, it is known as a cohesive fracture. However, when failure occurs at the glue-liner interface, this is known as glue failure. The pull-off strength at separation and the nature of the separation are reported. Figure 2.12 and Figure 2.13 illustrates the test procedures and failure modes seen on the dollies at the end of test. Low values of adhesion where the test was adversely affected by some imperfection in materials or experimental technique were considered outliers and eliminated.

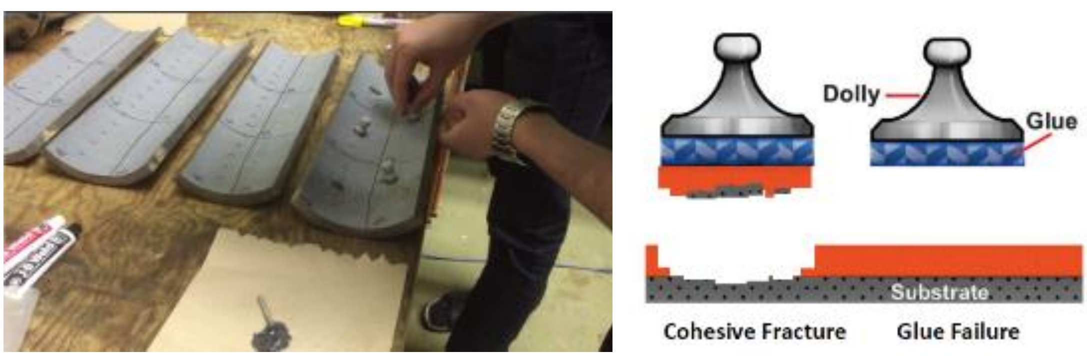


Figure 2.12: Application of dollies to liner surface and failure modes after the test.

Figure 2.13: Images showing cohesive fracture and glue failure.

The standard pull-off adhesion test method as presented by ASTM 4541 is not meant for curved surfaces but flat surface. Since the presence of curvature in the pipe samples can affect the recorded values, the smallest dolly size was used for this study. The average pull-off values are between 10.34 MPa and 13.79 MPa, which are lower than the required minimum of 17.32 MPa by ASTM F2831. However, as seen in Figure 2.14, all recorded pull-off values met the required minimum of 1.72 MPa based on ASTM F3182.

Another important point to consider is that pull-off adhesion is a technique that is subject to considerable deviation (Croll & Keil, 2014), so results must be treated with caution as seen in the large deviation in the results shown in Figure 2.14.

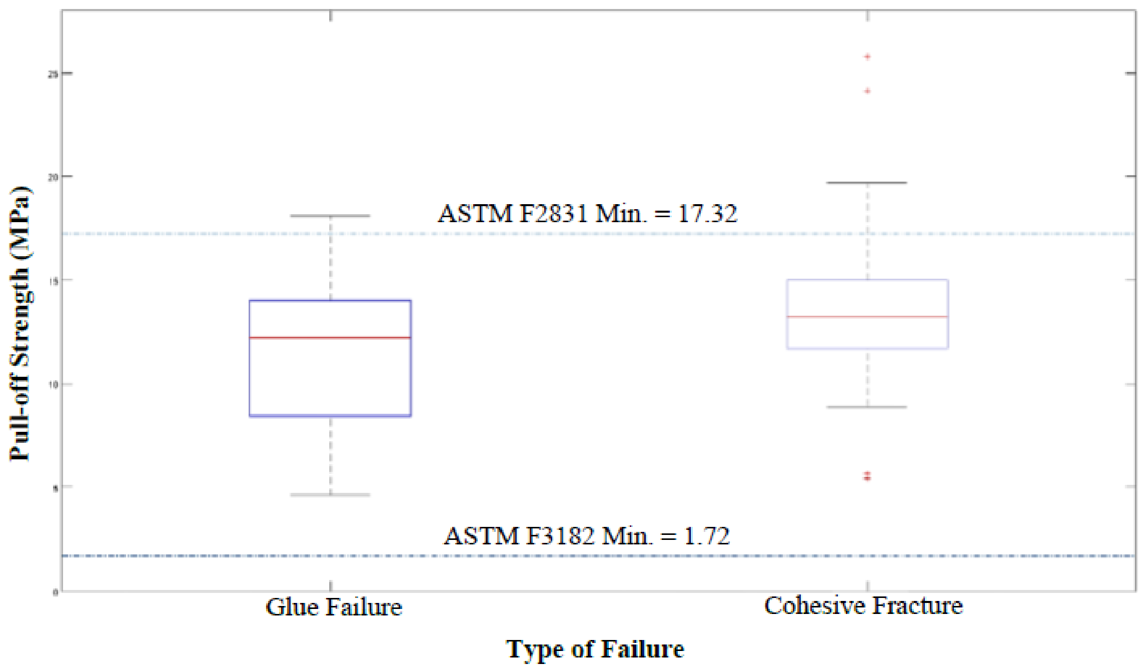


Figure 2.14: Adhesion results for samples from all sections.

2.5.3 Pinholes Detection

If there are holes in the liner, water can come in contact with the pipe and speed up rusting and corrosion. ASTM D5162: Standard Practice for Discontinuity (Holiday) Testing of Nonconductive Protective Coating on Metallic Substrates has been used to check for any existence of discontinuities in the liner.

Test Method A, using low voltage wet sponge, was used based on the liner thickness. This method is generally used to detect discontinuities in linings having a total thickness of 0.5 mm (20 mil) or less. Test Method B has the capability to detect pinholes in thicker liners. However, high voltage is required for the test and this would be destructive thereby damaging the lining.

Low voltage Model M/1 wet sponge holiday detector device from Tinker and Rasor has been used to sweep over the surface of the lined pipe. An audible signal or beep is emitted when any pinhole is found. Figure 2.15 shows the holiday testing using low voltage wet sponge tester. Although, the test method for pinholes detection requires no pinholes to be observed in the cured liner, a study conducted on epoxy coatings in 2006 specified that a sample fails holiday test if it has more than 200 pinholes/m^2 (Deb, Snyder, Hammel Jr, & Tyler, 2006).

No pinholes were detected in the tested samples except for one with about 2 pinholes/m^2. These pinholes were due to the application of heat during the lining process to possibly speed up the setting time of the lining product. However, this turned out to be detrimental to the liner.

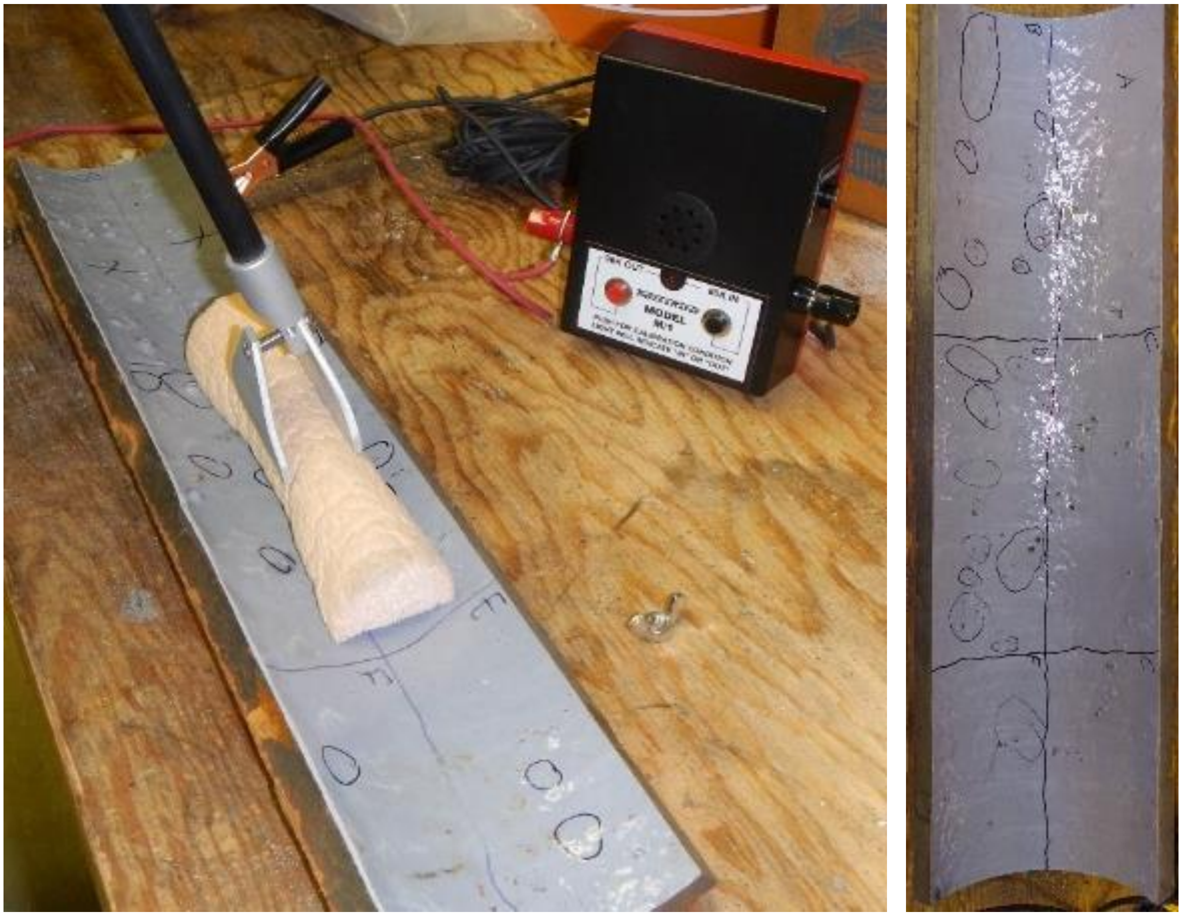


Figure 2.15: Testing of the only sample with pinholes from section 1.

2.5.4 Immersion Test

AWWA C210 specifies test panels (50mm x 150mm x 3.2mm) to be immersed in deionized water, weak acid, and weak base. The sample should be kept at 25ºC for 30 days. The uncoated side was sealed with resistant materials, and then the samples (from top and bottom sections) were placed in containers and immersed for over 30 days. The samples were taken out, left to dry for 24 hours, then examined for presence of peels or liner disbondment. Figure 2.16 shows the samples after they were removed from the water and left to dry for 24 hours. At the end of this test, no peels or any liner disbondment was noticed.

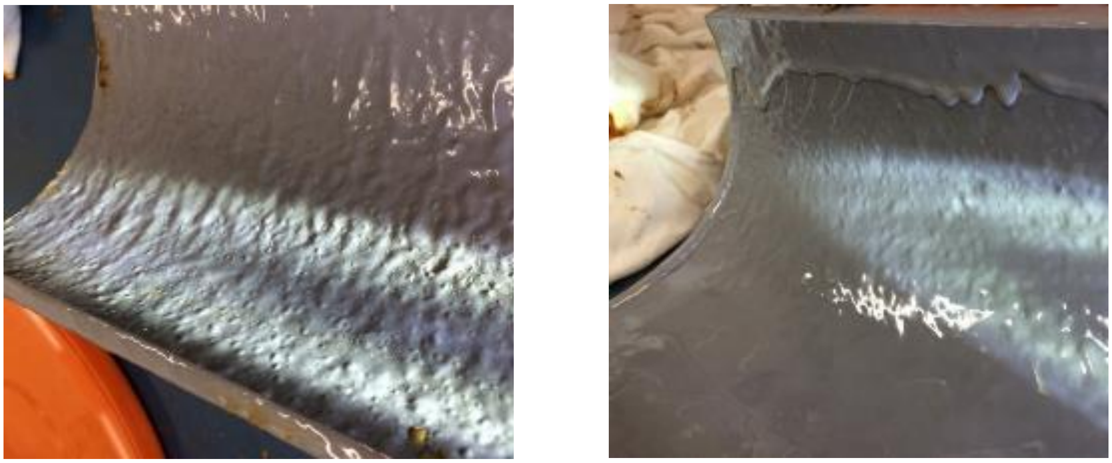


Figure 2.16: Images of top and bottom of pipe sample after immersion testing.

2.5.5 Blistering Evaluation

The immersion tested samples were evaluated for blisters and peels. This test is based on visual inspection, so the size and density of the blisters in the pictorial standard available in ASTM D714-02 was used to rate the liner performance.

Figure 2.17 below shows the relevant pictorial representations equivalent to the level of blistering in both top and bottom sections of pipe. The top appeared to be medium dense blister size eight, while the bottom section corresponds to medium blister size eight.

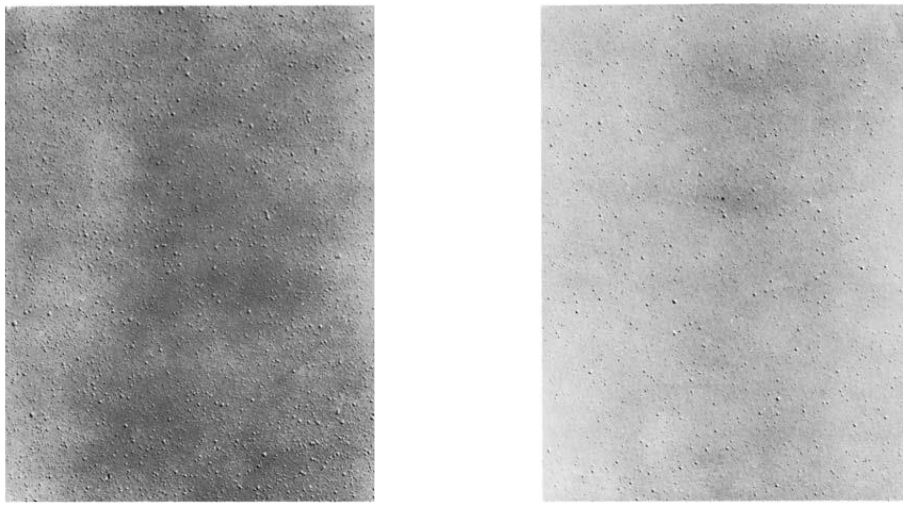


Figure 2.17: Images of relevant pictorial representations for the evaluation of blistering in top (Medium Dense blister size 8) and bottom (medium blister size 8) of Pipe sample after immersion in water.

2.6 Discussion

The Tomahawk cleaning technology used for preparation of pipe interior prior to lining was found to be effective enough to remove all tubercles, graphite and biofilms. Furthermore, the VAL bonded well to host pipe, which can be attributed to the absence of water and effective surface preparation that aids liner bond. The development and implementation of the application of VAL will be serve as useful documentation for pre-installation activities, liner installation and benchmark testing.

The new VAL has the potential to provide efficient rehabilitation for the interior surfaces of partially deteriorated water mains and extend pipe life. However, further development on lining product is required to ensure the lining product exhibit faster curing time and uniform thickness distribution.

Benchmark tests conducted for construction QA/QC requirements will help new technology developers determine key considerations for both cleaning and lining process.

2.7 Conclusions

Based on the field and laboratory evaluation of the Vacuum Applied Liner, the following conclusions are drawn:

1) The novel Tomahawk system, which is a waterless-based abrasive pipe cleaning method, cleaned the pipes to a near-white metal finish (SSPC-SP10/NACE. No. 2). This is because of the ability of the dry abrasives to remove all tuberculation and graphite.
2) Sections in the test sites having a PICA tool rating of “High”, were verified as the samples experienced cracks. This may due to graphitization, causing reduction in strength of the substrate.
3) The average thickness of the cured liner are between 0.41 mm and 0.77 mm. Due to slump in the applied lining product, the liner experienced higher values around the bottom than the top sections. However, the average thickness values still met the ASTM F2831 minimum required value of 0.2454 mm.
4) With an initial set time of 5 hours and ultimate cure time of 7 days, the lining material has limited ability to function as fast-setting lining products. Since the application of heat caused unacceptable blisters on the liner, possible improvements need to be made on the material properties to get the lining to cure faster.
5) The average adhesion pull-off strength values for the tested sections varied between 10.34 MPa and 13.79 MPa. These values are greater than the minimum required value of 1.72 MPa as per ASTM F3182. However, only the maximum values met the ASTM F2831 minimum value of 17.32 MPa. Since glue failures were observed to make up a major part of the testing, a stronger glue is needed to reduce the variability inherent in the adhesion testing methodology.

6) There were no pinholes detected in the cured lining, except in Section 1. The cause for these holidays or pinholes was due to the application of heat to possibly speed-up the curing process.

Chapter 3

Evaluation of an Innovative Spray Applied Liner for Renovation of Potable Water Distribution Pipelines

3.1 Overview

Renewal technologies being used for the repair and rehabilitation of deteriorating potable water distribution systems are generally effective, but there is still considerable room for the development of new technologies. To extend the life of water distribution systems that are only partially deteriorated, semi-structural spray applied liner can be used. This study presents the results from a field study program conducted in the City of London, Ontario. The purpose of this testing program is to (1) gather reliable performance data during the application of an innovative lining technology in the field, and (2) to develop test plan to validate minimum thickness value and material properties specified by the manufacturer of this new spray-on lining technology. First, the field demonstration compares three different cleaning methods, then a fast-setting polyurea lining product is evaluated. Then, benchmark tests are conducted on three identical test spools incorporated into random spots of an abandoned 150 mm diameter pipe section to quantify post-cleaning and post-lining conditions. Results show that the section cleaned without using water has superior pipe surface preparation. Also, average thickness values for all tested sections met the specified design value of 5.2 mm. However, there were visible gaps between the liner and host pipe before testing began, so early cracks were noticed in two sections during visual inspection. In conclusion, tests performed for this study found relatively low resistance to crack growth due to low tensile and flexural strain values below 2% for the tested lining product, therefore further work is proposed for the development of the innovative renewal lining technology for potable water distribution pipelines.

3.2 Introduction

The performance of water mains diminishes gradually as they become old, resulting in high maintenance costs, bad water quality and loss of hydraulic capacity. Although, the dig and replacement method has been employed in rehabilitating old distribution pipes, in-situ trenchless water pipe cleaning and lining technologies provide an economically viable and environmentally friendly alternative.

In North America, portland cement mortar lining is the conventional choice to renovate unlined cast iron pipe for mains with diameter greater than 100 mm. However, studies and field experience have shown that, in soft waters, the lining may corrode and adversely affect water quality for a sustained period as it deteriorates (WRc, 1997). Polyurethane and polyurea are gaining attention as water pipe lining material, particularly in the United Kingdom, where they are quickly supplanting both epoxy and cement mortar. The primary advantage of polyurea product is its rapid cure time, which enables same day return-to-service for rehabilitated water mains, thus avoiding the need for bypass piping systems (Rockaway & Ball, 2007).

According to American Waterworks Works Association (AWWA), water main lining renovation methods in North America are classified into three structural categories and four classes (AWWA, 2014):

- Class I Linings: These are non-structural systems, such as traditional Cement Mortar Lining (CML) and epoxy. The lining is applied to increase the service life by protecting the inner surface of the pipe from corrosion. However, it does not increase the structural integrity of the pipe and does not substantially reduce leakage. Non-structural lining is the most economical option whenever the host pipe is still considered structurally sound.

- Class II Linings: These are close-fitting semi-structural linings that can span holes and gaps in the host pipe, but have minimal thickness and require support from the host pipe to prevent collapse during depressurization.

- Class III Linings: These are similar to Class II linings, except they have sufficient thickness to resist buckling from external hydrostatic load or vacuum.

- Class IV Linings: These are fully structural linings, which involves placing a self-supporting, watertight structure inside a pipe. Fully structural linings are typically used in situations requiring minimum disruption to repair structurally unsatisfactory pipe where loss of flow capacity is acceptable. The resultant lining is capable of sustaining the maximum allowable operating pressure of the pipe section being renovated.

AWWA Class I and Class II Type Liners have no inherent ring stiffness, and thus rely on adhesion to the host pipe. Hence, the pipe wall must be properly cleaned and dried to ensure liner adhesion for these lining systems.

3.3 Cleaning and Lining Technologies

Current pipe cleaning technologies consist of flushing, air scouring, pigging, swabbing, hydro jetting, drag scraping, and rack-feed boring (Ellison, 2003). All these pipe cleaning methods use large quantities of water to assist with the cleaning process and are deemed to have limited ability to remove all pipe corrosion products, biofilms and are ineffective at removing internal coatings such as asphalt or coal tar bitumen. These limitations negatively affect the liner bond with the host pipe wall. However, the Tomahawk™ cleaning system dry-cleans pipes, thereby removing tuberculation, biofilms and old tar-based liners present in potable water pipes (Kezdi, 2016).

Cured In-Place Pipe (CIPP), Cement Mortar Lining (CML), Spray-In Place Pipe (SIPP), pipe bursting, slip lining and cathodic protection are examples of current water main rehabilitation techniques (AWWA, 2014). Of all these techniques, CIPP lining technology has been the most used.

3M Canada is currently developing a novel approach to applying SIPP to potable water distribution pipelines. In this process, pipe is cleaned, then the lining product is applied. This study presents the findings from the field study conducted to evaluate the new 3M™ Scotchkote™ pipe renewal liner.

3.4 Field Study

Field validation was carried out on 3M Canada Oxford Street facility located at the City of London, Ontario. A 150 mm diameter, 230 m long, cast iron fire-main was identified as the potential candidate for the field demonstration. The pipe was divided into three sections having some access pits: Section 1 (Pit 1 to Pit 3); Section 2 (Pit 3 to Pit 5); and Section 3 (Pit 5 to Pit 7). Figure 3.1 shows the three pipe sections and access pit locations. Three pipe cleaning methods namely: Tomahawk™ cleaning, ID-TEC SR-Series high pressure water jetting and Rack-feed bore were used to clean Sections 1, 2 and 3, respectively.

Pipe is cleaned out using the three cleaning technologies, cleaning effectiveness is quantified based on time and surface finish. Thereafter, visual inspection is performed after the lining is complete. Finally, lined pipe sections are tested to quantify the performance of the lining product for construction. Benchmark testing and material properties testing are conducted to evaluate liner performance compared to both minimum required values and manufacturer specified values.

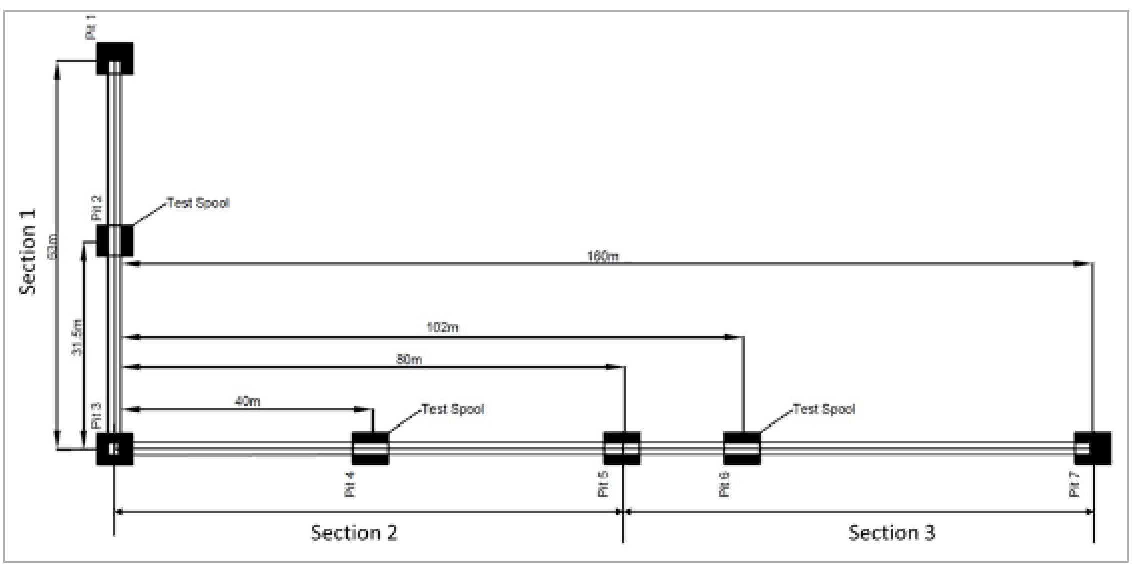


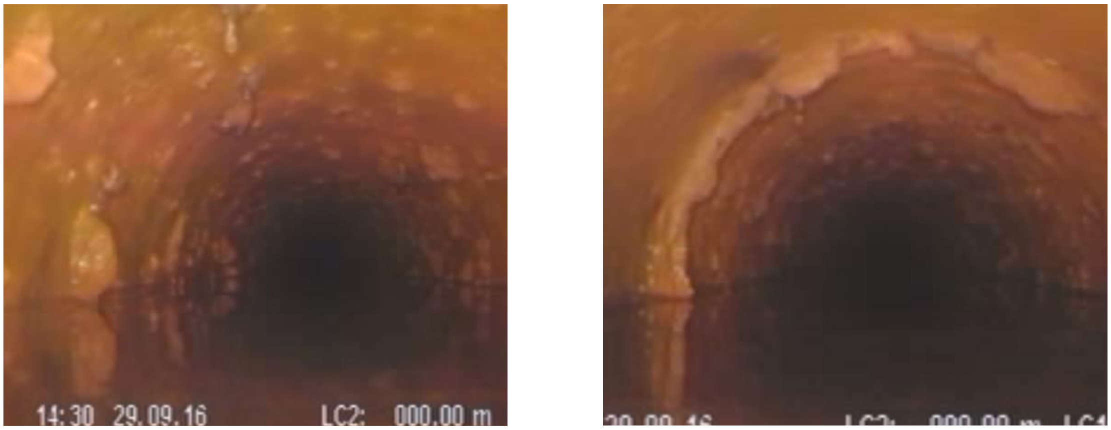
Figure 3.1: Pipe divided into three sections: Section 1, 2 and 3.

3.5 Preliminary work

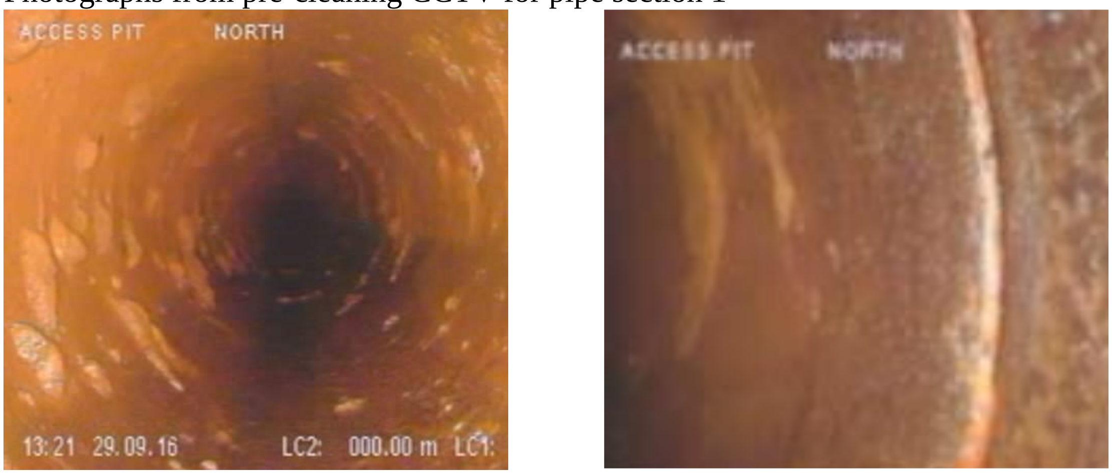
3.5.1 CCTV Pre-Inspection

About two weeks before the scheduled lining project, a pipe section was exhumed to ascertain pipe material, diameter and internal condition. This pipe sample was used to properly size the connections, fittings, couplings and tees for pipe spools.

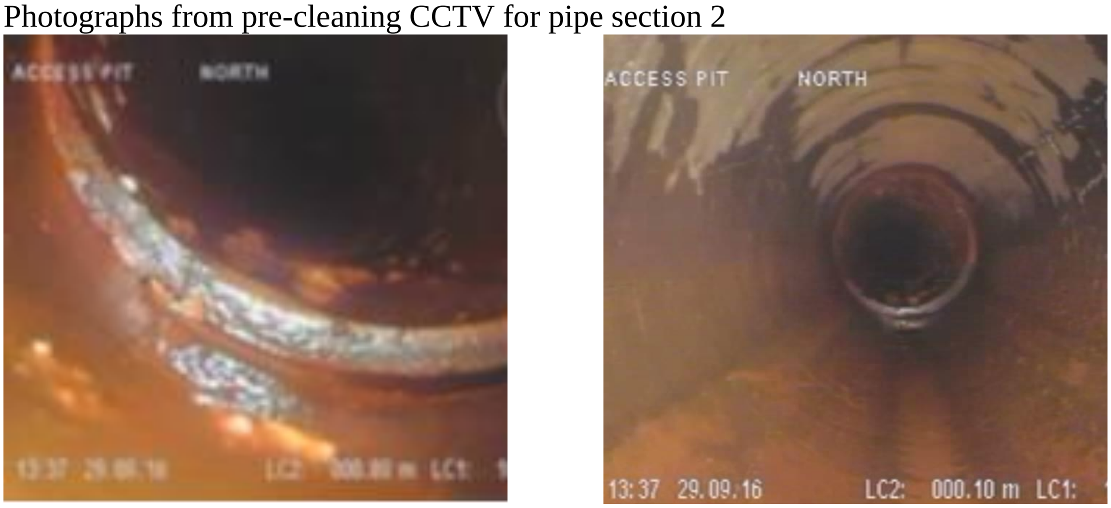
Figure 3.2 shows the photos from pre-cleaning video inspections. The existing pipe had both lined (cement mortar) and unlined sections. Some encrustation and open joints were visible. Excavations of pits, and installation of pipe spools (for test purpose) were carried out prior to pipe cleaning, inspection and lining activities.



a) Photographs from pre-cleaning CCTV for pipe section 1



b) Photographs from pre-cleaning CCTV for pipe section 2



c) Photographs from pre-cleaning CCTV for pipe section 3

Figure 3.2: Photographs from pre-cleaning CCTV for all three pipe sections.

3.5.2 Manufacturing and Installation of Test Spools

Three pre-fabricated test spools with service connections, saddle connections, tees, and couplings were installed at specific locations in Pits 2, 4, and 6. Figure 3.3 shows the spool and how it was being installed with the three sections on site.

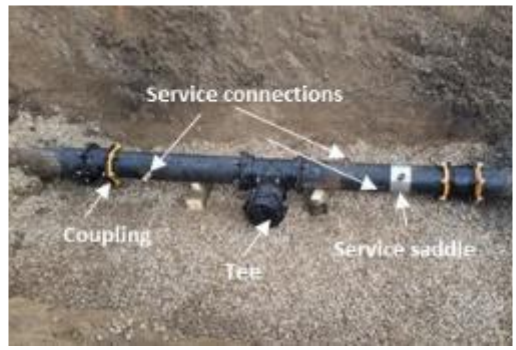


Figure 3.3: Installation of pipe spools with connections, tees and couplings.

3.5.3 Pipe Cleaning

Pipe surface preparation was done to clean out the three sections. Sections 1, 2, and 3, were cleaned using Tomahawk System, ID-TEC SR-Series high pressure water jetting, and rack-feed boring methods respectively.

The Tomahawk system is a new cleaning methodology that uses vacuum that creates high volume, low pressure air stream to draw crushed stones through the pipe. The stones become airborne as they travel through the pipe, and clean the pipe by dislodging and removing encrustation, scale and other debris. Figure 3.4 illustrates the process for the Tomahawk cleaning system.

ID-TEC SR-Series water jetting tool uses high pressure water jet for cleaning pipelines. ID-TEC SR-Series used water jet at 50 MPa (7,250 psi) with flow of approximately 20 litres per minute (5 gpm) to clean Section 2. Figure 3.5 shows the process for the water jet cleaning.

Rack-feed power boring is a mechanical pipe cleaning technique that uses spinning steel arms to remove tuberculation, encrustation and scale from the pipe wall. The process is illustrated in Figure 3.6.

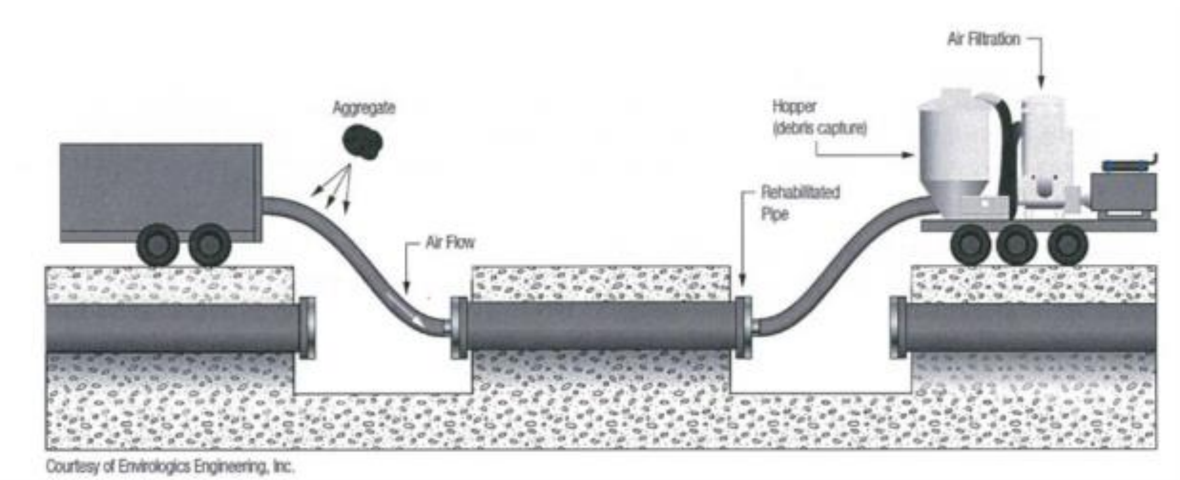


Figure 3.4: Tomahawk pipe cleaning system. (Tomahawk, 2017)

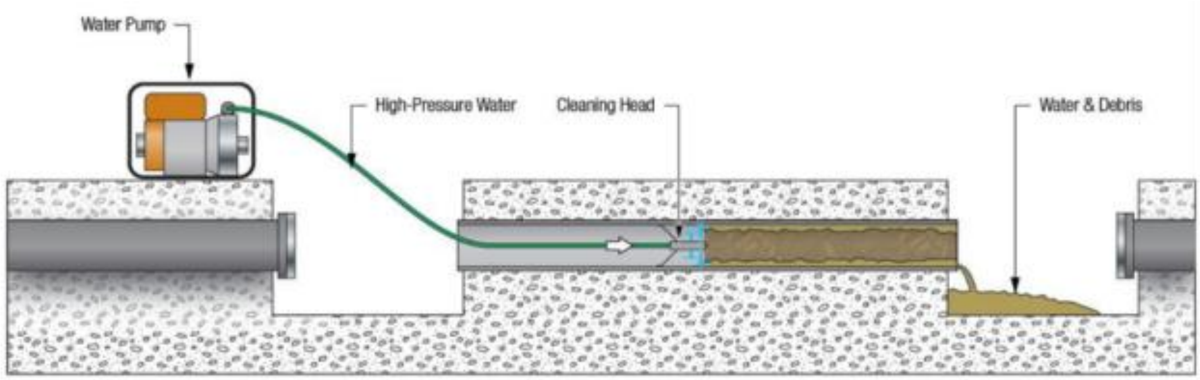


Figure 3.5: ID-TEC SR-Series water jetting tool. (Thorogood, 2015)

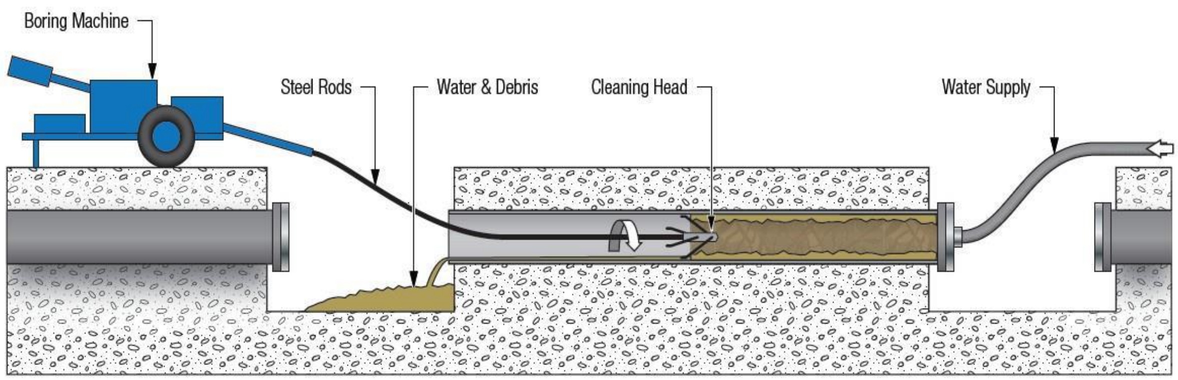


Figure 3.6: Rack feed power boring rig. (Thorogood, 2015)

Table 3.1 shows the time to complete the cleaning for Sections 1, 2 and 3. Tomahawk, ID-TEC and rack-feed boring took 115, 257 and 140 minutes respectively, to clean the three pipe sections.

Table 3.1: Time taken to complete pipe cleaning for Sections 1, 2 and 3.

Technology	Activity	Date	Elapsed Time (h:mm)	Total Time (h:mm)
Tomahawk (Section 1 – 63m)	Cleaning	27-10-2016	1:55	1:55
ID-TEC High Pressure Water Jetting (Section 2 – 80m)	Cleaning	27-10-2016	1:45	4:17
	Cleaning	28-10-2016	0:48	
	Swabbing	29-10-2016	1:44	
Rack-feed Boring (Section 3 – 80m)	Cleaning	27-10-2016	1:15	2:20
	Swabbing	28-10-2016	0:40	
	Swabbing	28-10-2016	0:25	

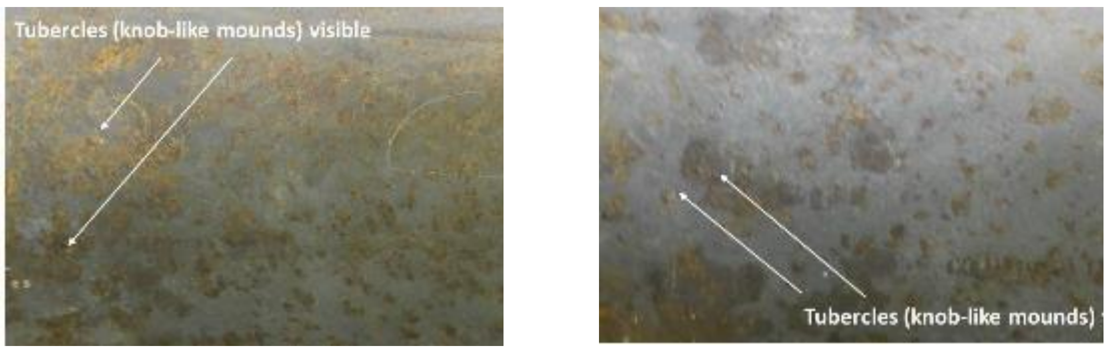
Tomahawk system proved to be the most effective method as there was no encrustation, tuberculation, or scale/debris observed in the cleaned pipe. The traditional rack-feed boring method removed some tubercles, but there were visible residues left on the pipe surface. The ID-TEC SR-Series high pressure water jetting was the least effective as tubercles and rust were visible on the pipe surface after cleaning. Figure 3.7 shows the difference in pipe cleaning and preparation levels for the three techniques.

ID-TEC SR-Series and Rack-feed boring methods use water to clean pipes. However, this leaves the pipe in a wet state. Although the pipe is dried using swabbing, this substantially increases the overall cleaning time.

Figure 3.7 clearly shows that the Tomahawk System removed all encrustation, tuberculation, and scale on the pipe wall. It also left the pipe with the roughest surface profile, indicating it removed more internal pipe corrosion products. Rack-feed boring was deemed the second best, but had encrustation residues and traces of rust. A rough pipe wall surface is deemed good as it will enhance liner interlock and friction when under positive internal pressure thus reducing the potential for liner longitudinal movements.

The Society for Protective Coatings (SSPC) and NACE International Joint Standards have produced Dry Abrasive Blast (DAB) and Wet Abrasive Blast (WAB) blast cleaning preparation standards. These standards classify the condition of the cleaned surface prior to and after abrasive blast cleaning using the following SP/NACE Classification from highest to lowest standard. The SSPC/NACE level of cleaning for each pipe section is provided in Table 3.2.

(a) Section 1 cleaned using Tomahawk System.



(b) Section 2 cleaned using ID-TEC SR-Series high pressure water jet tool.

(c) Section 3 cleaned using rack-feed boring equipment.

Figure 3.7: Cleaned pipe wall using Tomahawk System, ID-TEC SR-Series water jetting, and Rack-feed boring.

Table 3.2: SSPC/NACE Classification of condition of the cleaned pipe surface.

Technology	SSPC/NACE) Cleaning Classification	NACE No. Degree of Cleaning	SP No. Degree of Cleaning
Tomahawk (Pipe Section 1)	Near-White metal Dry Abrasive Blast (DAB)	2	10
ID-TEC High Pressure Water Jetting (Pipe Section 2)	Industrial Wet Abrasive Blast (WAB)	8	14
Rack-feed Boring (Pipe Section 3)	Commercial Wet Abrasive Blast (WAB)	3	6

The Tomahawk pipe cleaning system is deemed to have achieved near white metal Dry Abrasive Blast (DAB) cleaning SP 10 and NACE 2, rack-feed boring achieved Commercial WAB cleaning SP 3 and NACE 6 while hydro jet cleaning achieved Industrial WAB cleaning SP 8 and NACE 14. Although the minimum pipe cleaning level stated in ASTM F3182 is SP 7/NACE No. 4, Near-White Metal cleaning is deemed to provide a greater degree of cleaning than commercial cleaning but less than White Metal WAB cleaning. Commercial cleaning is deemed better than Industrial. (NACE, 2015)

3.6 New Lining Demonstration

3.6.1 Material

Shortly after the pipe cleaning process using Tomahawk, ID-TEC and rack-feed boring, a polymeric liner was installed inside the pipe. The Lining product is 3M™ Scotchkote™ Pipe Renewal Liner 2400, it is a two part, rapid-setting aliphatic polyurea product. As described by the manufacturer, the lining product is certified to ANSI/NSF-61, free from both bisphenol-A and Volatile Organic Compounds (VOCs).

3.6.2 Process

The 3M™ Scotchkote™ lining product is applied using a centrifugal spin-cast process. A sprayer head attached to an umbilical hose is pulled through the pipe thereby spraying the interior surface of the cleaned pipe. The spray head uses reverse direction motor, which helps to avoid any incomplete coverage or shadowing throughout the pipe interior.

The lining process includes setting up an umbilical hose, attaching spray-head to the hose, test-running the spray head, followed by lining. These activities are carried out after a post-cleaning Closed Circuit Television (CCTV) inspection. The gel time for this polyurea product is 1 minute, its film set time is 3 minutes and is cured and ready for CCTV inspection after 10 minutes. Figure 3.8 shows how the pipes during the pilot project look after lining using the 3M™ Scotchkote™ liner.

Figure 3.8: Appearance of the pipe after lining with 3M™ Scotchkote™ liner.

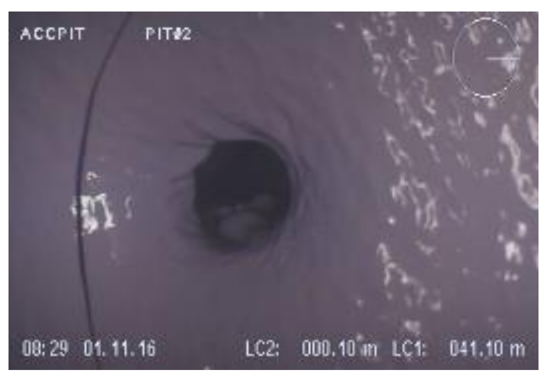
3.7 Visual Examination for Defects

Upon completion of lining operations and initial curing, a visual inspection at the entrance and exit points of the lined main was undertaken to verify that there is no evidence of uncured product. As required by ASTM F3182, a CCTV camera was deployed before and after lining. Careful attention was focused on ensuring fully cured, bonded coverage including service connections, joints, and other anomalies. The pipe section was also inspected for lining faults such as cracks, blisters, bubbles, sags, uncoated pipe, delamination, ringing, cuts, drips, holes, or service blockages.

3.7.1 Lining Cracks

Lining cracks were observed in Section 2 (Pit 3 to Pit 5) and Section 3 (Pit 5 to Pit 7). However, there were no cracks in Section 1 (Pit 1 to Pit 3). Figure 3.9 and Figure 3.10 shows circumferential and spiral cracks observed in the lining of Section 2 (Pit 3 to Pit 5) and Section 3 (Pit 5 to Pit 7). Figure 3.11 shows the spiral crack at the start of lining in Section 2 where the lining thickness was less than the proposed design thickness.

(a) Spiral crack at the start of Section 2 lining.



(b) Circumferential crack.

Figure 3.9: Lining condition at two ends of the same pipe section with spiral and longitudinal crack visible in the thinner lining.

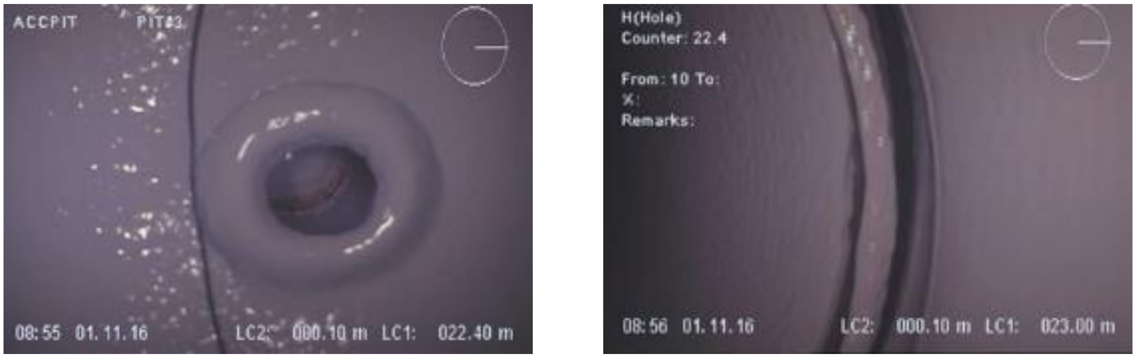


Figure 3.10: Circumferential lining cracks near joint and service connection in Section 3.

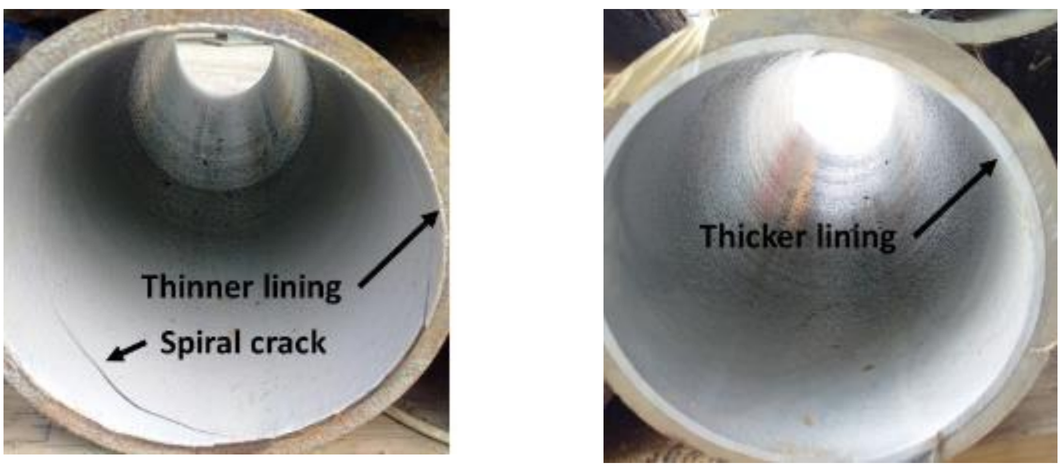


Figure 3.11: Lining thickness variation at two ends of the same pipe section with spiral crack visible in the thinner lining.

3.7.2 Lining Condition at Joints

Lining condition at joints depends on many factors that can include joint type, displacement, and separation of joined sections, alignment, and level of encrustation. According to 3M, Scotchkote liner "can seal pre-existing holes up to 0.24 in. (6 mm) in diameter, and gaps up to 0.20 in. (5 mm), in the host pipeline". To fix larger gaps, 3M recommends the use of mechanical sleeves either before or after lining host pipe. Lining condition at the joints were observed in the post-lining CCTV videos, as well as in the exhumed pipe sections. However, as shown in Figure 3.12 shows sections where lining gaps were observed at some joints.

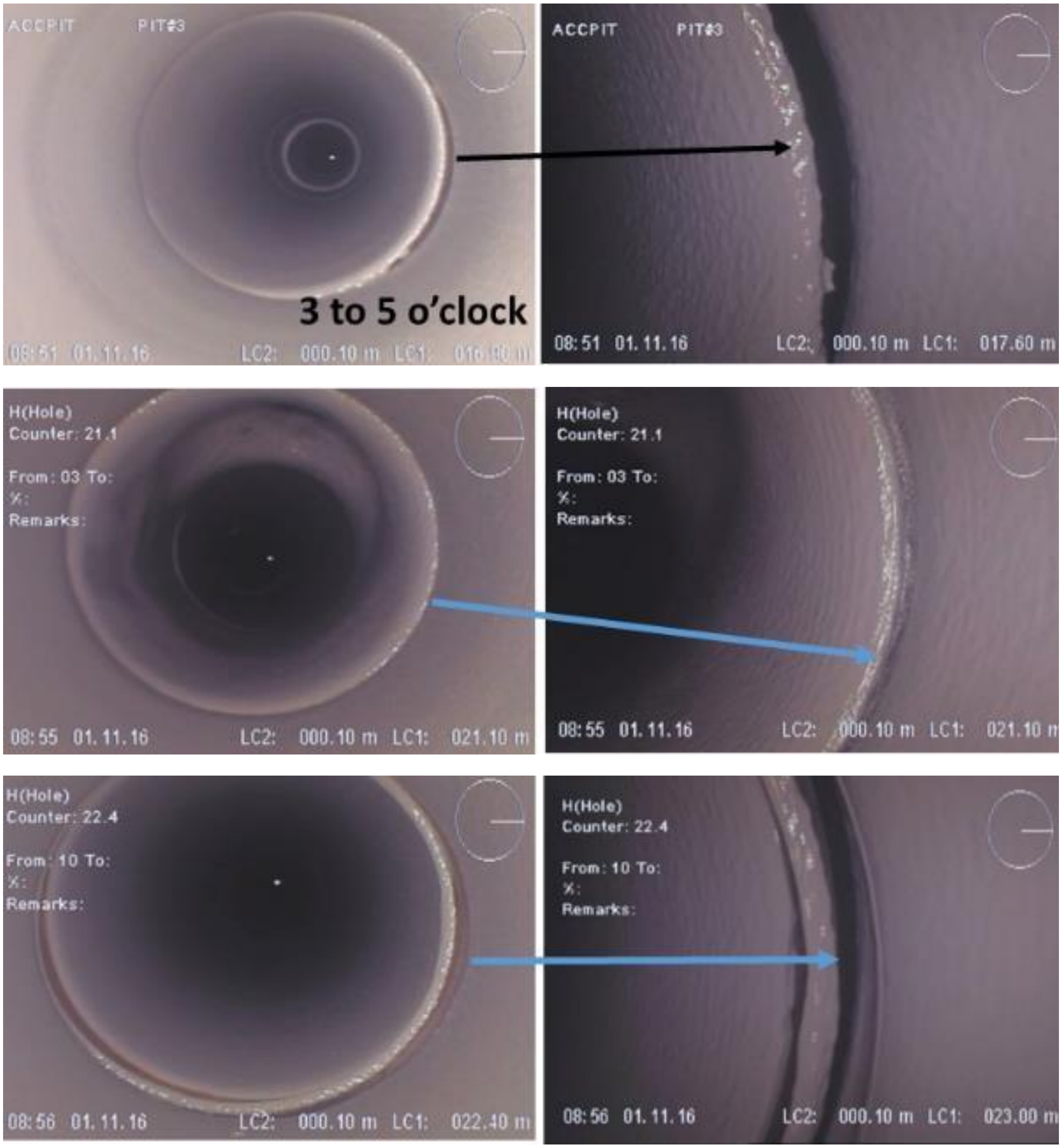


Figure 3.12: Lining gaps at joints in Section 3.

3.7.3 Lining Condition around Service Connections

Two service connections and a service saddle were installed in each of the three spools in Pit 2, Pit 4, and Pit 6 for pipe Sections 1, 2, and 3. Figure 3.13 shows a typical spool fitted with two service connections and a service saddle. The service connections and service saddles were cut out of pipe and then split into quarters using waterjet cutting. Figure 3.14 to 3.23 show the lining condition around the service connections and service saddles. There was good lining coverage around the service connections and service saddles and no shadow effect was observed. However, lining partly encroached the service connections and service saddles, and therefore reduced the service size. Therefore, there was some lining adhesion around the service connections. One of the intruding service connections in pipe Section 1 spool (refer to Figure 3.15) was cut using remote controlled ID-TEC equipment. In that case the lining got separated from the host pipe around the service connection. There was little to no adhesion of lining for service saddle connections.

Figure 3.13: Spool with service connections and service saddle.

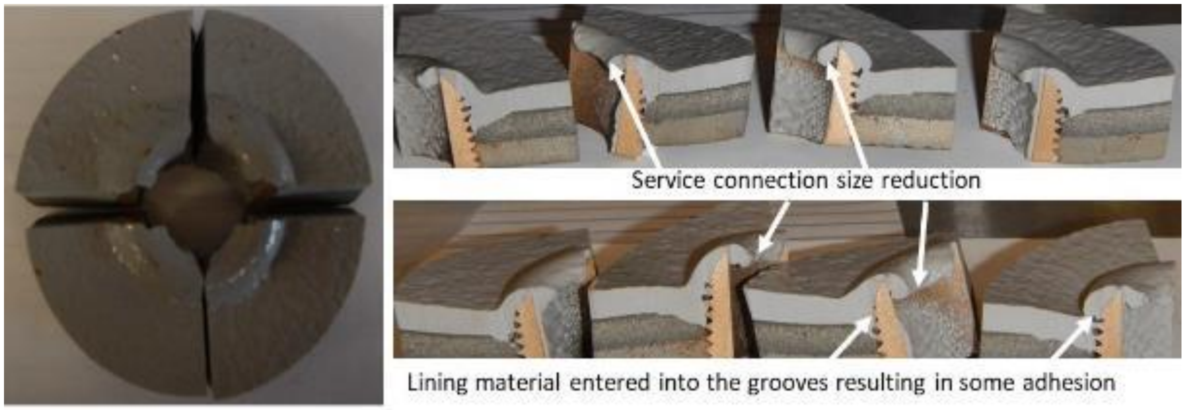


Figure 3.14: Service connection 1B1-2(1) for Tomahawk cleaned section.

Figure 3.15: Service connection 1B3-1(1) for Tomahawk cleaned section.

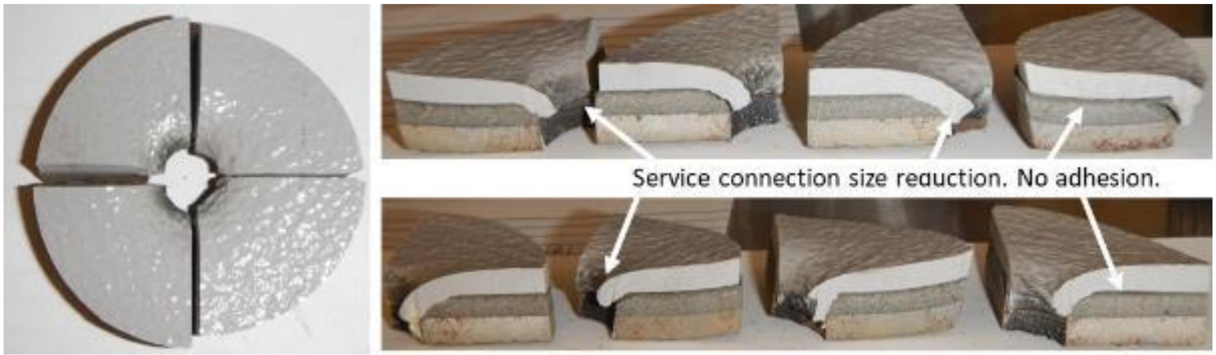


Figure 3.16: Service Saddle 1B1-2(4) for Tomahawk cleaned section.

Figure 3.17: Service saddle 2B4 for Rack bore cleaned section.

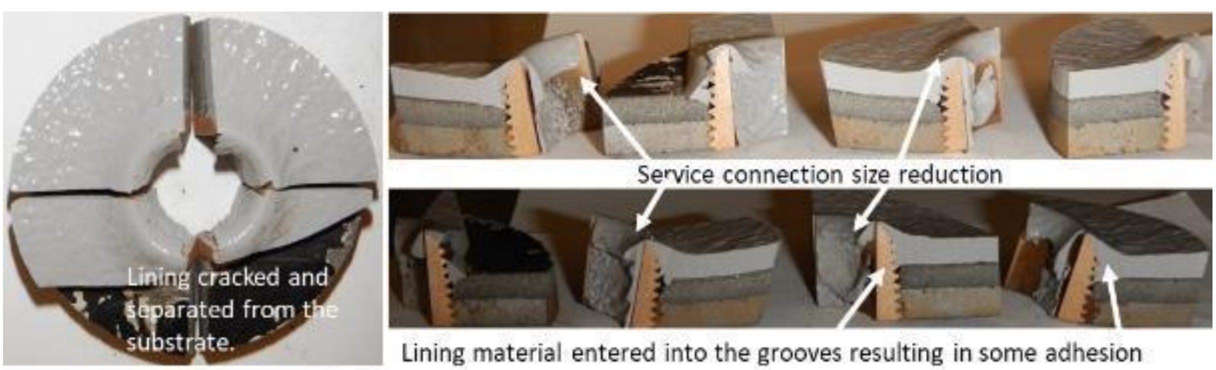


Figure 3.18: Service connection 2B6-2 for Rack bore cleaned section.

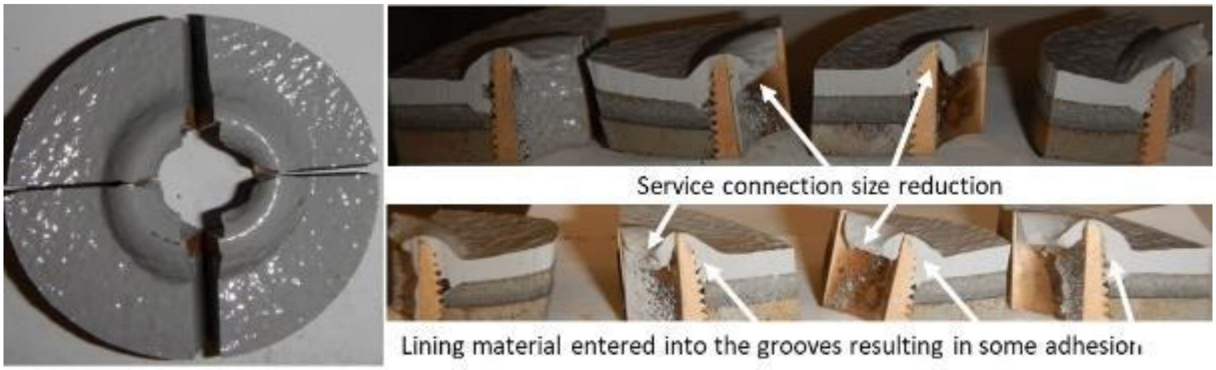


Figure 3.19: Service connection 2B4 for Rack bore cleaned section.

Figure 3.20: Service saddle 3B4-1 for Water jet cleaned section.

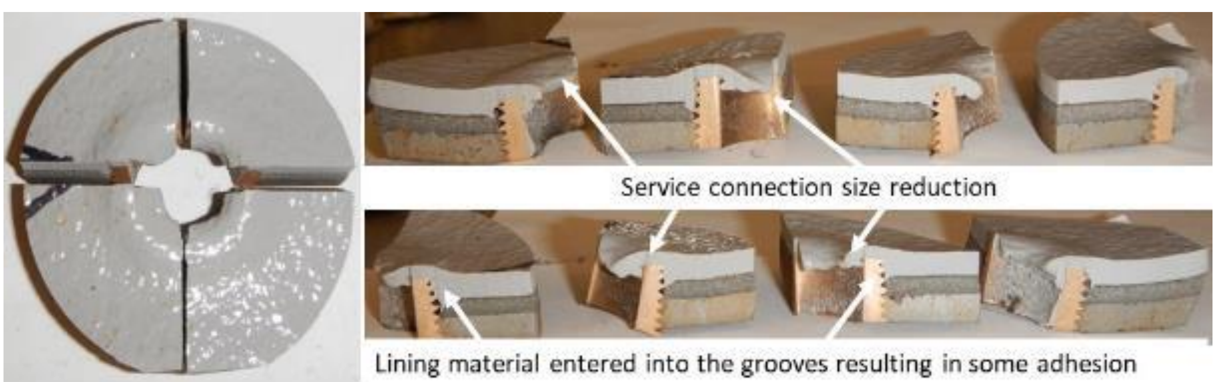


Figure 3.21: Service connection 3B4-4 for Water jet cleaned section.

Figure 3.22: Service connection 3B6-2 for Water jet cleaned section.

3.8 Benchmark Testing

Standard performance tests have been used to evaluate the lining, after the pilot field trials, the tests conducted are as follows:

3.8.1 Thickness Measurement

The manufacturer, 3M, carried out the lining design according to ASTM F1216-09 Appendix X1 and specified design thickness of 5.2 mm. 3M proposed to achieve the required thickness in two passes of 2.75 mm each.

Lined pipes were exhumed from some regions in Sections 1, 2 and 3. They were cut longitudinally into half and quarter pieces. The liner was removed from the host pipe and lining thickness was measured at every 3 cm interval along the length using a digital Vernier caliper. Table 3.3 and Figure 3.23 shows the thickness measurement results. The average thickness along the length for the three pipe sections varied between 5.17 mm and 5.75 mm. For Sections 1 and 2, the average lining thickness slightly decreased between the entry (spray head launch) and exit (spray head retrieval) pits. For Section 1, the average lining thickness are 5.66 mm, 5.55 mm and 5.17 mm for samples from Pit 1, Pit 2 and Pit 3, respectively. For Section 2, the average lining thickness decreased from 5.75 mm to 5.28 mm for samples from Pit 4 and Pit 5, respectively. The Section 3 samples had fairly uniform thickness. Figures 3.24 to 3.26 show lining thickness variation for samples from the three sections. Overall, the specified thickness value of 5.2 mm was achieved.

Table 3.3: Lining thickness vales for the end of sections removed from various pits.

	Section 1			Section 2		Section 3		
	Pit 1	Pit 2	Pit 3	Pit 4	Pit 5	Pit 5	Pit 6	Pit 7
Max (mm)	6.59	6.99	5.94	7.03	6.24	6.44	6.04	6.35
Min (mm)	5.11	4.79	3.93	5.04	3.54	4.79	4.47	3.10
Average (mm)	5.66	5.55	5.17	5.75	5.28	5.49	5.31	5.42
St. Dev. (mm)	0.26	0.30	0.47	0.33	0.60	0.29	0.69	0.46

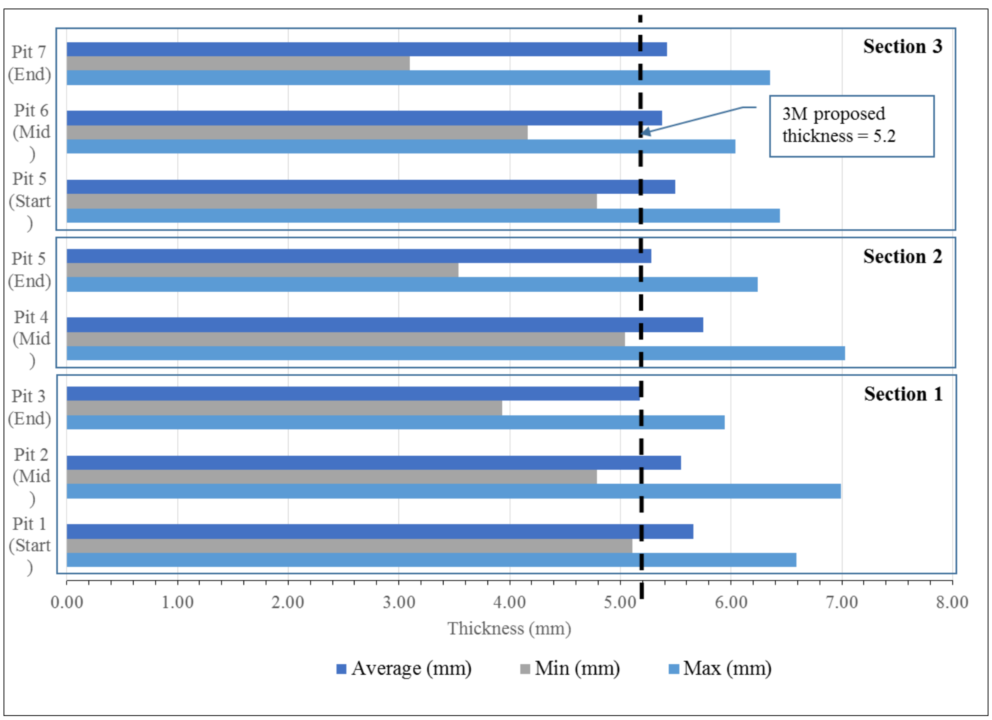


Figure 3.23: Lining thickness for the samples removed from various pits along Sections 1, 2 and 3.

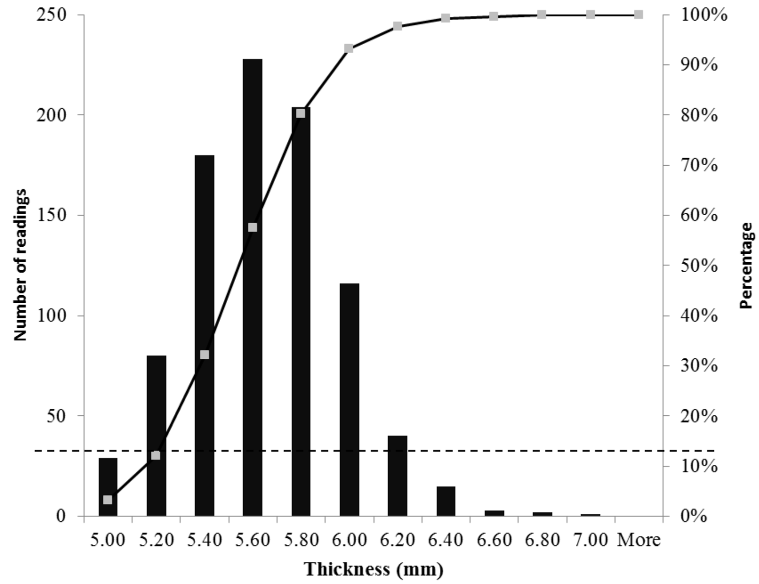


Figure 3.24: Lining thickness measurements for pipe samples from Section 1.

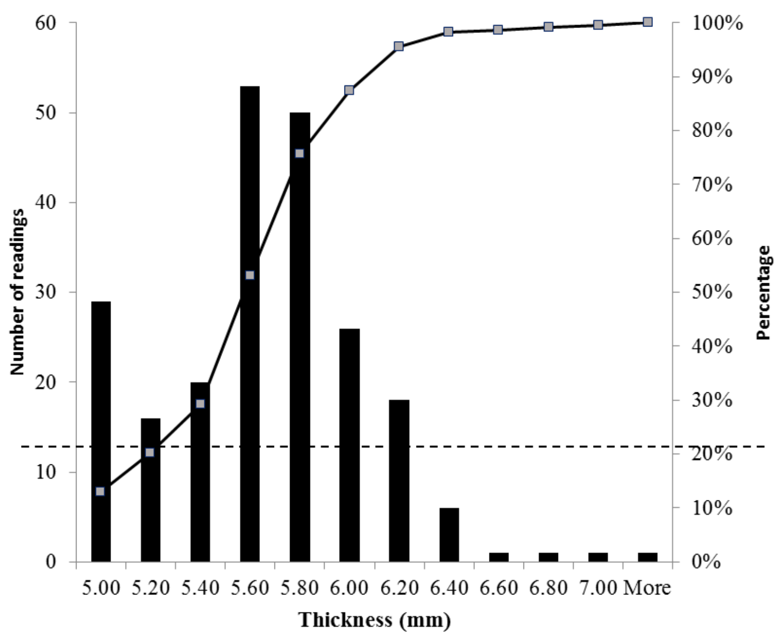


Figure 3.25: Lining thickness measurements for pipe samples from Section 2.

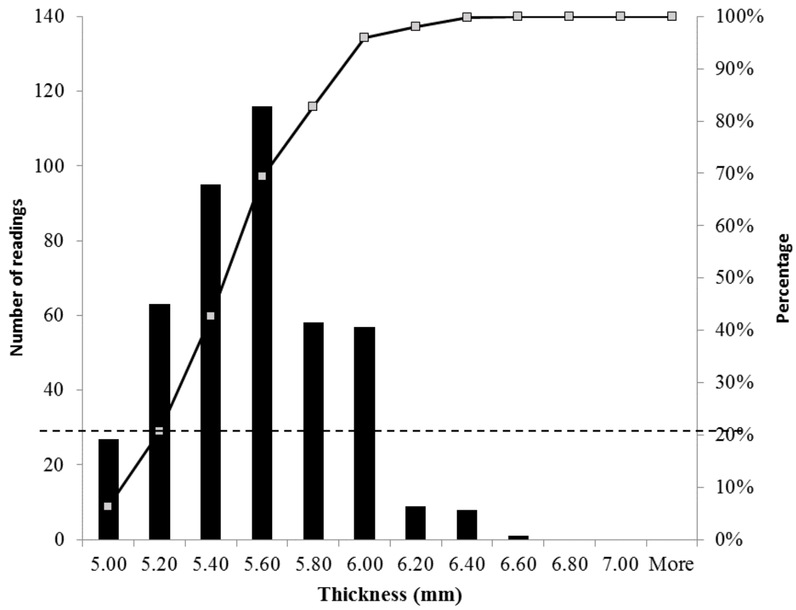


Figure 3.26: Lining thickness measurements for pipe samples from Section 3.

3.8.2 Lining Adhesion with the Host Pipe

The test pipe comprised of unlined and lined sections with Cement Mortar Lining (CML). The exhumed pipes were then cut in half and quarter sections in the longitudinal direction. However, no adhesion was observed between the 3M Scotchkote 2400 lining and host pipe for both the unlined and CML pipe sections except for some areas close to pipe ends (i.e., close to launch or removal of spray head). Also, gaps were observed in exhumed pipe sections. Figure 3.27 shows visible gaps between the lining and the pipe at the cut ends. When the lined pipes were cut longitudinally, the lining “fell off” from the host pipe, indicating that there was no adhesion between the lining and host pipe. Figure 3.28 shows how it was possible to remove the lining without effort when the pipe was jet-cut longitudinally.

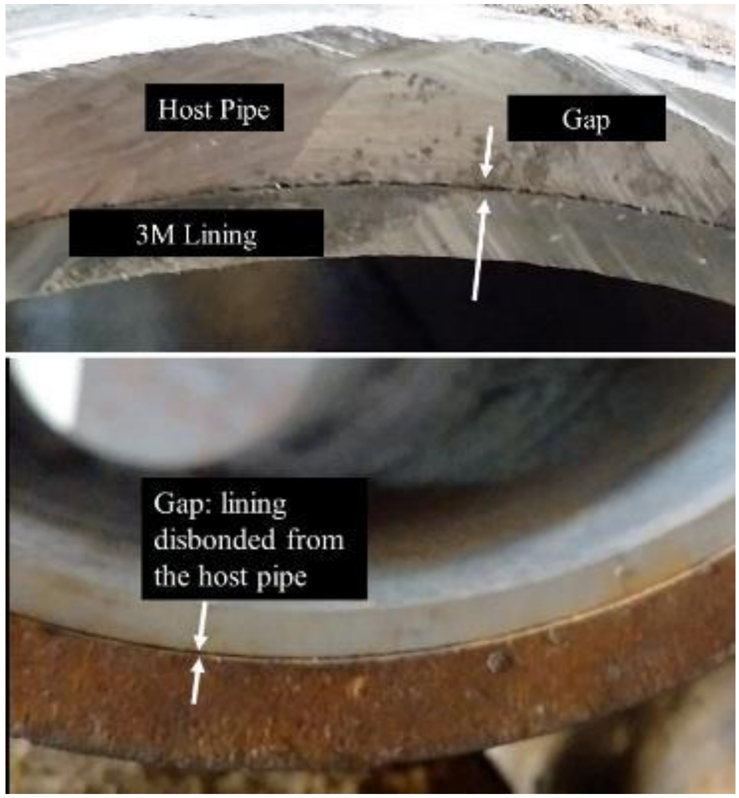


Figure 3.27: Lining gaps observed between the lining and substrate at the cut ends.

Figure 3.28: Pipe section with no lining adhesion with the host pipe as liner separated after jet cutting

3.8.3 Immersion test

Samples from all three sections were cut to size 50mm x 150mm x 3.2mm following AWWA C210 requirements. These samples were immersed in water, weak base and weak acid at a temperature of 25°C for a period of 30 days. The samples were taken out, left to dry for 24 hours, then they were examined for presence of peels or blisters. At the end of this test, there were no peels or blisters in liner.

3.9 Material Properties Testing

The lining material's tensile and flexural properties were evaluated using ASTM D638-14 and ASTM D790-10, respectively.

3.9.1 Tensile Test

Following ASTM D638, Type II dumbbell-shaped specimens were prepared and tested using an Instron Universal Testing Machine. These specimens were jet-cut from pipe samples taken from Section 1 and 3. Table 3.4 shows the specimens' dimensions, while Figure 3.30 shows the specimen and machine setup. According to ASTM D638, the change in grip separation relative to the original grip separation at break is defined as nominal strain at break. However, the crosshead displacement (i.e., change in grip separation) measurement has used to compute the strain at break.

The tensile strength values are compared with minimum values specified in ASTM F1216 and 3M values reported. These values are based on tests conducted on flat samples. However, for field validation, actual pipe samples (which possess curvature) are required for testing. Table 3.5 shows the tensile strength and nominal strain results.

Figure 3.31 shows the measure of tensile strength values of the tested specimens. For test specimens from Pipe Section 1, the tensile strength at break varied between 32 MPa and 38 MPa with an average value of 36 MPa. For test specimens from Section 3, the minimum, maximum and average tensile strength at break were 29 MPa, 32 MPa, and 31 MPa, respectively. Although, Section 3 values are seen to be lesser than the 3M reported minimum value, this cannot be said to have failed. This is because there will be difference in the results from a curved sample compared to testing flat sample. Also, there is surface roughness in the sample compared liner. Laboratory prepared product on flat plate will have smooth surfaces and edges.

After this test, separation of the layers of the liner was noticed. This may be due to other stresses induced in the curved coupons while testing. Figure 3.29 shows this separation. A suitable capping material could be placed at the ends of the specimen to make the intact while the tensile test is being conducted. This will ensure there are twists and no stresses induced in the specimens.

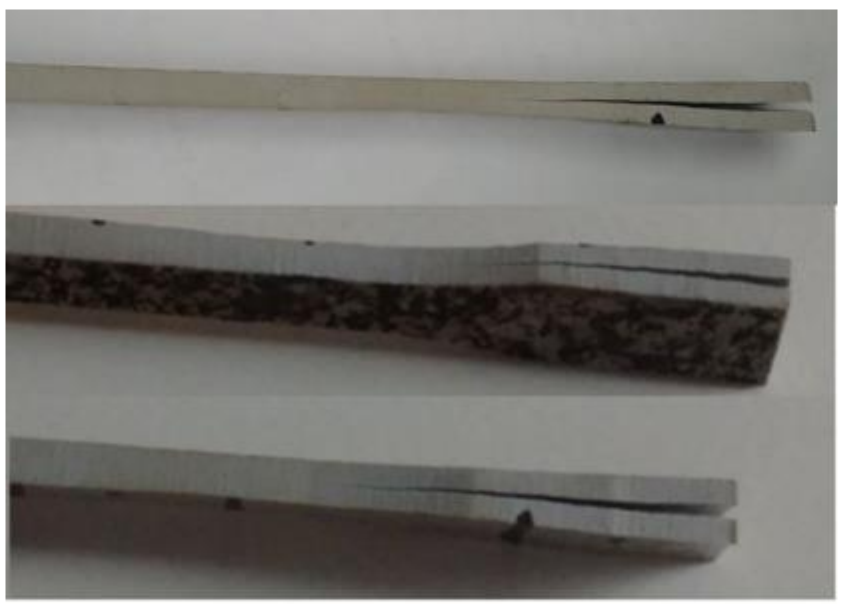


Figure 3.29: Separation of two lining layers in some tensile samples.

Figure 3.32 shows the nominal strain values. For lined specimens from Pipe Section 1, the minimum, maximum and average nominal strains at break were 1.47%, 1.99%, and 1.83%, respectively. The minimum, maximum and average nominal strains at break for lining test specimens from Pipe Section 3 were 1.62%, 1.79%, and 1.73%, respectively. These values are smaller than the 3M reported tensile elongation of 3%. Figures 3.33 and 3.34 show the stress-strain plots for lining specimens from pipe Sections 1 and 3. All the test specimens exhibited low ductility properties, which is characterized by less than 2% nominal strain at break.

Table 3.4: Tensile test specimen dimensions.

Section 1			**Section 3**		
Specimen No.	**Avg. Width**	**Avg. Thickness**	**Specimen No.**	**Avg. Width**	**Avg. Thickness**
	mm	mm		mm	mm
S-1A1-1	5.95	5.41	S-3A3-2	6.01	5.92
S-1A1-2	5.86	5.65	S-3A3-7	6.08	5.81
S-1A1-3	5.77	5.42	S-3A3-10	6.07	5.96
S-1A1-4	5.75	5.50	-	-	-
S-1A1-8	5.81	5.51	-	-	-
Average	5.83	5.50	Average	6.05	5.90
Std. Dev.	0.08	0.10	Std. Dev.	0.04	0.07
Min.	5.75	5.41	Min.	6.01	5.81
Max.	5.95	5.65	Max.	6.08	5.96

Figure 3.30: Specimens and tensile test setup.

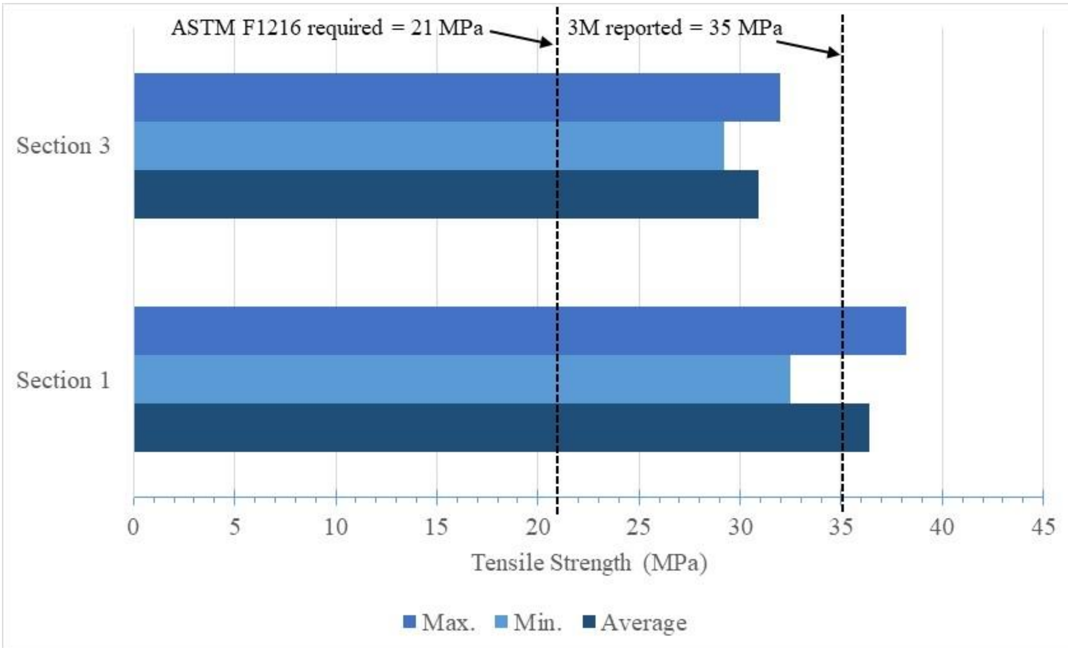


Figure 3.31: Tensile strength results and comparison with the ASTM F1216 and 3M values.

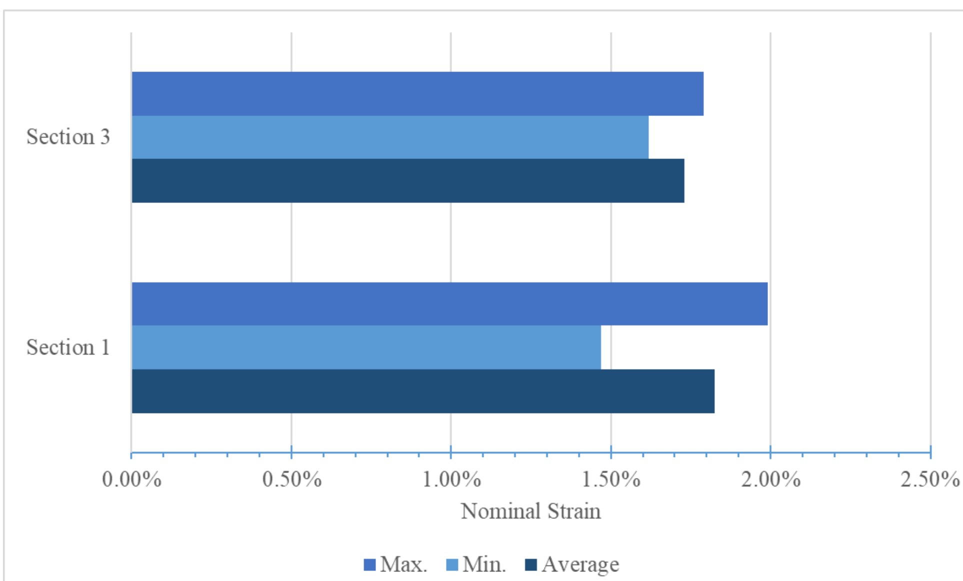


Figure 3.32: Nominal strain values.

Table 3.5: Tensile Test results.

Specimen (Section 1)	**Tensile Strength at Break**		**Nominal Strain at Break**	**Specimen (Section 3)**	**Tensile Strength at Break**		**Nominal Strain at Break**
	MPa	psi	mm/mm		MPa	psi	mm/mm
S-1A1-1	38	5,547	1.96%	S-3A3-2	29	4,238	1.62%
S-1A1-2	37	5,385	1.88%	S-3A3-7	31	4,559	1.78%
S-1A1-3	34	4,899	1.47%	S-3A3-10	32	4,641	1.79%
S-1A1-4	36	5,280	1.99%	-	-	-	-
S-1A1-8	32	4,713	1.47%	-	-	-	-
Average	36	5,278	1.83%	Average	31	4,479	1.73%
St. Dev.	2	348	0.26%	St. Dev.	1	213	0.09%
Min.	32	4,713	1.47%	Min.	29	4,238	1.62%
Max.	38	5,547	1.99%	Max.	32	4,641	1.79%
3M Reported Values (ASTM D638-08):				Tensile strength at breaking (in air) = 35 MPa Tensile elongation (in air) = 3%			

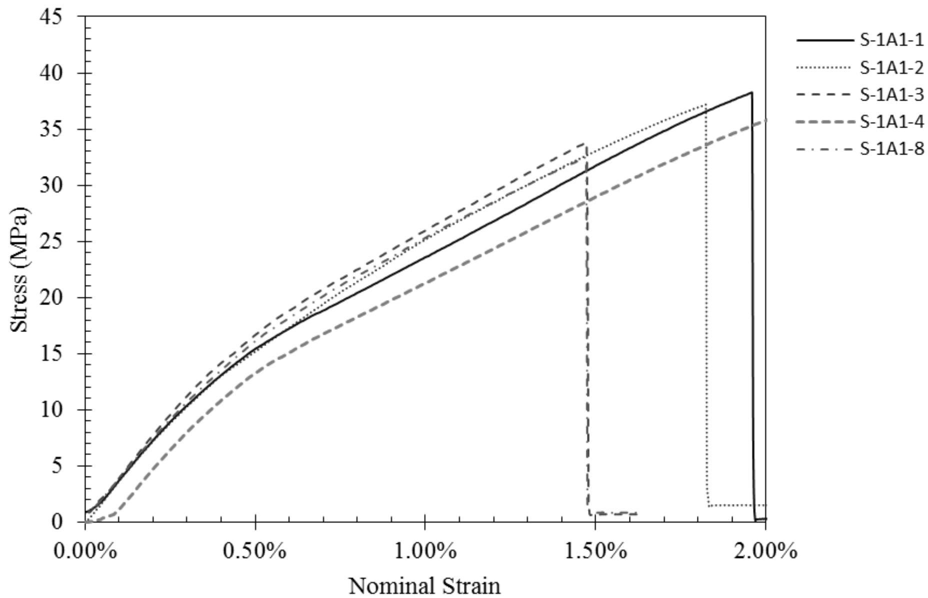


Figure 3.33: Chart between tensile stress-strain for Section 1 specimens.

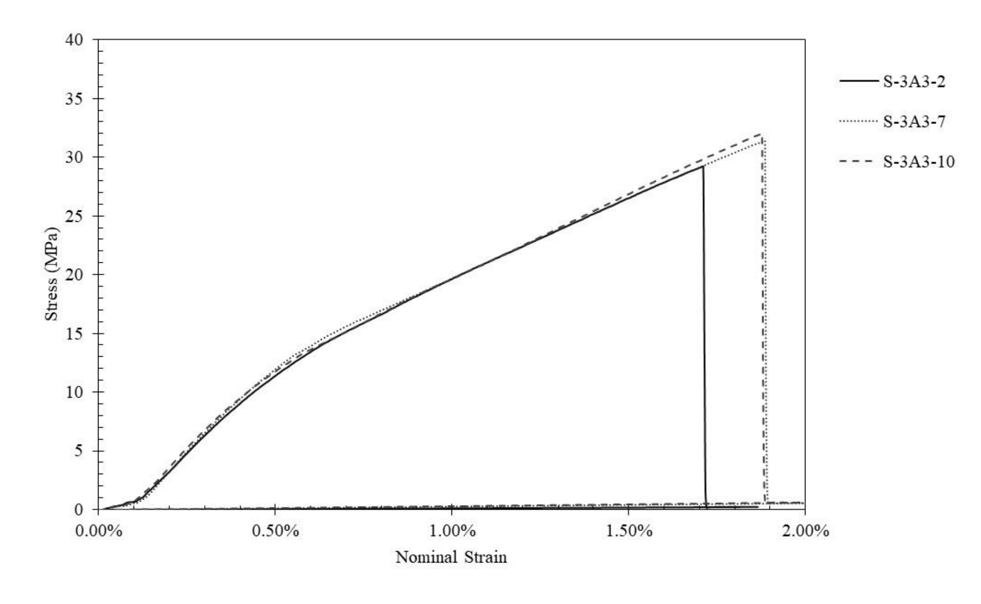


Figure 3.34: Chart between tensile stress-strain for Section 3 specimens.

3.9.2 Flexural Test

In accordance with ASTM D790, specimens from pipe Sections 1, 2 and 3 were tested for flexural properties, namely flexural strength, flexural strain, and tangent modulus of elasticity. Figure 3.35 shows the test setup with load cell and displacement transducer. The load cell and displacement transducer were calibrated before the tests. Table 3.6 shows the specimens' dimensions. Table 3.7 shows the manufacturer specified flexural test values. 3M reported flexural strength and flexural modulus of Scotchkote Liner 2400 as 53 MPa and 3,900 MPa respectively. Figures 3.36 to 3.38 present the flexural test results.

Table 3.8 to 3.13 present the Flexural strength for tested specimens for the three sections. For Section 1, the flexural strength varied between 39 MPa and 53 MPa with an average value of 50 MPa, whereas flexural modulus varied between 3,727 to 5,101 MPa with an average value of 4,500 MPa. The flexural strain for Section 1 specimens varied between 1.31% and 1.59% with an average value of 1.44%. For Section 2, the flexural strength varied between 38 and 49 MPa with an average value of 44 MPa, whereas flexural modulus varied between 2,643 to 4,546 MPa with an average value of 3,659 MPa. Flexural strain for Section 2 specimens varied between 1.17% and 1.68% with an average value of 1.45%. For Section 3, the flexural strength varied between 30 and 63 MPa with an average value of 51 MPa, whereas flexural modulus varied between 3,261 to 4,988 MPa with an average value of 4,335 MPa. Figures 3.39 to 3.41 present stress-strain curves for the lining specimens from three pipe sections. Flexural strain for Section 3 varied between 1.33% and 1.63% with an average value of 1.49%. Hence, the strain values are less than the specified 3% as all calculated values based on this study are seen to be less than 2%. The test specimens did not yield before break, which verifies that they all possess low ductility properties.

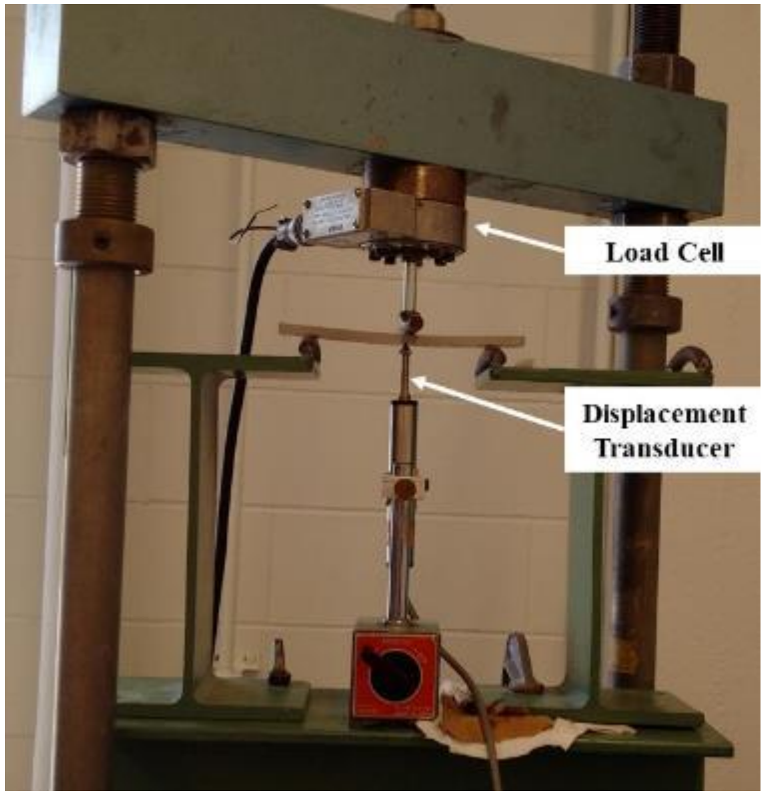


Figure 3.35: Flexural test set-up.

Table 3.6: Test specimens' dimensions.

Pipe Section	Test Specimen	Avg. Length	Avg. Width	Avg. Thickness
		mm	mm	mm
Section 1	S1-1	149.91	16.05	5.13
	S1-2	150.06	15.24	5.54
	S1-3	150.18	15.26	5.58
	S1-6	150.08	15.24	5.02
	S1-8	150.10	15.10	5.42
	Average	150.07	15.38	5.34
	Std. Dev.	0.10	0.38	0.25
	Min.	149.91	15.10	5.02
	Max.	150.18	16.05	5.58
Section 2	S2-2	150.02	15.08	5.43
	S2-4	150.07	15.22	5.66
	S2-5	150.11	15.50	5.74
	S2-7	150.16	16.27	5.32
	S2-8	150.03	16.25	6.21
	Average	150.08	15.66	5.67
	Std. Dev.	0.06	0.56	0.34
	Min.	150.02	15.08	5.32

	Max.	150.16	16.27	6.21
Section 3	S3-1	150.11	15.14	5.25
	S3-2	150.02	15.08	5.43
	S3-5	150.11	15.50	5.74
	S3-9	150.08	16.22	6.19
	S3-10	150.06	15.07	5.46
	Average	150.08	15.24	5.48
	Std. Dev.	0.05	0.22	0.25
	Min.	150.02	15.08	5.25
	Max.	150.11	15.50	5.74

Table 3.7: 3M reported flexural properties of cured lining.

Physical Characteristics	**Test Method**	**Reported Values** (MPa)	**Required Min. Values** (MPa)
		3M	**ASTM F1216**
Flexural Strength	ASTM D790-07	53	31
Flexural Modulus		3,900	1,724

Table 3.8: Flexural test results for five specimens from Section 1.

	Specimen Identification				
	S1-1	**S1-2**	**S1-3**	**S1-6**	**S1-8**
Average Depth (mm)	5.13	5.54	5.58	5.02	5.42
Test Span (mm)	112	112	112	112	112
Sample Length	149.91	150.06	150.18	150.08	150.10
Sample Width (mm)	16.05	15.24	15.26	15.24	15.10
Span to Depth Ratio	21.83	20.22	20.07	22.31	20.66
Flexural Strength (MPa)	51	39	53	53	53
Flexural Strain (%)	1.36%	1.40%	1.59%	1.31%	1.54%
Tangent Modulus of Elasticity (MPa)	4,863	3,727	4,305	5,101	4,504

Table 3.9: Summary of flexural test results for samples from Section 1.

	Average	**Standard Deviation**	**Maximum**	**Minimum**
Average Depth (mm)	5.34	0.25	5.58	5.02
Span to Depth Ratio	21.02	1.00	22.31	20.07
Flexural Strength (MPa)	50	6	53	39
Flexural Strain (%)	1.44%	0.12%	1.59%	1.31%
Initial Tangent Modulus of Elasticity (MPa)	4,500	531	5,101	3,727

Table 3.10: Flexural test results for five specimens from Section 2.

	Specimen Identification				
	S2-2	**S2-4**	**S2-5**	**S2-7**	**S2-8**
Average Depth (mm)	5.43	5.66	5.74	5.32	6.21
Test Span (mm)	112	112	112	112	112
Sample Length	150.02	150.07	150.11	150.16	150.03
Sample Width (mm)	15.08	15.22	15.50	16.27	16.25
Span to Depth Ratio	20.6	19.8	19.5	21.1	18.0
Flexural Strength (MPa)	45	49	46	41	38
Flexural Strain (%)	1.17%	1.54%	1.60%	1.27%	1.68%
Tangent Modulus of Elasticity (MPa)	4,546	3,727	3,364	4,014	2,643

Table 3.11: Summary of flexural test results for samples from Section 2.

	Average	**Standard Deviation**	**Maximum**	**Minimum**
Average Depth (mm)	5.67	0.35	6.21	5.32
Span to Depth Ratio	19.80	1.17	21.05	18.04
Flexural Strength (MPa)	44	4	49	38
Flexural Strain (%)	1.45%	0.22%	1.68%	1.17%
Initial Tangent Modulus of Elasticity (MPa)	3,659	714	4,546	2,643

Table 3.12: Flexural test results for five specimens from Section 3.

	Specimen Identification				
	S3-1	**S3-2**	**S3-5**	**S3-9**	**S3-10**
Average Depth (mm)	5.25	5.43	5.74	6.19	5.46
Test Span (mm)	112.00	112.00	112.00	112.00	112.00
Sample Length	150.02	150.02	150.11	150.08	150.06
Sample Width (mm)	15.14	15.08	15.50	16.22	15.07
Span to Depth Ratio	21.33	20.63	19.51	18.09	20.51
Flexural Strength (MPa)	63	54	47	30	62
Flexural Strain (%)	1.50%	1.33%	1.51%	1.63%	1.47%
Tangent Modulus of Elasticity (MPa)	4,899	4,988	3,595	3,261	4,932

Table 3.13: Summary of flexural test results for samples from Section 3.

	Average	**Standard Deviation**	**Maximum**	**Minimum**
Average Depth (mm)	5.61	0.37	6.19	5.25
Span to Depth Ratio	20.02	1.26	21.33	18.09
Flexural Strength (MPa)	51	13	63	30
Flexural Strain (%)	1.49%	0.11%	1.63%	1.33%
Initial Tangent Modulus of Elasticity (MPa)	4,335	837	4,988	3,261

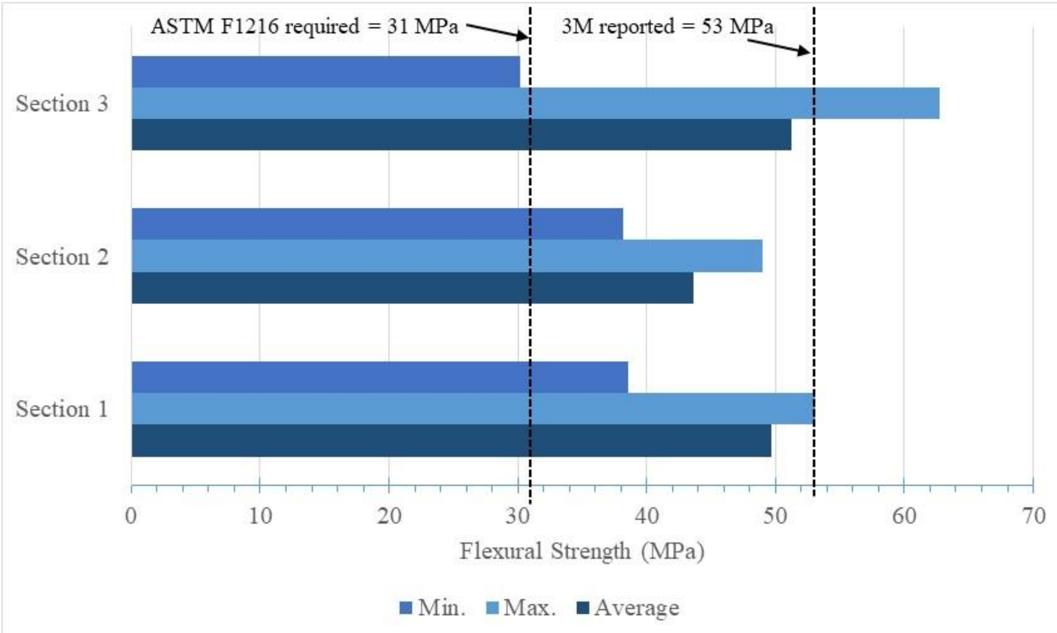


Figure 3.36: Flexural strength results and comparison with the ASTM F1216 and 3M minimum values.

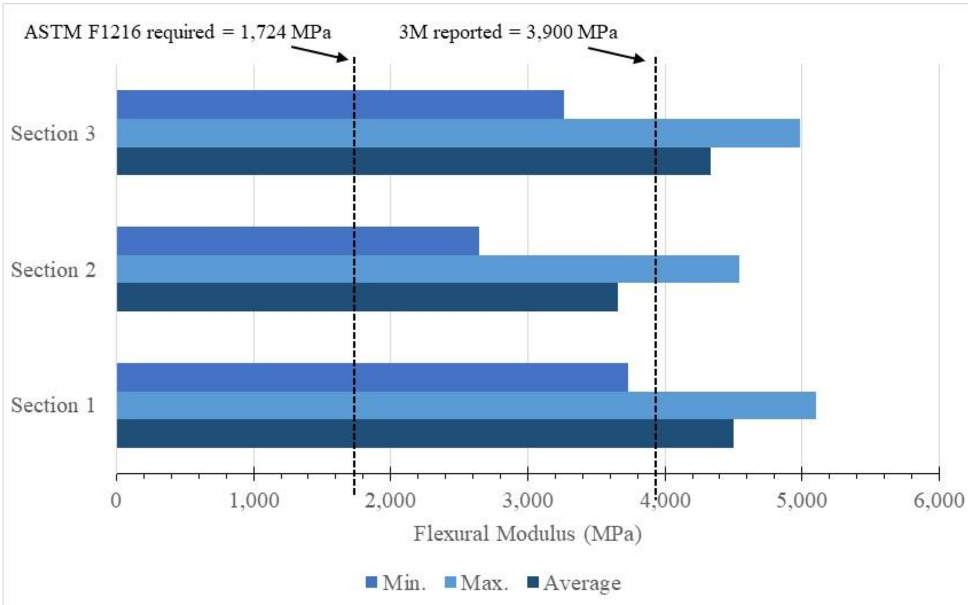


Figure 3.37: Flexural modulus results and comparison with the ASTM F1216 and 3M minimum.

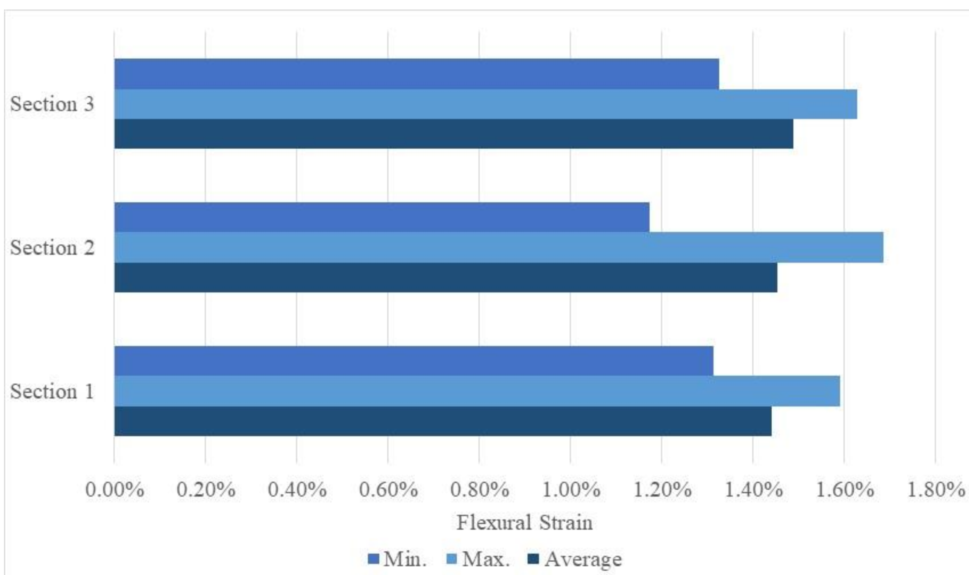


Figure 3.38: Flexural strain test results for Sections 1, 2 and 3.

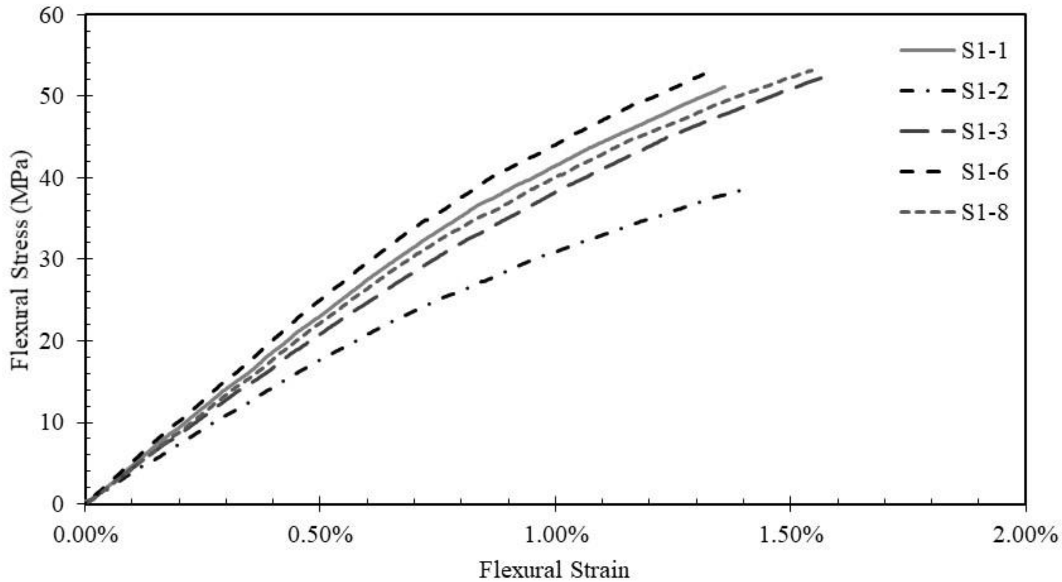


Figure 3.39: Stress-strain plots for lining specimens from Pipe Section 1.

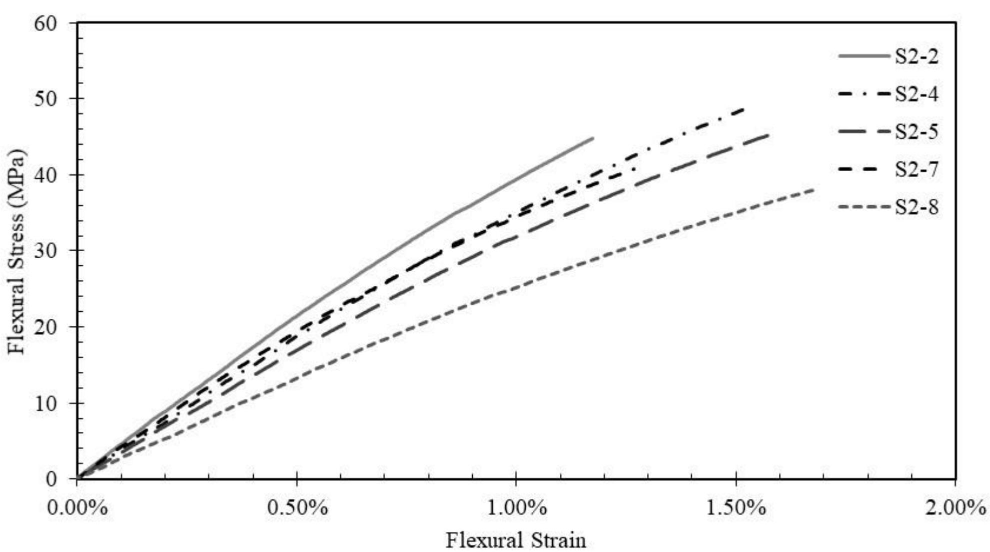


Figure 3.40: Stress-strain plots for lining specimens from Pipe Section 2.

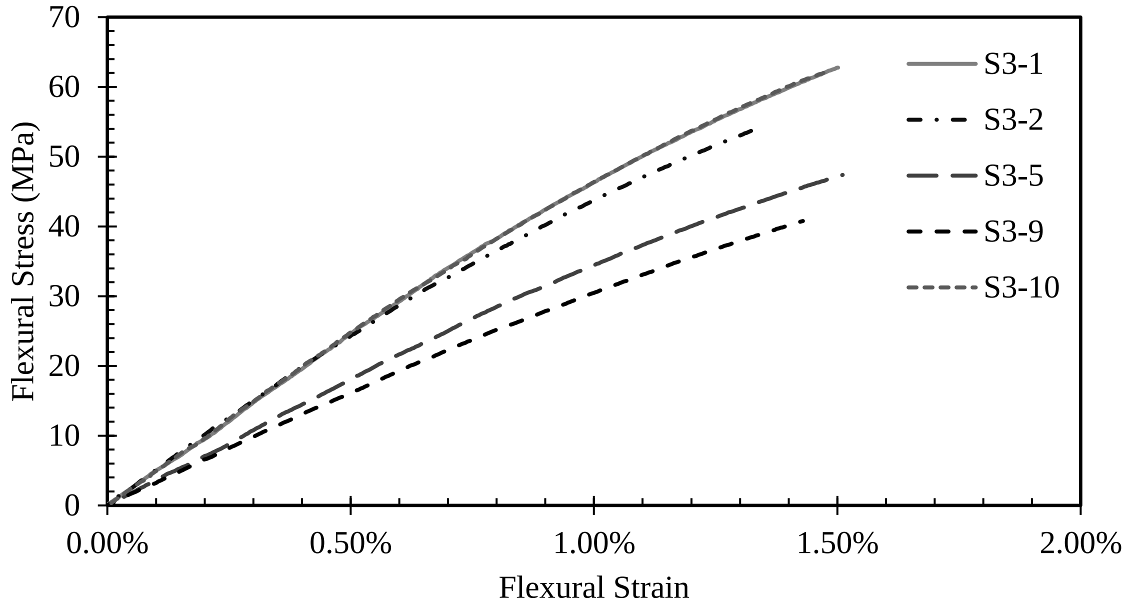


Figure 3.41: Stress-strain plots for lining specimens from Pipe Section 3.

3.10 Discussion

The development and implementation of this field demonstration for the three cleaning technology was instrumental in documenting performances for different cleaning processes. Although, the new lining technology was found to be fast and exhibits potential for same day return-to-service applications, the resulting liner did not show enough flexibility as cracks developed shortly after the lining installation. This shows the liner cannot withstand transient pressure surges developed in service for pressurized pipelines.

Cracks generated in Sections 2 and 3 can be due to a number of reasons such as temperature drop, material properties of the liner or presence of moisture. Also, there was no evidence of bond to host pipe, as there were visible gaps between the host pipe and the cured liner. Reasonable improvements should be made for development of this technology for distribution pipes. However, for Section 1, no shadowing (i.e., incomplete coverage on one side) or lining gaps were observed at the joints.

3.11 Conclusions

Based on the evaluation of the Spray Applied Liner, the following conclusions are drawn:

1. Visual inspections for all cleaned pipe surfaces revealed that the Tomahawk system is a more effective pipe cleaning method. This dry cleaning method removed all tubercles and residues in the pipe sections compared to the other two water-based cleaning methods (high pressure water jetting and rack-feed boring). In addition, the new cleaning system is observed to be about 1.5 times faster than other methods used in this study;

2. Cracks occurred in Section 2 and Section 3 of the abandoned pipe after lining. This is considered to be due to inadequate pipe surface preparation as there were no lining cracks found in Section 1, which was cleaned by the water-less Tomahawk cleaning technology;

3. The cured lining had relatively consistent thickness, but some sections had thin liner at pipe ends. Overall, 5.6 mm value made up 92%, 90%, and 85% of the thickness values from section 1, 2 and 3, respectively. Also, the average thickness values in all three sections met the manufacturer specified thickness of 5.2 mm;

4. The liner had no adhesion with the host pipe in all the three test sections. This was true for both cases involving cast iron and ductile iron pipes;

5. Although, tensile strength values are greater than the minimum required tensile strength value of 21 MPa as per ASTM F1216, some values were less than the 3M reported value of 35 MPa. Also, the lining product has low ductility characteristics causing premature cracks. This is because the nominal strain value at break, which varied from 1.44% to 1.99%, was less than the 3M reported value of 3%; and

6. The average flexural strength values for the tested specimens from all three sections are slightly less than the 3M reported value of 53 MPa. However, the flexural modulus values are greater than the ASTM F1216 minimum required value of 1,724 MPa, which are in turn greater than 3M's reported value. Ultimately, it is concluded that the lining material possess low ductility property. This is due to the low flexural strain values, which varied between 1.17% and 1.68%.

Chapter 4

Quality Assurance and Quality Control Protocol for Non-Structural and Semi-Structural Pipe Renewal Liners used for Water Mains

4.1 Overview

A set of performance documents informs Engineer on the best approach for monitoring the liner installations to confirm the acceptable level of performance has been obtained. Owing to the pace of emerging renewal technologies and the continued improvements of existing ones, strategic and specific QA/QC is needed for currently available non-structural and semi-structural liner technologies. For years, QA/QC requirements for CIPP have been adopted. However, AWWA Class I and II Type Liners require adhesion. This means the interaction with the host pipe needs to be evaluated, thereby rendering sampling method different from CIPP. This Chapter sets out protocols critical for collecting quantitative in-situ data regarding baseline performance of rehabilitated pipe for long-term performance. The resulting field validation protocol will ensure that materials, methods, and workmanship used for lining projects are installed to an extent satisfactory to the owner and engineer. Based on results from prior field demonstrations and key challenges faced in terms of improving the performance of new technologies, a rational and common design approach is used to present QA/QC procedures and acceptance testing for installation of new pipe renewal liners. This involves: 1) Ensuring proper surface preparation, 2) Comparing lining thickness to design value, and 3) Comparing material properties to manufacturer’s specified value. Consequently, performance QA/QC requirements are provided for field validation of new lining technologies.

4.2 Introduction

In water pipes, deterioration is more common by one or a combination of tuberculation scale buildup, flow capacity reduction, and water quality problems. There are different lining materials that can be applied to the interior of pipes to prevent these issues. Figure 4.1 shows two broad categories of materials used for pipe linings: cementitious, and polymeric (i.e.

epoxy, polyurea and polyurethane). More recently, there has been an effort to utilize chemically hardened polymeric linings as cost effective, fast curing alternatives to more traditional cement lining methods (USEPA, 2009)

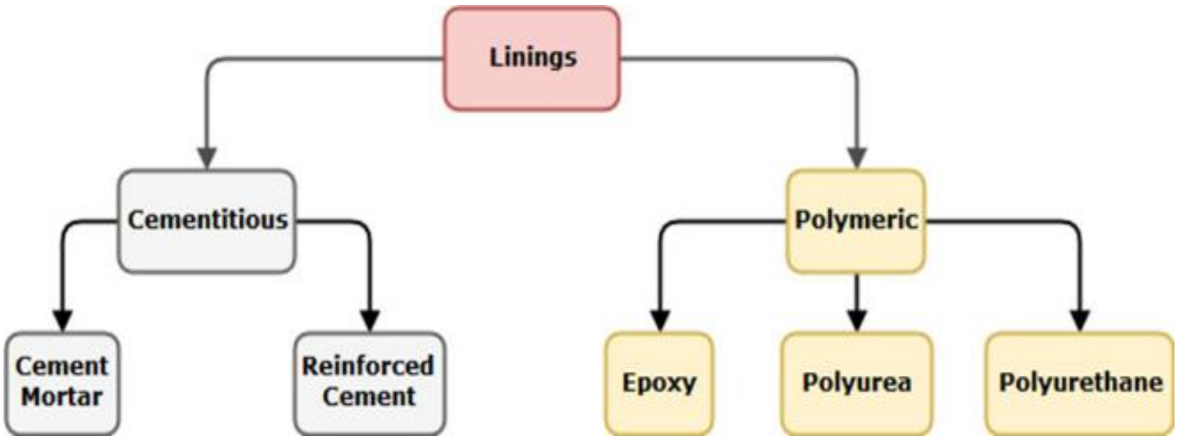


Figure 4.1: Lining Materials for Renewal of Potable Water Pipes

AWWA Manual M28 distinguishes linings into four classifications (AWWA, 2014):

- Class I Linings: These are non-structural systems, such as traditional cement mortar and epoxy.
- Class II Linings: These are close-fit semi-structural linings that can span holes and gaps in the host pipe. However, they have minimal thickness and require support from the host pipe to prevent collapse during depressurization.
- Class III Linings: These are similar to Class II linings, except they have sufficient thickness to resist buckling from external hydrostatic load or vacuum.
- Class IV Linings: These are fully structural linings, which involves placing a self-supporting, watertight structure inside a pipe.

According to Knight (2017), non-structural linings are about 0.25 – 0.5 mm thick and are designed to extend the pipe's service life by up to 50 years. These linings' material properties prevent pitting from re-occurring. It also fills pits to stop and prevent pinhole leaks.

This study is being conducted to ensure that non-structural and semi-structural lining products applied in the field are "as designed". A construction Quality Assurance/Quality Control (QA/QC) testing protocol is developed to guide the process of liner qualification thereby averting liner faults and failures. First, benchmark test must be conducted on the liner product before going to field – to validate liner properties. Then, the liner installation is properly executed conforming to contract specifications. Finally, field validation is conducted using various benchmark testing and mechanical properties testing to ensure good quality work and successful installation.

4.2.1 Establishing the QA/QC criterion

According to USEPA (2011), a systematic approach to QA/QC is lacking in the water rehabilitation industry, especially as the governing patents for new rehabilitation techniques expire and proprietary systems become commodity products. To provide strong incentive to adopt improved technologies for water system rehabilitation, cost-effective methods and protocols for collecting quantitative in-situ data regarding the baseline performance of the rehabilitated pipe are critical and will facilitate the establishment of successful installation QA/QC and long-term performance monitoring programs among utilities. Quality assurance is a systematic activity implemented to provide confidence that a product or service will fulfill requirements for quality. Quality control is the operational techniques and activities used to fulfill requirements for quality. Often, "quality assurance" and "quality control" are used interchangeably, referring to the actions performed to ensure the quality of a product, service or process (Russell, 2012).

While no ASTM or AWWA standard specifically addresses QA/QC concerns for the non-structural and semi-structural lining processes, sections in ASTM F3182 and ASTM

F2831 has been adapted. These standards require that the contractor to provide QA and also perform various QC tests. Based on on-going research on VAL technology and lessons learned from the pilot project discussed in Chapters 2 and 3, a detailed list of QA/QC requirements, which addresses the owner and contractors has been formed.

4.2.2 QA/QC Procedures and Protocol

It is very important that all materials supplied to the work site should be properly labeled according to Workplace Hazardous Materials Information System (WHMIS) standards. That is to say, labels should include polymer manufacturer, product name, instructions, precautions, limitations and material expiry dates. However, the lining product should first be validated before they are supplied to be used in the field. Results of the cured sample testing should be reviewed. The sample should be tested for bond strength, mechanical properties, and porosity. In situ thickness should also be measured using an ultrasonic thickness gage calibrated for the particular polymeric material being applied.

In developing QA/QC guidelines for non-structural and semi-structural lining technology, some tests must be conducted to ensure linings applied to the interior surfaces of water mains perform well.

Table 4.1 and

Table 4.2 show all the laboratory and field tests and standards applicable to new non-structural lining technologies and semi-structural liners. Also, Figure 4.2 and Figure 4.3 present construction QA/QC procedures to assist in decision making before, during and after any lining project.

Table 4.1: Minimum standard requirements for AWWA Class I and II liners.

QA/QC Tests and Checks	**Kind of Test**	**Class I Liner**	**Class II Liner**	**Relevant Standard**	**# of Samples**	**Class I Minimum Requirement**	**Class II Minimum Requirement**	**Benchmark Acceptance Criteria**
Surface Preparation	Field	YES	YES	ASTM F2831	N/A	Conform to SSPC-SP 6/NACE. No. 3	Conform to SSPC-SP 6/NACE. No. 3	Totally dry pipe with light shadows of rust ≤ 33% of surface
Thickness	Field	YES	YES	ASTM D7091	Six test samples	0.2454 mm	1 mm	≥ 87.5% of the manufacturer's recommended value
Adhesion	Field	YES	YES	ASTM 4541	One sample	17.24 MPa (2500 Psi)	1.72 MPa (250 Psi)	≥ 87.5% min value
Pinholes	Field/On Spool	YES	NO	ASTM D5162	One sample	No pinholes or holidays	N/A	No holiday/pinholes
Immersion	On Spool	YES	YES	AWWA C210	One sample	Absence of peeling and liner disbondment	Absence of peeling and liner disbondment	No peeling and/or disbondment
Blistering	Field	YES	YES	ASTM D714	N/A	No blisters	No blisters	No "dense" blisters
Hole Spanning	Field	NO	YES	ASTM F1216	N/A	N/A	Bridge holes and gaps	Complete spanning of holes ≤ 6 mm

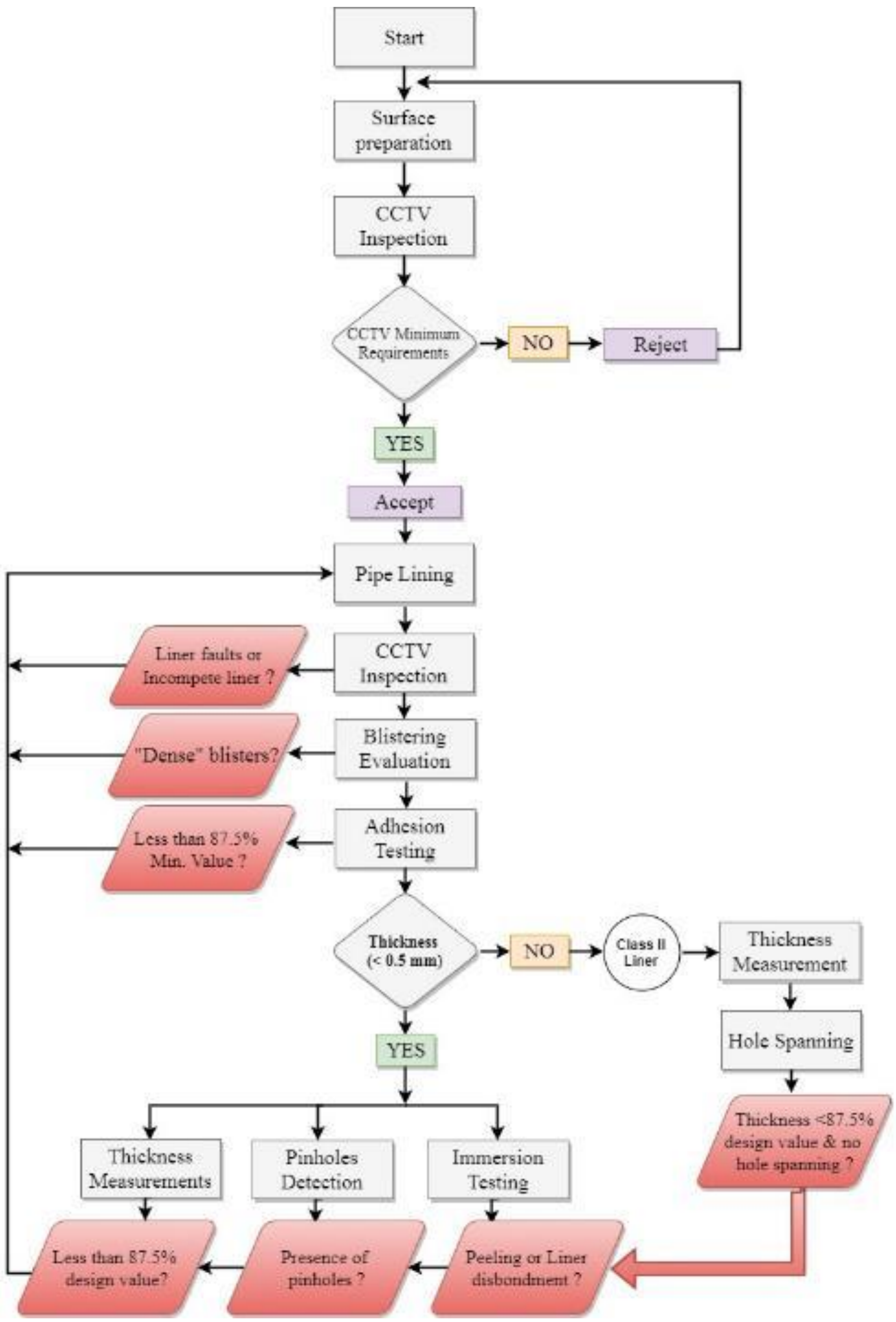


Figure 4.2: Decision making chart for AWWA Class I and II liners.

Table 4.2: Minimum standard requirements for AWWA Class III liners.

QA/QC Checks	Kind of Test	Class III Liner	Relevant Standard	# of Samples	Minimum Requirement	Benchmark Acceptance Criteria
Surface Preparation	Field	YES	ASTM F2831	N/A	Conform to SSPC-SP 6/NACE. No. 3	Totally dry pipe with light shadows of rust and old coatings ≤ 33% of surface
Thickness	Field/On Spool	YES	ASTM D7091/ D5813	Six test samples	1 mm	If not < 87.5% of manufacturer specified value
Bond between layers	Field/On Spool	YES	ASTM F3182/ D5813	One sample	Rating of 8. No free knife movement within layers	No delamination between successive coating layers
Tensile Testing	Lab/On Spool	YES	ASTM D638/ F1216	Five test samples	21 MPa (Strength)	≥ Minimum value, but can ± 87.5% manufacturer specified value
Flexural Testing	Lab/On Spool	YES	ASTM D714	Five test samples	31 MPa (Strength) 1724 MPa (Modulus)	As Above
Hole Spanning	Field	YES	ASTM F1216	N/A	Bridge holes and gaps	Complete spanning of holes ≥ 6 mm

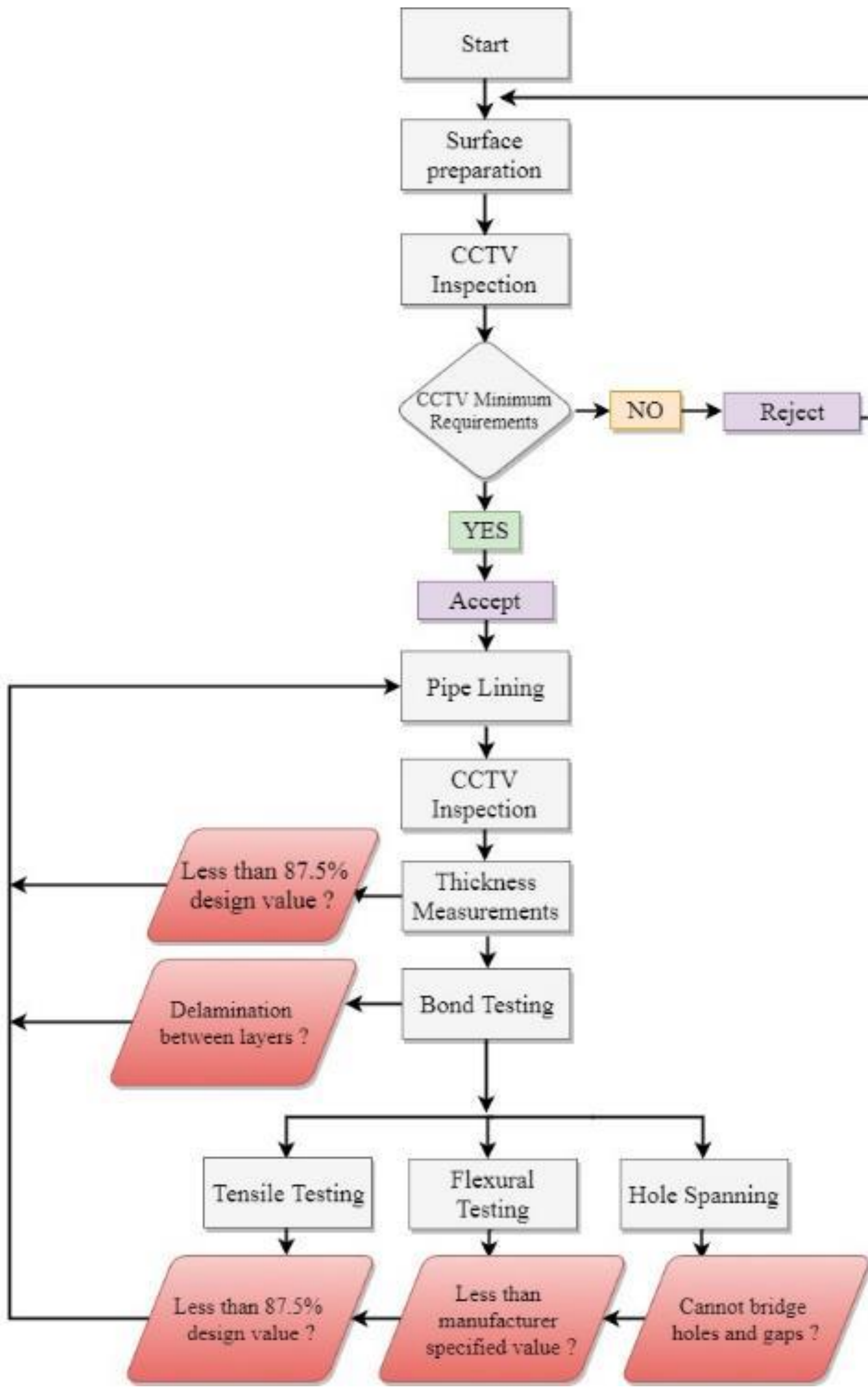


Figure 4.3: Decision making chart for AWWA class III liners.

4.2.3 Pipe Cleaning Requirements

Pipeline surface preparation is key to liner performance for both non-structural and semi-structural systems. As required by ASTM F3182, visual inspection with the aid of a CCTV camera is required before, after cleaning and before lining. The CCTV inspection of the pipeline should be performed and observed by the owner to ensure internal pipe surfaces are clean and free of standing water, deposits, and other debris or contaminants so as to ensure proper liner bonding to the pipe wall.

According to AWWA C210, when using abrasive blast cleaning method such as the new Tomahawk™ system, the pipe surfaces should be abrasive blast cleaned to achieve a near-white metal surface conforming to SSPC-SP 10/NACE No. 2. However, irrespective of the cleaning method, the minimum specification by ASTM F3182 must be achieved - a clean metal surface conforming to the SSPC-SP 7/NACE NO. 4 standard for the pipeline and the SSPC-SP 6/NACE NO.3 standard for service connections and terminations.

4.3 AWWA Class I and II Liner Qualification

4.3.1 Material Sampling and Field Validation

As described by the AWWA M28 manual, Class I and II Type Liner requires adhesion. This means the interaction with the host pipe needs to be evaluated, thereby rendering sampling method different from CIPP. Benchmark testing should be performed on field lined pipes and/or a test spool. Depending on the contract agreement, a part of the first lined section can be cut and tested following proper QA/QC protocol.

4.3.2 Visual Inspection

Blemishes in the lining and other deviations from an ideal installation should be given a thorough review by a CCTV camera. Lining faults such as ringing or ridging, incomplete lining, slumped linings, linings with water damage, and blisters are unacceptable. Also, any service blockages are unacceptable and should therefore be reinstated by remote robotic drilling.

According to ASTM F2831 (2012), for a liner to pass visual inspection it needs to be evenly distributed with no signs of blisters, sags, uncoated metal, delamination, ringing, or cuts. Apart from the CCTV videos that are used as visual aids after the lining process, cut samples should be first evaluated for visible defects.

4.3.3 Thickness Measurement

The lining thickness is the key design parameter to ensure that lining specifications have been met. The liner thickness should be measured at the pipe ends and on exhumed pipe samples. The average thickness must not be less than the specified thickness. Thin or incomplete lining should be pointed out. Although, these liners are not designed to have thick walls, the lining product should have sufficient thickness to prevent pinholes and to span holes and gaps. Adopting minimum thickness specification in ASTM D5831, The minimum wall thickness at any point shall not be less than 87.5 % of the specified thickness. Standard test methods in ASTM D7091 and ASTM D1005 should be use for the comparison of thickness readings along the length and also across the circumference of the pipe.

4.3.4 Adhesion Test

Tensile pull off strength test (ASTM D4541) should be carried out on field samples, a minimum value of 17.32 MPa should be achieved before a cohesive fracture is noted. The lining bonding is also key to the performance of Class I and II liners. Although the specified minimum value is based on tests conducted on flat plates, measured values obtained from measurements on curved surfaces should be within 87.5 % of the specified pull off values.

4.3.5 Pinhole/Holiday Detection

Poor installation of the liner may result in pinholes, water then may come in contact with the pipe metal and reduce the effectiveness of the liner. For a well-constructed lining, holiday density should be zero. This means that no pinholes are acceptable as these may generate corrosion concentration points in the substrate.

4.3.6 Immersion Test

The purpose of this is to test the properties of the lining material after immersion in water, acidic or alkaline solution. This is done before and after the lining. Conforming to AWWA C210 requirements, the samples should be kept covered at 25^{o}C for thirty days. After visually inspecting the samples if there is any blistering, peeling or disbondment of the liner, the liner is said to have failed.

4.3.7 Blistering Evaluation

Blistering may have occurred during the application of the internal linings. However, these should not be excessive. ASTM D714 provides photographic references for the classification (based on size and density), therefore comparisons are made based on visual inspection. No dense sized blisters are permissible for Class I and II liners.

4.3.8 Holes Bridging Capability

This characteristic feature distinguishes the AWWA Class II liners from the Class I liners. It is essential that a Class II lining is able to plug pre-existing holes up to 5 mm and gaps up to 4 mm in the host pipe. For larger gaps at joints, other repair methods should be used before or after lining.

4.4 AWWA Class III Liner Qualification

4.4.1 Material Sampling and Field Validation

As described by the AWWA M28 manual, class III type liner do not requires adhesion. This means the interaction with the host pipe is not a primary concern. However, the material properties are essential. The sampling method used for CIPP can be adopted. Benchmark testing should be performed on field lined PVC pipes and/or a test spool. In addition, plate samples should be used to test the chemical resistance and structural properties of the liner.

4.4.2 Visual Inspection

Blemishes in the lining and other deviations from an ideal installation should be given a thorough review by a CCTV camera. Lining faults such as ringing or ridging, incomplete lining, slumped linings, linings with water damage, and blistered linings should be watched out for. Also, any service blockages are unacceptable and should therefore be reinstated by remote robotic drilling.

According to ASTM F2831 (2012), for a liner to pass visual inspection it needs to be evenly distributed with no signs of blisters, sags, uncoated metal, delamination, ringing, or cuts. In addition, presence of cracks are checked closely around the joints and service connections.

4.4.3 Thickness Measurement

The lining thickness is the key design parameter to ensure that lining specifications have been met. The liner thickness should be measured at the pipe ends and on exhumed pipe samples. It is imperative that the lining meets or exceed the minimum thickness established by the design process.

Standard test methods in ASTM D1005 should be use to physically measure the thickness along the length and also across the circumference of the pipe. Thin or incomplete lining should be pointed out because strength is directly dependent on the thickness of the lining. Adopting minimum thickness specification in ASTM D5831, The minimum wall thickness at any point shall not be less than 87.5 % of the specified thickness.

4.4.4 Immersion Test

This is done before and after the lining. The lining material is evaluated after undergoing immersion in water, acidic or alkaline solution. Conforming to AWWA C210 requirements, the five samples should be kept covered at 25ºC for thirty days. After visually inspecting the samples if there is any blistering, peeling or disbondment of the liner, the liner is said to have failed.

4.4.5 Bond Test

The finished SIPP must fit tightly to the host pipeline at all observable points. The layers of the SIPP liner should be uniformly bonded so that they act as a whole. The liner should not be able to separate from its layers with a probe or point of a knife blade such that the knife blade moves freely between the layers. This is absolutely prohibited as the liner does not rely on adhesion but on its inherent ring stiffness capability.

4.4.6 Tensile Testing

The materials properties of the finished SIPP are required to conform to the minimum structural standards for tensile strength as measured by ASTM D638. The tensile strength of samples exhumed from the field will determine if the field product met the product design standards. The values are also compared with the design value for the liner since ASTM F3182 specifies that it is the manufacturer's responsibility to provide minimum tensile strength requirements. ASTM F1216 specifies a minimum of 21 MPa for the tensile strength.

4.4.7 Flexural Testing

The materials properties of the finished SIPP are required to conform to the minimum structural standards for flexural strength and modulus as measured by ASTM D790. The measured values of samples exhumed from the field will determine if the field product met the product design standards. ASTM F1216 specifies a minimum of 21 MPa and 1,724 MPa for the flexural strength and modulus respectively.

4.5 Conclusions

This study designed a performance QA/QC document regarding activities involving the design, manufacturing, and installation of non-structural and semi-structural lining systems. Minimum performance parameters has been identified and specified to ensure the finished lining product's installation assure long term performance.

Due to susceptibility to defects during liner installation, adequate project monitoring has been identified to ensure longevity of non-structural and semi-structural systems. Acceptance criteria has been documented, guidelines for sample preparation, number of samples, and field validation QA/QC tests are provided. Compared to other liners, benchmark tests on AWWA Class I Type Liners must performed be on field samples as the interaction with the host pipe needs to be evaluated.

Testing on the liners included: thickness, pull-off adhesion, pinholes, immersion, and blistering evaluation and mechanical properties validation. To this end, lining faults such as ringing or ridging, incomplete lining, and blisters are unacceptable. Semi-structural liners need sufficient thickness to prevent pinholes and to span holes and gaps. These are required to have the capabilities to plug pre-existing holes up to 5 mm and gaps up to 4 mm in the host pipe. Although it is the manufacturer's responsibility to provide design values, minimum tensile and flexural strength requirements, these values are not permitted to fall below the required standard minimum and/or should with be within 87.5% of manufacturer specified value.

Chapter 5
Conclusions and Recommendations for Future Work

5.1 Conclusions

The research presented herein provides a comprehensive study on both non-structural and semi-structural liners, which are used in the renovation of partially deteriorated potable water distribution pipelines. Based on field validation and demonstrations, experimental parameters such as liner-host pipe bond strength, thickness, and other physical properties of the lining product has been investigated. Three manuscripts have been developed to document findings regarding a testing program performed on two innovative lining technologies. Based on this study, the following can be concluded:

1) A new waterless pipe cleaning method removed all tubercle, biofilms, and graphite to prepare the pipes surface to a near-white metal SSPC 10/Nace No. 2 finish. Compared to water-based cleaning methods, the dry cleaning method ensured there are no visible gaps between the liner and host pipe;
2) Non-structural liner with thickness value below 1 mm exhibited zero discontinuity/pinhole, good adherence to host pipe up to 13.79 MPa pull-off strength value, no pinholes, and chemical resistance;
3) AWWA Class III Semi-Structural Type Liners require flexibility to avoid the generation of cracks after liner installation. Cracks noticed at an early stage in the field study was attributed to brittle behavior of liner as both tensile and flexural strain values are below 2%;
4) For QA/QC field testing, which involves evaluation of curved samples, factors such as curvature, roughness of material, and test methods are observed to impact reproducibility of test results. This is true for adhesion, tensile and flexural testing.

5.2 Recommendations for Future Work

A new testing methodology has been used in this thesis to test new non-structural and semi-structural internal pipe linings. However, there are some limitations to the experiments performed, and therefore needs to be improved in the future. Specific recommendations for future research work are listed as follows:

1) For this project, test sections were mainly abandoned pipes. It will be better to repeat these pilot studies on pipelines that would be put back in service;
2) Test methodology presented herein needs to be developed to perform liner qualification tests on curved pipes materials in the field; and
3) Further studies may be conducted to modify the components of the lining product for possible reduction of the slow curing of the Vacuum Applied Liners and prevention of early cracks generated in Spray Applied Liners.

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